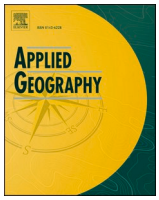
Applied Geography 190 (2026) 103977

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog



Too little space for renewables? Modeling carbon-neutral energy futures in southern Germany

Dragan Petrovic [a,*], Friederike Schrade [a], Stephan Bosch [a,b], Harald Kunstmann [a,b,c]

[a] Institute of Geography, University of Augsburg, Alter Postweg 118, 86159, Augsburg, Germany
[b] Centre for Climate Resilience, University of Augsburg, Universitätsstraße 12, 86159, Augsburg, Germany
[c] Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Campus Alpin, Kreuzeckbahnstraße 19, 82467, Garmisch-Partenkirchen, Germany

1. Introduction

The ongoing polycrisis – climate change, biodiversity loss, and rising sea levels – demands rapid action from the EU and its member states, as climate science stresses a narrow window for transformation (UNEP, 2022). EU policy aims to renew the energy system, targeting a 55% reduction in greenhouse gas emissions by 2030 (compared to 1990), carbon neutrality by 2050, and negative emissions thereafter (EC, 2024). In Germany, renewable expansion must accelerate substantially to reach a 42.5% share of final energy consumption by 2030 (UBA, 2024a). Current measures fall short to achieve the reduction targets for 2030 (-55% compared to 1990) and 2050 (-95%), requiring a three-to sevenfold increase in transformation speed (UBA, 2024a). However, achieving this in a densely populated country is uncertain due to limited land and strict spatial constraints from nature conservation, monument protection and large distances from settlements (Bosch, 2021).

German spatial planning appears ill-prepared for the renewed localization of energy production in rural areas. Despite its strong economy, Germany's planning law historically dealt little with energy generation or climate protection. The government's climate targets have never been systematically assessed against spatial constraints. Limited data exist on the land required for a full energy transition, its availability under current law, or potential siting options. Densely populated countries with ambitious energy goals often lack empirical evidence on spatial and technological feasibility (Pijlman & Bosman, 2014). Although the Reiner Lemoine Institute's *PV and Wind calculator* indicates sufficient land potential in Germany, numerous legal restrictions hinder site designation (Saerbeck et al., 2021). An explicit method for optimally locating renewable energy (RE) systems that aligns with both the Paris Agreement and existing planning regulations is still missing.

Identifying suitable, low-conflict sites for RE is vital but poses complex planning challenges. National energy goals often diverge from local planning decisions (Quentin, 2019). In Germany, there are also concerns that suitable wind and photovoltaic (PV) sites may be limited further, for example through expanded species protection zones, so that reaching state- and regional-specific spatial targets for RE sites will become more difficult (Weber et al., 2023). Identifying RE sites is often connected to spatial trade-offs between RE production, nature conservation and landscape aesthetics. Such trade-offs occur when the achievement of one sustainability goal interferes with another goal (de Magalhães et al., 2019; Weber et al., 2023). These trade-offs mainly include competition for sites with other land uses like species protection, forestry, agriculture and settlements (e.g., Armstrong et al., 2016; Bulling, 2016; Dale et al., 2011; de Magalhães et al., 2019; Straka et al., 2020; Tafarte & Lehmann, 2021). The extent of spatial trade-offs depends on the social and ecological prerequisites of the specific locations. For example, certain locations are more prone to collisions between species and wind turbines than others (Bulling, 2016; Schuster et al., 2015; Tanaka et al., 2022). Even though RE sites reduce CO_2-emissions in the electricity sector, their use in climate change mitigation can conflict with biodiversity. This dilemma is also known as the 'green-on-green' dilemma (Straka et al., 2020).

Geographic information system (GIS)-based methods are widely used to identify optimal sites for RE systems, particularly wind and solar. Most studies apply multi-criteria analyses that evaluate RE potential based on factors such as land availability, grid proximity, environmental and technical constraints, social acceptance, and economic or political conditions. For overviews of the constraining criteria, see also Jbaihi et al. (2022) and Fakharizadehshirazi & Rösch (2024). Various weighting techniques are used, including the Network Analysis Process (NAP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and especially the Analytic Hierarchy Process (AHP), which is commonly applied in recent research e.g., by Höfer et al. (2016), Saraswat et al. (2021), Shorabeh et al. (2022a) and Fakharizadehshirazi & Rösch (2024). Adedeji et al. (2020) offer an overview of these multi-criteria decision-making methods and their relative strengths and limitations. Multi-criteria analyses have been conducted worldwide and across all spatial scales – from continents to cities. Wind power studies

* Corresponding author.
E-mail address: dragan.petrovic@uni-a.de (D. Petrovic).

https://doi.org/10.1016/j.apgeog.2026.103977
Received 30 October 2025; Received in revised form 23 February 2026; Accepted 12 March 2026
Available online 20 March 2026
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include cases from Germany's Aachen district (Höfer et al., 2016), Iran (Shorabeh et al., 2022b), and Iraq (Nassif et al., 2024). PV research spans Morocco (Jbaihi et al., 2022), China's Shanxi province (Cui et al., 2023), northern Spain (de Luis-Ruiz et al., 2024), and Germany (Fakharizadehshirazi & Rösch, 2024). Combined analyses of wind and solar have been conducted in India (Saraswat et al., 2021) and Africa (Doorga et al., 2022).

GIS-based RE site selection approaches without multi-criteria analysis include McGhee (2023), Benalcazar et al. (2024), and Okedu et al. (2024). Benalcazar et al. (2024) present a GIS tool for regional land suitability and techno-economic assessment of utility-scale PV in Poland. Okedu et al. (2024) offer a holistic GIS-based evaluation of RE potentials in Nigeria. McGhee (2023) introduces the Geospatial Opportunity Mapping (GOMap) tool, originally for Glasgow, which identifies unrestricted land, assesses technical feasibility, and produces detailed maps for wind and PV deployment. GOMap is GIS-compatible and allows scenario-based analysis of policy and technical constraints.

In most of the studies mentioned above, the main focus is primarily on identifying the potential for RE development. However, an accurate simulation of the distribution of the respective sites over time, based on planning regulations, energy demands, CO_2-budgets, and socio-spatial balance is often missing. Instead, the studies are mostly limited to maps that only visualize the current suitability of sites for specific RE technologies. Bosch and Kienmoser (2024) go one step further. By using a GIS-based approach, they model different scenarios by modifying the regional planning guidelines for the deployment of REs until 2045 for the planning region of Augsburg, Germany. Wiehe et al. (2021) developed a GIS-based model that integrates RE potentials for Wind and PV as well as vulnerabilities of nature and humans for Germany. Their goal was to identify ways in which the expansion of REs can be reconciled with environmental and social concerns until 2050. To implement this, two scenarios were used for the RE site selection: one with a strong focus on nature and human compatibility, and one with compromises between energy targets and other interests. McKenna et al. (2022) analyze spatial trade-offs between landscape quality, land use, and resource potential for onshore wind and PV in the UK through 2050. Using GIS data and 'scenicness' ratings, they show that scenically attractive areas have lower planning success for wind energy. Delafield et al. (2024) use the ADVENT-NEV model, a spatially explicit approach that combines energy system modeling with natural capital assessment for the UK up to 2050. They show that optimal locations for onshore wind, PV, and bioenergy shift significantly when ecological values are taken into account. This can reduce environmental impacts and generate large-scale social welfare gains.

Several studies have examined RE site deployment in Germany. Jung et al. (2018) developed wind turbine siting scenarios to achieve a 40% share of wind energy in gross electricity consumption, varying in distribution criteria, administrative responsibilities, repowering rates, and turbine types, using a 200m × 200m national grid. Meier et al. (2024) analyzed the effects of spatial planning policies on wind deployment, building on earlier work by Lauf et al. (2020) and Stede & May (2020), which focused on setback rules in Bavaria and designated area impacts in Germany and Sweden. Their study covers the time period 2000–2016. These studies lack analysis to what extent deviations from current planning law, which are possible, probable or even necessary as land use variants in the future, would facilitate or hinder the development of a carbon-neutral energy supply. It is also unclear what social and environmental impacts would be associated with such spatial shifts in a carbon-neutral energy system. None of the studies provides a concrete model of both wind and PV sites over time and in relation to (changing) planning guidelines, energy demands, and CO_2-budgets.

Thus, the aim of this study is to model the expansion of wind and PV systems for a large region of Germany – the Allgäu region – in a way that meets national and international climate protection goals. Using a GIS-based approach it aligns regional energy planning with Germany's target of carbon neutrality by 2045 while ensuring that the remaining global CO_2-budgets under the two-degree limit are proportionally respected.

First, the study examines how current planning regulations enable or restrict RE deployment, identifying areas that could become technically overdeveloped and those excluded due to strict legal constraints. It then explores alternative scenarios by varying planning laws, such as reducing competing land-use restrictions or redistributing landscape burdens more equitably, to analyze different siting options. By integrating region-specific CO_2-budgets, energy demands, and technological progress, the study models RE deployment year by year under multiple policy and planning scenarios.

From these objectives we derive the following research questions:

1. How can regional (renewable) energy landscapes be modeled within spatial planning constraints to achieve carbon-neutral electricity in line with the Paris climate goals?
2. To what extent do current planning regulations impede the realization of a carbon-neutral electricity sector?
3. What socio-technical implications accompany the changes to the landscape?
4. How would changes in planning law influence the availability of land for RE deployment?

A specially developed siting algorithm serves as a tool for optimal placement of RE sites. This algorithm operates at a very high spatial resolution of 100 m, allowing highly precise localization of wind and PV systems. Moreover, it directly incorporates actual climate targets into the modeling process, ensuring that energy expansion is fully aligned with policy objectives. By analyzing the sociotechnical impacts and exploring how technologies, people, and environments interact, the study sheds light on how adaptive planning laws and innovative technologies can shape future energy landscapes.

The core innovations of this study include RE siting in line with the Paris 2015 climate goals, a combination of a GIS-based approach and a siting algorithm and the implication of different planning pathways. This way, we can identify potential spatial corridors for a carbon-neutral electricity supply that reflects current planning law and include spatial deviations from it. It allows exploration of alternative weightings of fairness, nature conservation, distance areas, technological progress, and electricity demand. The exclusion areas, which cover various criteria and will be described in more detail in the following sections, ensure that the RE site distribution complies with regulations and minimize land use conflicts. The siting algorithm is a decisive extension compared to Bosch and Kienmoser (2024), as we place individual wind turbines with their corresponding dimensions and respective spacing rules instead of using areas of wind energy. This allows for enhanced spatial precision.

2. Methodology

In this section a description of our methodological approach is given. First, we describe how basal data such as (regional) CO_2-budgets, electricity demand, population data and their projections were derived. This is followed by an explanation of the GIS-based procedure for generating the spatial input data required for the siting algorithm. Next, we give a detailed description of the land use scenarios we work with. Finally, we present our siting algorithm, which represents a new and innovative distribution method for RE sites to model the different energy landscape options. We refer to energy landscapes as the part of the physical environment affected by energy transitions (Pasqualetti, 2013; Selman, 2010; van der Horst & Vermeylen, 2011). These landscapes are the socio-spatial manifestations of energy systems that embody the dynamic relationships among technologies, people, their environments, and their perceptions of them (Calvert et al., 2019).

2.1. Determination of CO_2-budgets and electricity demands

The permissible duration of the energy transition process is limited by regional CO_2-budgets, which must not be exceeded. As long as fossil-fueled power plants continue to generate electricity, the CO_2-emissions per kWh generated are deducted from the current total regional CO_2-budget. The calculation of total regional CO_2-budgets for the 2023-2045 modeling period is based on IPCC (2021). With regard to our objectives, we are guided by the two-degree target budget, which we aim to achieve with an 83% probability. Our modeling approach is therefore based on the IPCC defined budget value of 900 Gt, which results in a global CO_2-budget of 791 Gt for 2023, considering the CO_2-emissions already emitted in 2020-2022 (109 Gt) (Friedlingstein et al., 2022; Statista, 2024a). Assuming an average world population of 8.764 billion over the modeling period, which is derived from world population projections to 2100 (Statista, 2024b), this results in an absolute per capita budget of 90.3 tons of CO_2. Regional CO_2-budgets are then calculated by multiplying this figure by the regional population.

To determine the electricity demand of the study region (Allgäu region), the gross electricity demand of Germany in 2023 (UBA, 2024b) was converted to the number of inhabitants in the respective region on September 30, 2023 (StatBay, 2023). Based on a study by the transmission system operators, an overall increase in electricity demand of 110% is expected by 2045 compared to 2023 (Statista Research Department, 2025; Uebertragungsnetzbetreiber, 2023). From this, the electricity demand for each individual year up to 2045 can be derived. The main reason for the increase in demand is the electrification of industry, transportation, and heating. Hydrogen utilization and increased electromobility play a particularly important role in this context (Kemmler et al., 2021; McKinsey and Company, 2024; BEE e.V., 2025; Stobbe et al., 2025). By 2045, the share of RE in electricity production should be 100% (cf. policy goal of carbon neutrality). In 2023, the starting point of our modeling, these shares represent 46% in the Allgäu planning region (Bavarian State Government, 2025). The shares will increase gradually each year during the modeling period and this expansion will be modeled spatially. As the share of renewables in electricity production is expected to reach 100% by 2045, no further expansion takes place in that year. With regard to PV demand, we assume, in line with the photovoltaic strategy of the Federal Ministry for Economic Affairs and Energy (BMWK, 2023), that future deployment will be evenly distributed between ground-mounted and rooftop PV systems. This study only models ground-mounted PV systems, as this solar technology path causes major and controversial changes to rural landscapes. For reasons of grid stabilization in the face of fluctuating weather conditions, it is also assumed that 50% of the electricity demand is met by wind and 50% by PV. The modeled PV capacity therefore covers only 25% of the total electricity demand.

2.2. GIS-based restriction analysis

The GIS-based spatio-temporal modeling approach utilized in this study is underpinned by a siting algorithm that draws upon a set of spatial input data. The identification of suitable and available areas for RE expansion was undertaken using the GIS software *ArcGISpro*. The data foundation of our spatial modeling is a digital landscape model (BVV, 2023), which includes both diverse land uses (e.g., agricultural landscapes) and administrative boundaries (e.g., municipalities). As pointed out by Risch et al. (2022), a digital landscape model is superior to the Corine Land Cover data set (Copernicus Programme, 2018), that was used in Bosch & Kienmoser (2024). As an initial step, a basic grid with a resolution of 100 m was created for the study region, providing a structured spatial framework for further analysis. The centers of the grid cells were defined as reference points. This grid acts as a spatial reference system, facilitating the division of the region into uniform cells and providing a structured basis for the subsequent analysis of the spatial data. The individual reference points were linked to the natural site factors (global radiation and wind speed), and consequently, the yields of the reference plants were determined for each point. The energy potentials were then used to determine the yields for the reference plants.

In order to determine the areas available for expansion, it was first necessary to define the areas that are fundamentally suitable for the expansion of the energy systems under consideration: For wind power plants, these areas included arable land, grassland, semi-natural areas and forest areas with a slope of less than 30°. For ground-mounted PV systems, the relevant areas were arable land, grassland, semi-natural areas and conversion areas with a slope of less than 45° and a north-facing orientation of less than 30°. The exclusion areas for the base scenario, representing the prevailing planning regime, were then defined (see Tables 1 and 2) and subtracted from the potential areas. In terms of legal suitability, only exclusion zones, such as distances from settlements and infrastructure or nature conservation areas, were considered. As a result, specific planning at individual sites would require more detailed analysis at the micro level to weigh up the various spatial restrictions.

To prevent installations from encroaching into neighboring exclusion zones or areas unsuitable for their installation, exclusion zones for the construction of wind turbines were given an additional buffer equivalent to one rotor length of the reference turbine. The suitability zones for ground-mounted PV systems, on the other hand, were buffered inwards by half a grid cell (-50 m) to prevent them extending into areas that are unsuitable for their installation (e.g., forest areas). The difference in approach is due to the fact that wind turbines are modeled as points, while PV systems are modeled as grid cells, each of which covers an area of 1 ha (100 × 100 m).

Finally, the entire study area was classified as either suitable or unsuitable for the installation of the RE systems considered. This classification was then assigned to the grid centers using the *spatial join* function. The resulting table was exported for further analysis. In addition, the *spatial join* function was used to calculate the area proportions of the land use types on which the modeled installations are located.

The input dataset for the base scenario comprises the following variables in a 100 m raster format: Projected latitude and longitude coordinates, affiliation to the rural district or municipality (BVV, 2023), the average (1991-2023) global radiation (Deutscher Wetterdienst,

Table 1
Suitability and exclusion criteria considered in the wind turbine modeling/baseline scenario.

Land types generally considered suitable	
arable land, grassland, semi-natural areas and forest areas	
Exclusion criteria	
Technical	areas > 30°
Nature conservation	national parks, legally protected biotopes, protected landscape elements, natural monuments, nature conservation areas, Alpenplan zone C
Water protection	50 m buffer: First-order water bodies & standing waters >1 ha, buffer strips, water protection zones I and II
Military	military training areas, maximum height limitation
Infrastructure	seismic stations with mandatory buffer zones, stations of the German Meteorological Service with mandatory buffer zones, railway lines with 150 m buffer, commercial airports with 4.000 m buffer, other airports with 1.500 m buffer, pipelines and cableways with 1 rotor diameter buffer, motorways with 40 m buffer, federal roads with 20 m buffer, state roads with 20 m buffer, county roads with 15 m buffer, existing wind turbines with 4-fold rotor diameter buffer
Forest conservation	natural forest areas
Settlement distances	inner residential areas with 700 m buffer, outer residential areas with 460 m buffer, health and recreation areas with 750 m buffer, industrial and commercial areas with 300 m buffer, sports, leisure and recreation areas with 400 m buffer

Table 2
Suitability and exclusion criteria considered in the ground-mounted PV modeling/baseline scenario.

Land types generally considered suitable	
arable land, grassland, semi-natural areas and conversion areas	
Exclusion criteria	
Technical	areas > 45° and areas > 30° north-facing
Nature conservation	national parks, legally protected biotopes, protected landscape elements, natural monuments, nature conservation areas, Alpenplan zone C, designated areas for farmland bird habitat (lapwing), designated areas for meadow-breeding birds, legally established compensation and replacement areas
Water protection	50 m buffer: First-order water bodies & standing waters >1 ha, buffer strips, water protection zones I and II
Military	military training areas

2024a), the average (1981-2010) wind speed at 160 m hub height (DWD, 2024b), derived wind and PV energy yields based on the reference systems used for wind turbines (Enercon, 2022) and ground-mounted PV systems (Canadian Solar, 2022), as well as an indicator of whether the site is technically and legally suitable for wind and/or PV systems under the current planning regime.

2.3. Land use scenarios

In developing land use scenarios, we are guided by the criteria of Dewald et al. (2019) and Bosch & Kienmoser (2024). According to this, the modeled potential energy futures must be plausible, i.e. possible in principle, and the assumptions should be coherent, distinguishable from each other and comprehensible to potential users (policy and planning). The challenge of GIS-based analysis also lies in the choice of a meaningful level of aggregation. In the trade-off between processing capacity and informative value, data collection for large areas oscillates between being as precise as necessary and as abstract as possible.

We create and model different types of scenarios as part of our analysis. All scenarios have the same normative character – cf. Börjeson et al. (2006) – as we base our calculations on national and international climate protection guidelines. The starting point of our first scenario is the assumption that nothing will change in the current legal, political and spatial framework. Using this forecasting approach, we extrapolate existing trends to cover a very likely development in the RE expansion. The other scenarios represent alternative energy futures that are not yet possible under current planning law but are conceivable and possibly necessary in view of the social debates and discursive dynamics surrounding the energy transition.

Six scenarios are modeled for this study. The analysis starts with a baseline scenario in which the current socio-technical framework is maintained. Several factors and spatial implications are altered in the other scenarios. We distinguish the scenarios as follows: *1. Baseline*, *2. Wind Efficiency & Demand Sufficiency*, *3. Municipal PV*, *4. Wind Power Density*, *5. Nature Conservation Plus* and *6. Nature Conservation Minus*.

As its name suggests, our *Baseline* scenario is the foundation upon which all analyses are built. This scenario is based on the calculated energy demand of the study region and uses a specific WPP model, the *Enercon E-138 EP3*. The PV calculations are based on the *CanadianSolar HiKu6 Mono PERC* model. The size of each PV system is 1 ha. Wind and PV plants are distributed across the entire region, starting with the most efficient sites. The *Wind Efficiency & Demand Sufficiency* scenario assumes that the projected energy demand is halved over the entire modeling period and uses a newer and more efficient wind turbine model, the *Enercon E-175 EP5* (Enercon, 2023). This model has a larger rotor diameter, which has an impact on the spacing of the wind turbines, as they also become larger. Reduced future energy demand could be the result of technological advances in industry and the economy, as well as a change in the energy awareness of the population. In the *Municipal PV* scenario, the wind turbines are distributed in the same way as in the *Baseline* scenario, but the distribution of the PV sites is based on the energy demand of the respective municipalities. This distribution contributes to spatial equity by spreading the spatial load more evenly and according to specific local needs. Municipalities with a surplus or deficit can export or must import energy. The *Wind Power Density* scenario is an experiment to explore the effects of changes in legislation regarding minimum distances of wind turbines from residential areas. It involves halving the minimum distances that a wind turbine must legally comply with. In the *Nature Conservation Plus* (NCP) scenario increased nature conservation efforts are simulated, resulting in less total land available for RE sites. In the *Nature Conservation Minus* (NCM) scenario, nature conservation is reduced to a maximum, making more land available for REs. For reference, Table 3 provides an overview of each scenario, accompanied by explanatory notes.

2.4. Siting algorithm

The siting algorithm was created using the R programming environment, which offers numerous useful features.

The R script works as follows: first, suitable sites for wind and PV are identified. Wind sites are distributed prior to PV sites, as they have significantly higher yields per hectare. The potential wind sites are first ranked in descending order of estimated yield. Distance ellipses are then created around each potential site, aligned with the dominant southwesterly wind direction in the region. The length of the primary main axis of the ellipses is five times the rotor diameter of the wind turbine used, while the length of the secondary axis is three times the rotor diameter (FA Wind, 2019). Next, the overlapping areas between each ellipses are identified. If the overlap includes the core of another ellipse, the ellipse belonging to the point with the lower wind yield potential is removed, as the distance between the individual turbines would be insufficient. In the next step, the remaining wind sites are assessed for their ability to meet the wind energy needs of the region. The annual number of wind turbines required is then determined on the basis of the potential yields. For the last year, in which the demand cannot be fully covered, all remaining wind turbines are installed. The remaining wind demand of that last year is added to the PV demand of the same year. The demand for all remaining years with no more wind potential left is added to the PV demand for those years. This is what we call the *Switch* from wind to PV energy when there is insufficient wind potential.

Once all the wind sites have been distributed, the next step is to distribute the PV sites. Up to this point, the steps are identical in all scenarios. In each scenario except *Municipal PV*, the steps for the PV site distribution are as follows: first, the sites are sorted in descending order of potential. The annual PV and additional *Switch* requirements are then

Table 3
Overview of the scenarios applied.

Land use scenario	Description
Baseline	WPP: *Enercon E-138 EP3*; PVP: *CanadianSolar HiKu6 Mono PERC*; energy demand as calculated.
Wind Efficiency & Demand Sufficiency	WPP: *Enercon E-175 EP5*; PVP: *CanadianSolar HiKu6 Mono PERC*; energy demand halved.
Municipal PV	WPP: *Enercon E-138 EP3*; PVP: *CanadianSolar HiKu6 Mono PERC*; energy demand as calculated; distribution of the PV sites municipality based depending on the respective demands.
Wind Power Density	WPP: *Enercon E-138 EP3*; PVP: *CanadianSolar HiKu6 Mono PERC*; energy demand as calculated; the legally required minimum WPP distance to all surfaces is reduced by half; distribution of the PV sites across the entire region.
Nature Conservation Plus	WPP: *Enercon E-138 EP3*; PVP: *CanadianSolar HiKu6 Mono PERC*; energy demand as calculated; increased nature conservation efforts reducing the available land for RE sites.
Nature Conservation Minus	WPP: *Enercon E-138 EP3*; PVP: *CanadianSolar HiKu6 Mono PERC*; energy demand as calculated; reduced nature conservation efforts increasing the available land for RE sites.

determined. Subsequentially, the respective PV plants are distributed. Finally, a data table is compiled containing information on the coordinates of each installed wind turbine and PV system, the year of installation, and the corresponding yield. This dataset is transferred back to the GIS for visualization.

The distribution of both wind and PV is based purely on potential, i.e. the best locations are occupied first, followed by those with less potential. An exception to this is the *Municipal PV* scenario. While the wind turbines are distributed in the same way as in the other scenarios, PV sites are distributed based on whether the site belongs to a municipality. To do this, it is necessary to identify which municipalities do not have (enough) land available for PV. The demand of these municipalities is then added to the demand of all other municipalities for the whole modeling period. An assessment is conducted to determine the number of municipalities that initially have sufficient potential. If this is not the case, all PV sites are initially distributed over the entire period. The differences to the remaining demand are then added to the demand of the remaining municipalities and a new assessment is carried out. This process is repeated until either all PV demand is met, or all PV sites have been distributed. Within each municipality, the sites are also distributed according to potential, starting with the best sites. By taking into account municipal boundaries, clusters of PV sites are avoided. As mentioned above, this procedure contributes to spatial equity.

3. Results

The cartographic and quantitative results of the different energy futures modeled are presented below.

3.1. Baseline

Fig. 1 illustrates what a future carbon-neutral energy system could look like under the current planning framework. It shows the spatial and temporal distribution of the different energy technologies over the modeling period.

Wind turbine sites are fairly evenly distributed across the region, with the exception of significantly fewer turbines in the central and western areas. Although all possible sites have been investigated, the current planning regime does not allow for enough potential wind sites to meet half of the region's projected energy needs. Furthermore, the existing wind conditions are not sufficient to compensate for the limited number of suitable sites. The PV potential is sufficient for the entire modeling period up to 2045, including the need for a *Switch* from 2028 on to compensate for the lack of wind potential. Two PV clusters are clearly visible: in the extreme northeast and in the extreme west. The rest of the area remains largely unoccupied by PV. These clusters result from the potential-driven distribution. The spatial concentrations therefore also represent the highest values of global radiation.

In this scenario, wind power meets about 41% of the projected demand. While 100% of the PV demand is met, there is theoretically potential for around ten times the calculated demand. A total of 470 wind turbines is installed, corresponding to an area requirement of 235 ha and installed capacity of 2 GW. Around 64% of installations are located in forest areas, with the remaining 36% situated in agricultural areas. The number of PV systems installed in this scenario is 10,977, which corresponds to the same number of hectares and a capacity of about 46 GWp. 99.95% of the systems are installed on agricultural land, with the remainder being located on conversion areas.

3.2. Wind Efficiency & Demand Sufficiency

As shown in Fig. 2, the use of more efficient wind turbines, combined with more optimized energy use, leads to a significant reduction in installation density. This is because the total capacity can be achieved

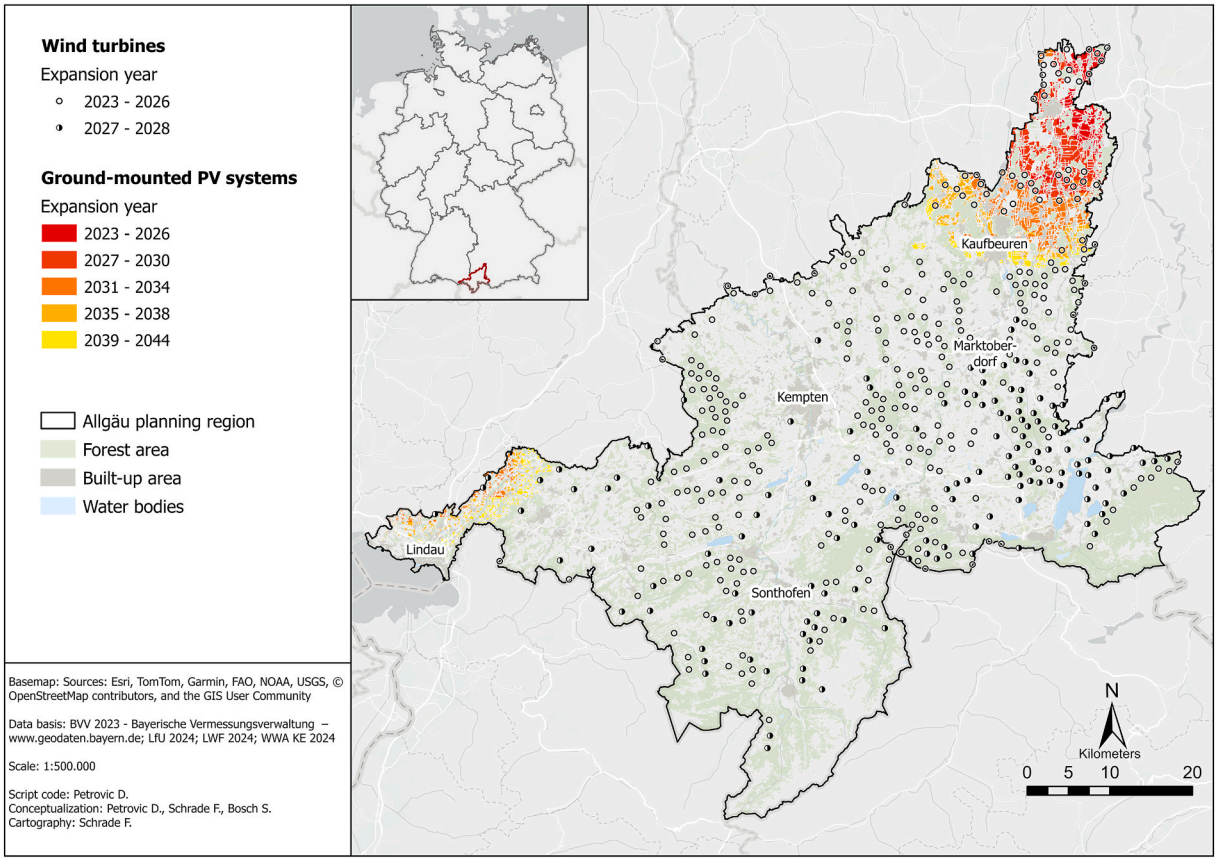

Fig. 1. *Baseline* scenario for the Allgäu region in the year 2045. Data basis: ;BVV, 2023; LfU, 2024; LWF, 2024; WWA KE, 2024.

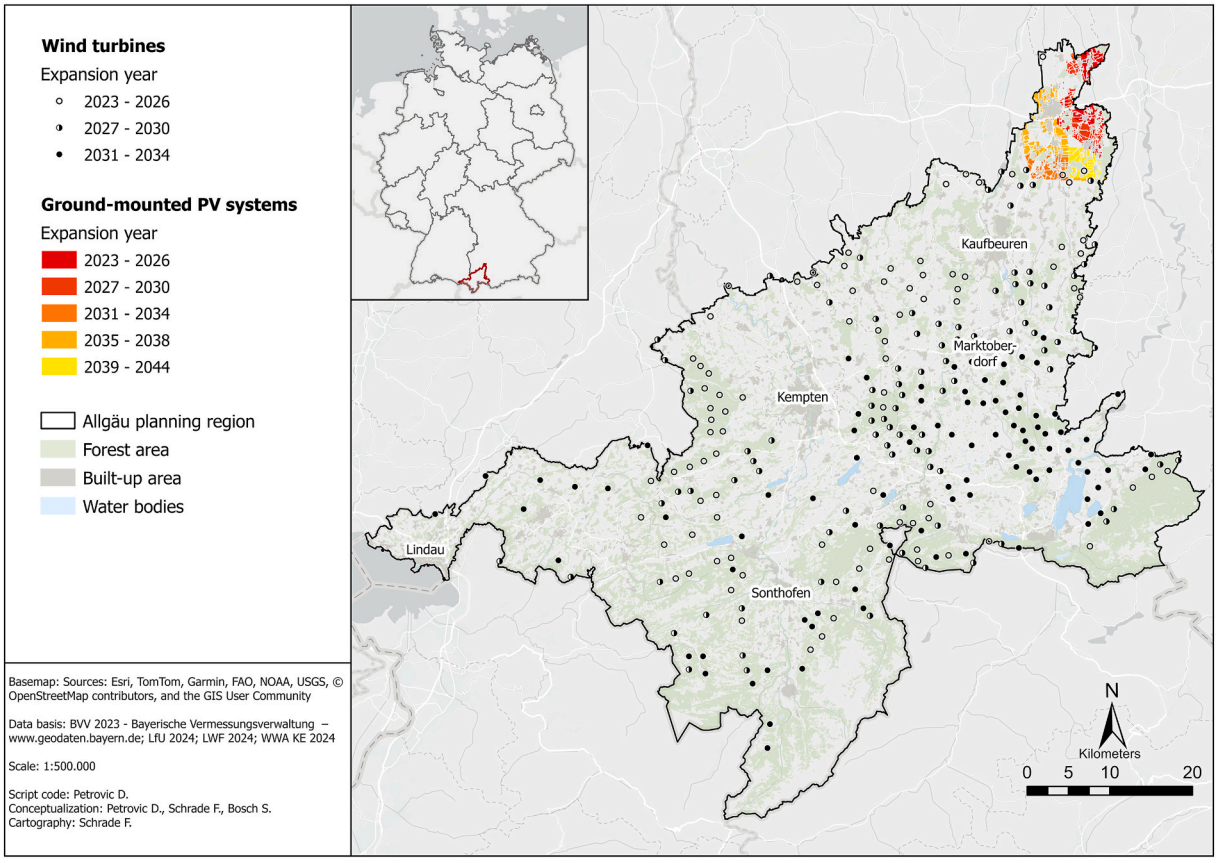

Fig. 2. *Wind Efficiency & Demand Sufficiency* scenario for the Allgäu region in the year 2045. Data basis: BVV, 2023; LfU, 2024; LWF, 2024; WWA KE, 2024.

with fewer units. However, it is also not possible to split the energy demand between 50% wind and 50% PV over the whole period.

Compared to *Baseline*, there are significantly fewer wind turbines in this scenario, but they are more efficient. The lower number of turbines is due to the larger rotor diameters, which require greater distances both between individual wind turbines and between turbines and exclusion zones. The combination of more efficient wind turbines and halved energy demand ensures that the wind potential lasts until 2034, six years longer than in *Baseline*. After that, the *Switch* is applied. However, unlike *Baseline*, the wind turbines are less evenly distributed across the region and are more concentrated in the eastern area. Again, there is sufficient PV potential to meet all PV demand, including the *Switch* demand for the entire period. The difference is that this scenario requires significantly fewer installations than *Baseline*. The PV systems are only installed in the northern area, resulting in only one PV cluster compared to *Baseline*, which is also significantly smaller.

In this scenario, wind power can meet around 77% of demand, which is significantly more than in *Baseline*. PV can also meet 100% of demand, while there is potential for around 20 times the demand. These figures illustrate the huge PV potential in the region. A total of 277 wind turbines are installed in this scenario, 193 fewer than in *Baseline*. The number of PV systems here is 3,640, equaling 7,337 fewer than in *Baseline*. This corresponds to a land requirement of 138.5 ha for wind turbines (-96.5 ha compared to *Baseline*) and 3,640 ha for PV systems (-7,337 ha compared to *Baseline*). Around 68% of the wind area is forest, while the remaining 32% is agricultural land. All PV systems are installed on agricultural land in this scenario. The wind capacity installed here is 1.66 GW, the installed PV capacity is about 15 GWp. Thus, the overall wind capacity is smaller in this scenario compared to *Baseline*, even though the individual wind turbines are more efficient here.

3.3. Municipal PV

The distribution results for the *Municipal PV* scenario, where the specific energy demand of each municipality in the study area determines the PV capacity allocation, are shown in Fig. 3.

The distribution of wind sites, as well as the duration of the expansion and the subsequent application of the *Switch* is identical to that in *Baseline*. The distribution of PV sites, however, is different in this scenario. Not only are the sites sorted according to their potential for the region as a whole, but municipal boundaries are also taken into account. Initially, each municipality is supposed to cover its own demand as far as possible. The distribution within the municipalities themselves is also based on potential, i.e. the best sites are used first.

The even distribution of PV across the entire region contrasts sharply with *Baseline*. Concentrations in the north and west, as in *Baseline*, are eliminated. This deconcentration of PV sites is the biggest and hoped for effect in this scenario. As the best PV sites are initially selected within each municipality rather than across the whole study area, this approach ultimately requires more sites overall. 11,276 PV systems are installed, covering the same number of hectares. This is 299 systems or hectares more than in the *Baseline* scenario. 99.96% of the systems are installed on agricultural areas, the rest is situated on conversion areas. The installed wind capacity matches that from *Baseline* (2 GW), while the PV capacity is about 47 GWp and thus slightly higher than in *Baseline*.

3.4. Wind Power Density

Fig. 4 shows the distribution of RE sites for the hypothetical case of halving the legal setback requirements for wind turbines. This would allow for significantly more wind turbines to be installed.

The tremendous impact of halving the setback areas is clearly visible. The number of wind turbines has increased because almost the entire

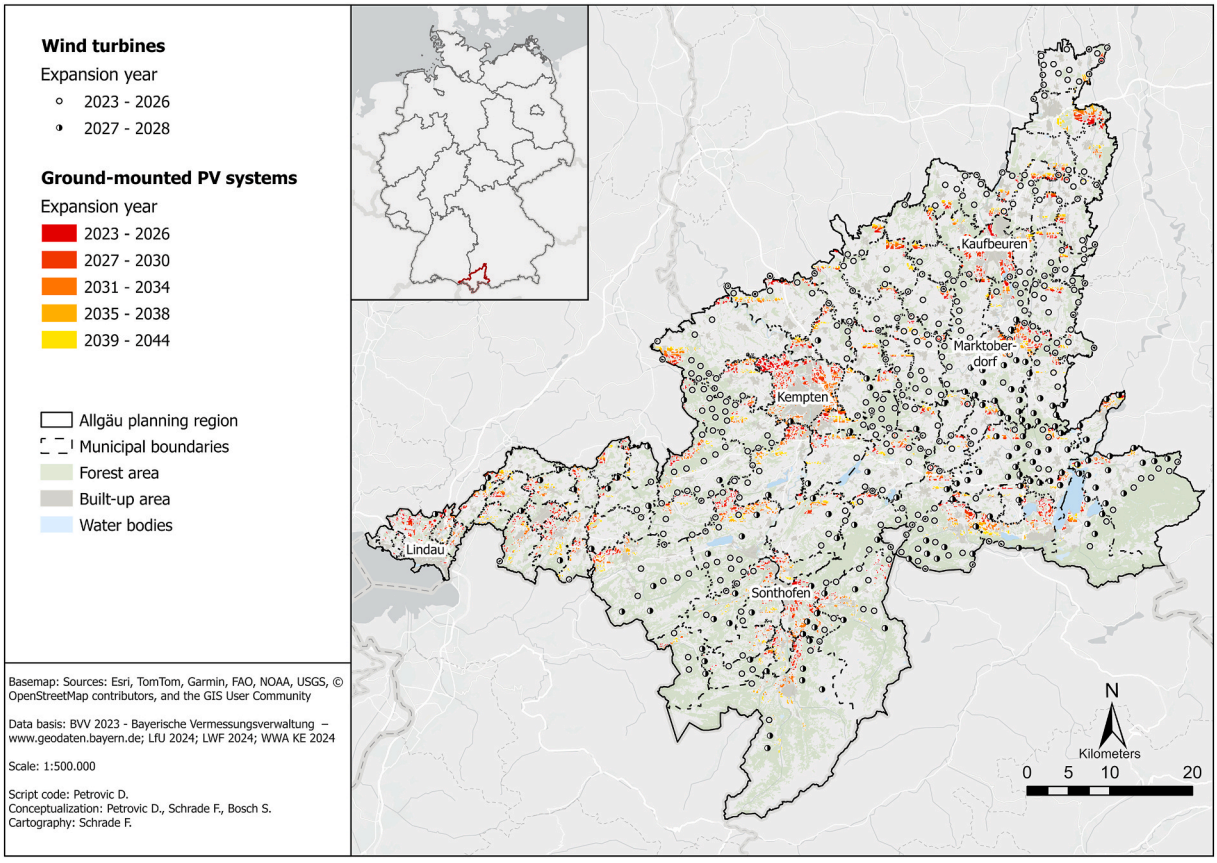

Fig. 3. *Municipal PV* scenario for the Allgäu region in the year 2045.

region can now be occupied by wind turbines. The only exceptions are areas in the far south, in the east and around the city of Kaufbeuren. The figure also shows which areas have very little to no wind potential or where it is not possible to install wind turbines. Thanks to the additional capacity, wind power lasts until 2033 in this scenario, five years longer than in the *Baseline* scenario. However, this is still not enough to meet all the demand for wind power. As a result, the *Switch* to PV energy is also necessary here. This also illustrates that the overall impact on the wind potential is greater in the *Wind Efficiency & Demand Sufficiency* scenario, as it lasts for one more year until 2034 in that scenario (see 3.2). However, due to the higher wind potential, which allows for more suitable sites and consequently a lower *Switch*, fewer PV systems are required. In direct comparison with the *Baseline* scenario, this is shown by the fact that the two PV clusters in the north and west are both smaller here.

Around 73% of the wind energy demand can be met in this scenario, which is significantly more than in *Baseline*. Around ten times the demand would be possible for PV. The number of installed wind turbines is 904, 434 more than in *Baseline*. This is reflected in a wind turbine area of 452 ha, 217 ha more than in *Baseline*. 50% of the turbines are located on forest land and 50% on agricultural land. The total PV area here is 7,688 ha with the same number of systems, which is 3,289 ha less than in *Baseline*. All PV systems are installed on agricultural areas. The wind capacity installed in this scenario is 3.85 GW, the installed PV capacity is about 32 GWp.

3.5. Nature Conservation Plus (NCP)

Increased conservation efforts are simulated in the *NCP* scenario and shown in Fig. 5. Although less land is available for RE sites, carbon neutral electricity production is still possible for the Allgäu planning region in this scenario.

Overall, the *NCP* scenario has the fewest available sites for wind turbines. Accordingly, the wind potential only lasts until 2026, two years less than in *Baseline*. In a direct comparison with *Baseline*, the wind sites are lacking in the south of the region, as well as in the eastern and central areas. There is a significant increase in the number of areas that are completely free of wind and PV. Compared to *Baseline*, this mainly affects the area west of Sonthofen. The lower wind potential results in more unmet demand. Accordingly, the *Switch* is larger here, which in turn means that more PV areas are required compared to *Baseline*. This is reflected in the fact that the two clusters in the north and west of the region are both larger in this scenario.

Wind power meets about 31% of the demand. For PV, the potential is around 9.5 times the demand. The number of wind turbines installed is 356, 114 less than in *Baseline*. Correspondingly, the number of PV systems is 11,969 and thus 992 more than in *Baseline*. The same applies to the PV area. The wind turbines in this scenario occupy an area of 178 ha, which is 57 ha less than in *Baseline*. About 56% of the turbines are installed on forest areas, the rest on agricultural areas. About 99.95% of the PV systems are located on agricultural land, the rest on conversion areas. The wind capacity installed in this scenario is 1.52 GW, the installed PV capacity is about 50 GWp. This means that the difference between the two technologies is greater here than in any other scenario.

3.6. Nature Conservation Minus (NCM)

The *NCM* scenario simulates the effects of removing conservation restrictions and is shown in Fig. 6. This opens up more areas for RE installations. Although the expansion corridor for wind turbines in this scenario is significantly increased by the removal of environmental restrictions, there are still not enough wind sites available to achieve an equal split of 50% wind and 50% PV.

The increase in the number of wind turbines is particularly

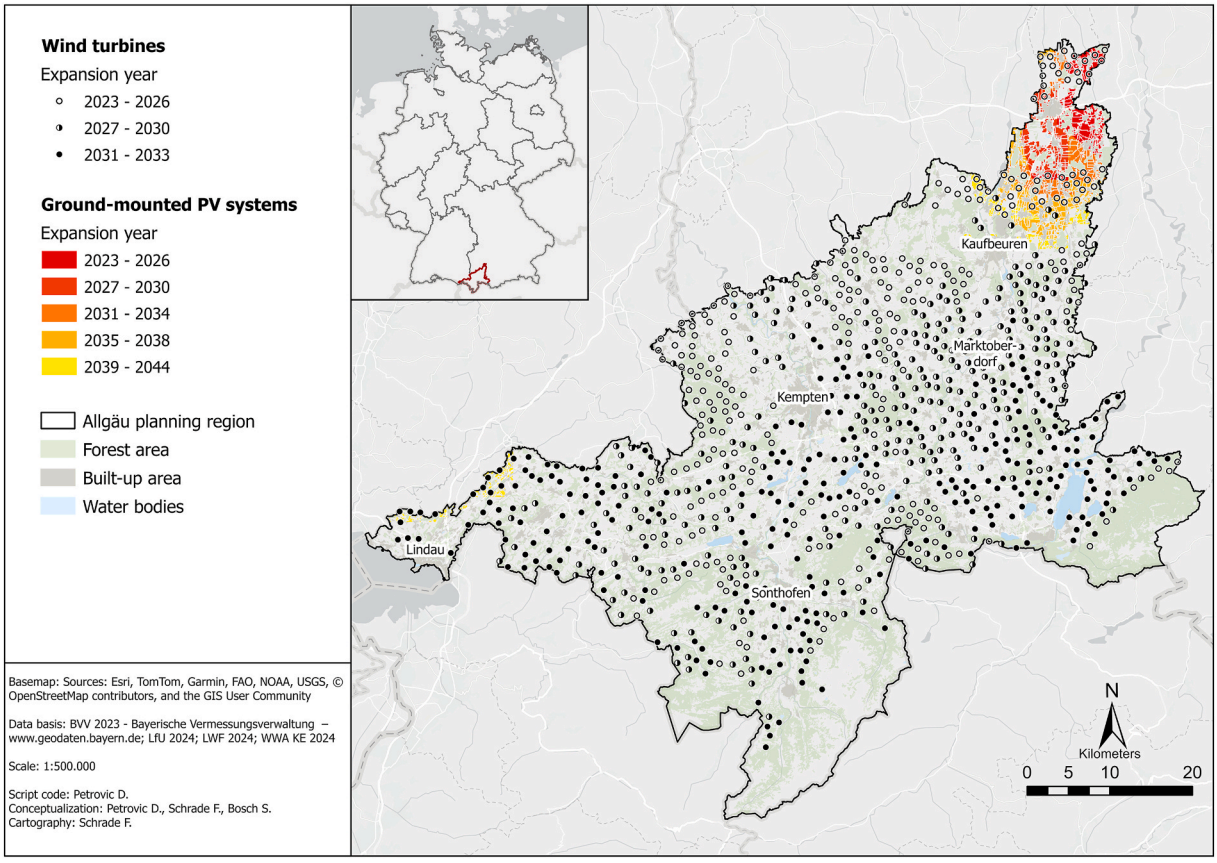

Fig. 4. *Wind Power Density* scenario for the Allgäu region in the year 2045. Data basis: BVV, 2023; LfU, 2024; LWF, 2024; WWA KE, 2024.

pronounced in the southern and eastern parts of the region. The additional wind potential ensures that demand can be met until 2033, five years longer than in *Baseline*. As a result, the *Switch* is lower and therefore significantly less PV area is required than in *Baseline* and *NCP*. Compared to these two scenarios, only the PV cluster in the north of the region remains. It is also significantly smaller.

In this scenario about 70% of the demand is met by wind energy. For PV, the potential is around 12 times the demand. The total number of installed wind turbines is 720, 250 more than in *Baseline*. This corresponds to an area requirement of 360 ha. This is 125 ha more than in *Baseline* and about twice as much as in *NCP* (187 ha). About 56% of this area is forest, the remaining 44% is agricultural. PV requires 8,015 systems and therefore the same number of hectares, which is 2,962 less than in *Baseline*. All PV systems are installed on agricultural land. The wind capacity installed in this scenario is 3.07 GW, the installed PV capacity is about 33 GWp.

4. Discussion

4.1. Discussion of the study results

Even without an even distribution of wind and PV capacity, each of the scenarios analyzed allows the region to achieve carbon neutral electricity production by 2045. This means that the Allgäu can become carbon neutral in electricity production not only under current planning conditions, but even with a significant tightening of nature conservation measures. This is one of the key findings of the study. The *Baseline* scenario shows that carbon neutrality is achievable even under the current framework conditions. However, in none of the scenarios it is possible to achieve the desired split of energy demand between 50% wind and 50% PV. In every single scenario, the *Switch* from wind to PV was necessary at some point to allow PV to compensate for the lack of wind sites. This is an indication of the restrictive stance taken by Bavarian state government policy towards wind energy in general. Since the beginning of the transition, the government has viewed wind energy as an aesthetic threat to valuable recreational landscapes and has therefore given it too little space. Depending on the scenario, the duration that the wind energy capacities can cover varies (Table 4).

The table clearly shows the large differences between the individual scenarios. The *NCP* scenario has the lowest wind potential due to the increased nature conservation efforts. As a result, the wind potential here only extends until 2026 and covers only 31% of the demand for wind energy. The potential is therefore lower than in the *Baseline* or *Municipal PV* scenarios, where wind energy extends to 2028 and covers 41% of demand. The *Wind Efficiency & Demand Sufficiency*, *Wind Power Density* and *NCM* scenarios are quite close to each other in terms of their values. In the *Wind Efficiency & Demand Sufficiency* scenario, the wind potential lasts the longest (until 2034), one year longer than in the other two scenarios. Demand satisfaction is also the highest at 77%. This underlines the large effect of halving energy demand combined with more efficient wind turbines. The proportion of demand met here is almost twice as high as in *Baseline*. Halving the distances between wind turbines (*Wind Power Density*) also has a large effect, as more than 30% of the wind demand can be met. The same is true if nature conservation measures are reduced (see *NCM*-scenario). As no scenario achieves 100% coverage of wind energy demand, every single possible wind turbine is needed. For PV, well over 100% of demand is available in every scenario. This is true even with the *Switch*, underlining the immense PV potential of the region.

The amount of land needed to expand RE systems is substantial in all scenarios modeled. Expressed as a relative share of the region's total area, the value varies between 1.1% in the *Wind Efficiency & Demand Sufficiency* scenario and 3.6% in the *NCP* scenario. In the *Baseline* scenario, this proportion is approximately 3.3%. This land demand is an

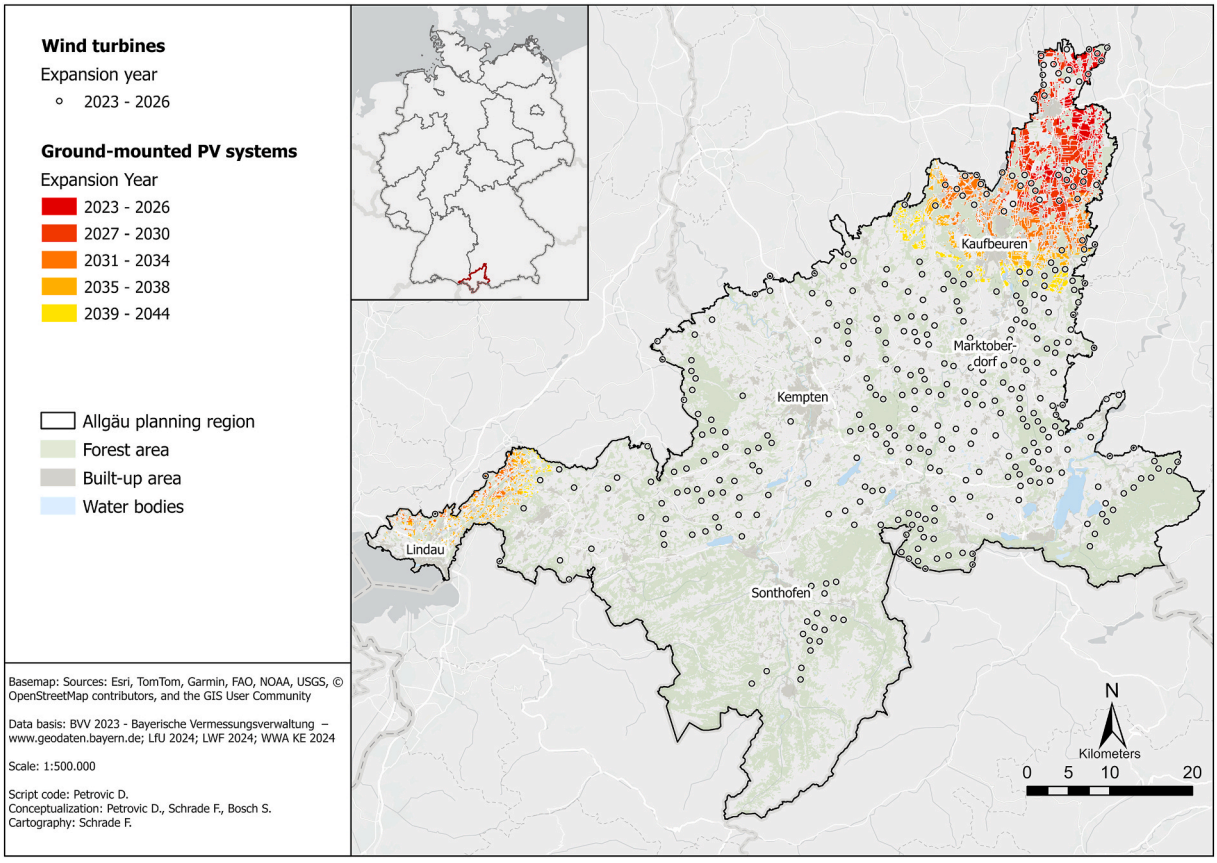

Fig. 5. *Nature Conservation Plus* scenario for the Allgäu region in the year 2045. Data basis: BVV, 2023; LfU, 2024; LWF, 2024; WWA KE, 2024.

essential part of the energy transition, leading to significant changes in the landscape. Fig. 7 illustrates the land requirements of the RE systems in the different scenarios.

There are significant differences not only in the land requirements of the different scenarios, but also in the resulting energy landscapes. The more stringent the conditions, the fewer wind turbines can be installed. This is clear for *Baseline* and *Municipal PV* as well as for *NCP*, where the wind area is 235 and 178 ha respectively. The low value for *NCP* illustrates the major constraints in this scenario. The wind area in *Wind Efficiency & Demand Sufficiency* is the smallest. However, it should be noted that the wind turbines used in that scenario are more efficient than in the other scenarios and the total energy demand is significantly lower. Therefore, this scenario also has the smallest total area of RE systems (3,778.5 ha). The largest area of wind turbines (452 ha) is immanently in the *Wind Power Density* scenario, as more wind turbines can be installed here. The second largest wind area is in the *NCM* scenario with 360 ha. It is clear that the smaller the wind areas, the larger the PV areas in each scenario. This is because wind is much more efficient per hectare than PV. As the wind turbines are distributed first, the PV dimensions depend entirely on the wind potential. It can be deduced that the stricter the restrictions on the expansion of wind turbines, the larger the total area required for RE systems. This is obvious in the *NCP* scenario, where the smallest wind area (178 ha) is combined with the largest PV (11,969 ha) and total area (12,147 ha). The difference between the maximum total area required for *NCP* and the minimum total area required for *Wind Efficiency & Demand Sufficiency* is 8,368.5 ha. This difference roughly corresponds to the total area required for *Wind Power Density* and *NCM*.

Whichever scenario is considered, the expansion of RE required to achieve carbon neutral electricity production would have a significant impact on the landscape. It is unclear what kind of reaction such a far-reaching change would provoke, but previous studies suggest that resistance from the local population is to be expected (e.g., Bauwens et al., 2016; Giordono et al., 2018; Reusswig et al., 2016). The reasons are diverse and include for example concerns about changes to scenic landscapes (Gkeka-Serpetsidaki & Tsoutsos, 2023), impacts on biodiversity (Thaxter et al., 2017), ecosystems (Galparsoro et al., 2022), human health (Bakhiyi et al., 2014; van Kamp & van den Berg, 2021) and local economies (McKenna et al., 2025). The use of PV on primarily agricultural land also harbors a certain potential for conflict (e.g., Adeh et al., 2019; Calvert & Mabee, 2015; Sargentis et al., 2021). One possible way to mitigate these conflicts, at least in part, could be to use agri-voltaic systems for compensation (e.g., Dinesh & Pearce, 2016; Needham-McTiernan et al., 2025; Pascaris et al., 2021). Especially in wind turbine deployment, setback distances play a crucial role. In their literature review, Lehmann et al. (2023) found that in many studies the costs of local disamenities can be substantial. Important factors influencing these disamenities are the distance to the RE site and the size of the affected population at a specific site (Lehmann et al., 2023). Stede & May (2020) showed that increased setback distances can have a negative effect on wind power deployment in Bavaria. Meier et al. (2024) also highlight the effects of setback distances. As clearly shown in the *Wind Power Density* and the two *Nature Conversation* scenarios, wind turbine distances can play a major role regarding the overall wind power capacity. Apart from the *Wind Power Density* and *Nature Conversation Minus* scenarios, the resulting RE sites presented here are in line with exclusion areas (Tables 1 and 2) and thus should not pose major land use conflicts. As Weber et al. (2023) mention, there are also possibilities to combine biodiversity efforts with RE siting. Armstrong et al. (2016) point out that biodiversity could increase under PV modules if managed properly. In addition to the spatial and quantitative aspects of expanding RE sources, the qualitative landscape-related dimension of technological development in rural areas must also be considered. The visibility of these installations, which often extends several kilometers beyond the

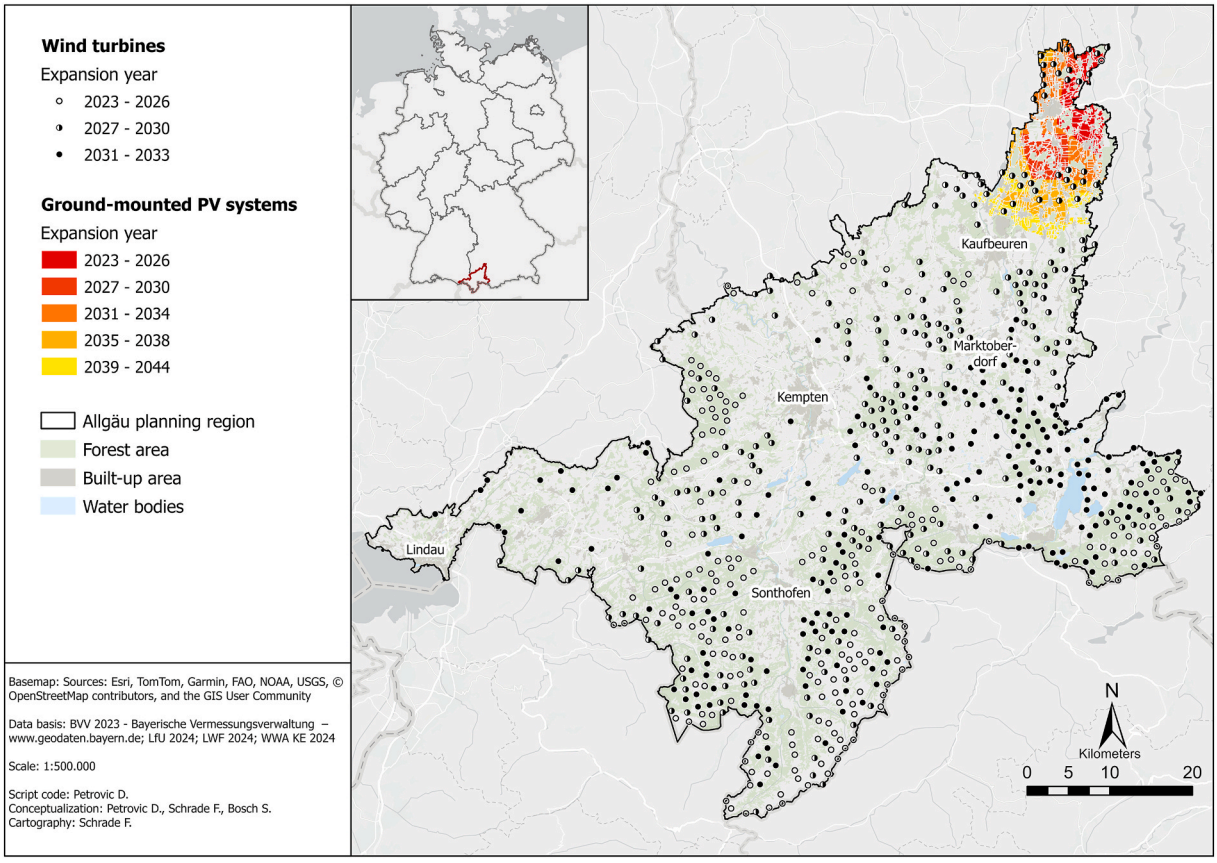

Fig. 6. *Nature Conservation Minus* scenario for the Allgäu region in the year 2045. Data basis: BVV, 2023; LfU, 2024; LWF, 2024; WWA KE, 2024.

Table 4
Overview of the last possible wind year and the coverage of wind demand for each scenario.

Land use scenario	Last year of wind coverage	Wind demand coverage [%]
Baseline	2028	41
Wind Efficiency & Demand Sufficiency	2034	77
Municipal PV	2028	41
Wind Power Density	2033	73
Nature Conservation Plus (NCP)	2026	31
Nature Conservation Minus (NCM)	2033	70

installation and foundation areas, plays a significant role in public acceptance. Since the beginning of the energy transition, the aesthetic implications for the landscape have been a significant reason for opposition to wind turbines. The movement of the rotors and the vertical alignment of the turbines are both visually disturbing. The turbines break up the horizontal structure of the landscape typical of rural areas (Bosch & Peyke, 2011; Bosch & Schmidt, 2020). Wind turbines in low-wind areas, such as southern Germany, must be tall to reach the frictionless wind zone. Technological advances that allow low-wind areas to be exploited for wind energy exacerbate this negative landscape effect. To address this issue, Schöbel (2012) developed a concept for integrating wind turbines into the landscape, aiming also to consider the aesthetics of areas neighboring installation sites. In this sense, carbon-neutral energy landscapes can have an aesthetic impact on neighboring areas and regions, potentially becoming key drivers of mobilization against the energy transition. This must be considered when evaluating the quantitative extent of the spatial impact.

In the *Baseline* scenario, the PV concentration leads to large spatial injustices (Yenneti et al., 2016). This is true in any scenario where this spatial concentration occurs, and relatively small part of the region bears the brunt of large landscape interventions for energy production, while the large remainder experiences little or no constraints. As described in the results, the majority of PV systems are installed on agricultural land. These areas are mainly located (approx. 96% BVV, 2023) in the eastern part of the region, with the majority in the north-east. In addition to the factor of the best solar radiation values, this is the reason why the majority of PV areas are located in this region in the *Baseline* scenario. The areas of concentration are therefore technically overdeveloped, while the rest is spared from deployment. The overall result is spatial-technological polarization. Possible solutions to these injustices lie, for example, in financial compensation. Exports from areas with a high concentration of RE or municipalities with a surplus of PV to areas with no local production or too little potential would generate financial income for the area or the municipalities and ultimately for the local population. This could be a win-win situation (see for example Lindvall, 2023; Parkins et al., 2022; van Wijk et al., 2021). Generally, it must be noted that there are always different perceptions of spatial equity or justice, depending on the different contexts and actors (Bailey & Darkal, 2018; Cha, 2020; Urkidi Azkarraga & Gurrutxaga, 2024; Yenneti et al., 2016). Local energy production can also bring benefits in terms of autonomy, as the areas concerned would be more independent in their energy supply (Juntunen & Martiskainen, 2021). In the *Municipal PV* scenario, grid resilience could be improved, especially against outages that may result from extreme events (Arkhangelski et al., 2018; Liu et al., 2018). Local energy production can also increase social acceptance (Azarova et al., 2019). Installation costs of the PV systems, however, would be higher compared to *Baseline*, since 299 more PV systems are needed in this scenario. These 299 PV systems correspond to

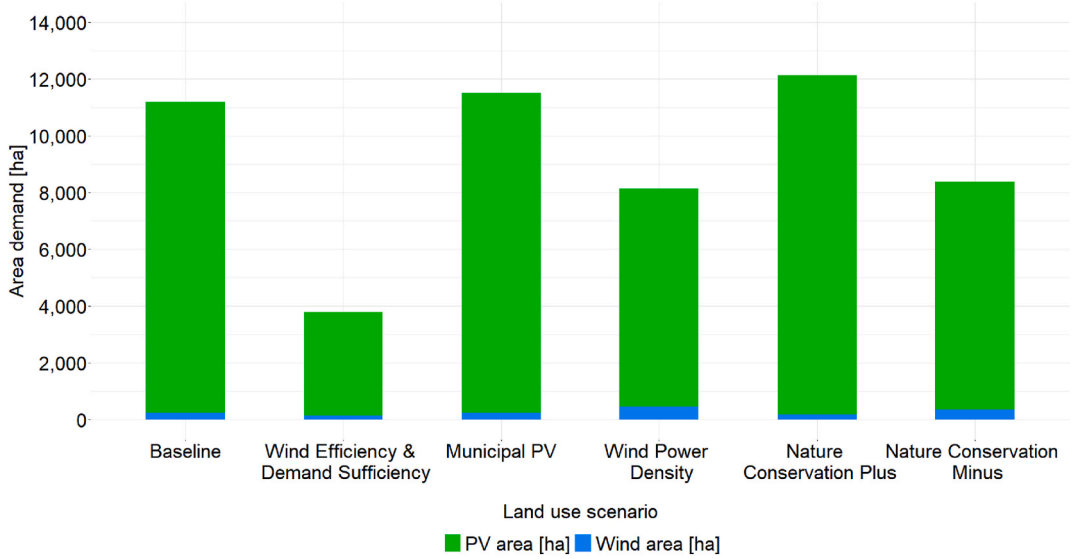

Fig. 7. Graphical representation of the space requirements.

the same number of additional hectares of land required in the *Municipal PV* scenario compared to *Baseline*. However, this relatively small increase in space requirements would lead to a significant reduction in spatial concentration (Fig. 3) and would therefore be more than compensated for by a greater degree of distributional justice. Busch and McCormick (2014) name potential benefits of local municipality energy production. On the one hand, there are economic impacts like jobs and income as well as tax revenues, that could be used to finance civil services. On the other hand, there are social benefits like strengthening of the community and experience of progress. In a democratic country such as Germany, the local level is crucial for the success and acceptance of the energy transition. Here, resistance can easily block the implementation of projects. Participation, like in the *Municipal PV* scenario, could be a key to successful RE expansion (e.g., Stadelmann-Steffen and Dermont, 2021; Zoellner et al., 2008). In the *Wind Efficiency & Demand Sufficiency* scenario, the main load from the wind turbines is in the east. PV is also concentrated in one area in the north, where the entire load would be. The effects would be similar to those in *Baseline*, perhaps even more acute. As noted by Wiese et al. (2022), who conducted a meta-analysis of studies on key strategies for the transition to carbon neutrality in Germany, reducing energy demand is one of the most important levers for achieving the goal of carbon neutrality. This effect is visible here in the *Wind Efficiency & Demand Sufficiency* scenario. Halving the energy demand has a huge impact. In the *Municipal PV* scenario, spatial equity is achieved through PV deconcentration and the even distribution of systems across the entire region. The equal burden on each municipality, based on their respective population figures and corresponding needs, could well be justified to the population. Therefore, less resistance is to be expected. Decentralization of PV capacity would also lead to greater grid stability. It can be assumed that the distribution of wind power shown in the *Wind Power Density* scenario would meet with very strong resistance from the population due to the large number of wind turbines and the associated immense impact on the landscape throughout the area. Nevertheless, it would be slightly fairer than in *Baseline scenario*, as the impact of the wind would be spread evenly across the region, so that the whole region would have to contribute. Again, this would be a form of spatial equity.

4.2. Limitations of the study

It is important to note the limitations of our study. The issue of energy storage, which is central to REs, is not addressed here. The efficient use of energy storage systems could potentially reduce the number of RE plants required and therefore would have an indirect impact on land use. In this context, it is also important to mention off-times, which are not taken into account here. The inevitable occurrence of these off-times due to always-changing natural and meteorological conditions (e.g., Hou et al., 2020; Liu et al., 2018; Suh et al., 2017; Zhang et al., 2020) means that the capacities mentioned cannot, be fully achieved. Nevertheless, the exclusion of these factors does not alter the core findings of this study, as there is significantly more potential available in the region than is needed. It should also be mentioned that the Federal Network Agency for Electricity Supply (2025) assumes that 22 to 35.5 GW of buffer capacity will need to be installed by 2035, for example through gas-fired power plants, pumped storage, or battery storage, in order for both the energy transition and the coal phase-out to succeed. The exact size of this buffer will depend on the extent of the delays in the energy transition. One point that should also be noted, particularly in the *Municipal PV* scenario, is the relationship between minimizing electricity generation costs and energy system costs, which arise, for example, from the expansion of grids and storage facilities (Lehmann et al., 2023). This is, of course, not sufficiently reflected here. Nevertheless, this does not affect the core messages of this study. The quality of our modeling is highly dependent on the accessibility and accuracy of the geospatial data used as input. Certain areas, including security-critical military areas, for which geospatial data is not available, are excluded from inclusion in our studies. This could have an impact on the availability of land for RE energy systems. However, we do not expect this impact to be large enough to alter the main conclusions. Much more efficient wind and PV systems may emerge in the future, offering significantly more potential under the same meteorological conditions. Such potential developments are not included in our modeling; the scenarios assume the same technologies throughout the modeled period. However, the core statement that carbon neutral electricity production is possible in the Allgäu planning region would not be altered by better or more efficient technologies. However, the transformation would be accompanied by a reduction in the amount of land required and thus, under certain circumstances, have less of an impact on the landscape and potential residents. Another factor not considered is the potential repowering of technologies, which would allow existing turbines to be replaced with newer, more efficient ones over time. This would enable more power to be generated from the same site. However, this would not affect the main findings of this study. Another point that must be considered is that the plans and targets assumed here are, to some extent, only a political snapshot. It is possible that there will be major policy changes in the future, due to changes in government or due to extraordinary and

unforeseen events, such as the Russian invasion of Ukraine or, as is currently being discussed again, the end of combustion engines in Germany, which is actually scheduled for 2035. However, these issues are difficult to anticipate and therefore to plan for, so we are bound by our current plans and objectives. In this study, one site could only be occupied with either a wind or PV system, as described in the methods section. In fact, both technologies can sometimes be hosted by the same area (e.g., Chinaris et al., 2025; Lindberg et al., 2021; Sawle et al., 2016). If applied here, that could have spared some areas by getting occupied with PV. However, this would be more complex to add in the siting algorithm and would not impact on the key messages of the study. The sole focus on solar radiation potential for optimal PV siting can also be subject to discussion. Other factors like landownership, land prices, and lease agreements might counterbalance the sometimes minor differences in radiation, that decide about siting the PV systems or not. However, as these data are not available given the size of our study area, this remains speculative. Thus, the approach employed is consistent with the maxim "the best first". Lastly, the aspect of access to power infrastructure needs to be discussed. The rapid expansion of RE plants poses a significant challenge for energy planning, particularly regarding the grid connection location criterion (Ortmann, 2024). In southern Germany, grid expansion has been delayed over the past 25 years, meaning that including this factor in GIS analyses would have a spatially differentiating effect. However, as Valov (2020) notes, assessing grid connection suitability requires detailed knowledge of local conditions. Key considerations include plant compatibility with local grid operation, available capacity at the connection point, technical plant specifications (e.g., rotating generator or static energy source, control limits, rated power, nominal voltage), connection concept (e.g., direct connection or via power electronics), applicable connection rules (e.g., national regulations or the grid operator's special regulations), required remote control, data exchange, and monitoring, model validation for grid calculations, and impacts on grid stability. Given this complexity, grid connection issues are best addressed at the micro level, where renewable expansion is implemented locally. Our approach instead provides meso-level, large-scale spatial pre-selection by assessing the spatial requirements and feasible alternatives for carbon-neutral power generation. As grid expansion has accelerated in recent years, we expect connection conditions to improve, reducing the spatial differentiating effect of this factor in future micro-level planning. Apart from that, off-grid locations and areas with limited grid capacity have so far been economically viable for RE operators, as grid operators must prioritize renewables and compensate for congestion-related losses. However, the Ministry of Economics plans to remove these privileges by labeling weak-grid regions as "bottleneck-prone," ending compensation payments and allowing grid operators to choose whom to connect (Widmann, 2026). This reform would significantly impact the spatial distribution of a carbon-neutral power supply.

5. Conclusions

Germany has committed to becoming carbon-neutral by 2045. This ambitious goal can only be achieved by transforming the energy sector. These political ambitions have yet to be supported by an appropriate spatial planning concept. It requires a massive expansion of RE, especially wind and solar power. As current measures are far from sufficient, this expansion needs to be accelerated. The energy transition in Germany is challenged by limited land availability and diverse spatial restrictions, including recreational areas, nature conservation and settlement distances which limit the necessary expansion of wind and PV plants.

As the results from our study region show, carbon neutral electricity production in southern Germany is in principle technologically and spatially feasible – even under the current legal framework. The Allgäu region can thus contribute to the overall decarbonization goals. This is mainly due to the region's great PV potential. The potential is so great that PV can cover the shortfall in wind power in every scenario. In none of the scenarios is the wind potential sufficient to cover the entire period up to 2045. In the *Baseline* scenario, the wind turbines are distributed fairly evenly across the region, with sufficient wind potential until 2028. The PV systems are concentrated primarily in two large areas. In the *Wind Efficiency & Demand Sufficiency* scenario, wind potential lasts until 2034, requiring significantly less PV energy, so that there is only one region where the plants are concentrated. The key driver here is the assumed halving of energy demand. The *Municipal PV* scenario shows the possibility of an even distribution of PV systems across the region, thus contributing to spatial equity. The *Wind Power Density* scenario shows the consequences of reduced setback distances between wind turbines. This significantly increases their number, resulting in wind turbines covering most of the region. This way the wind potential will last until 2033. The *Nature Conservation Plus* scenario illustrates the effects of increased nature conservation. This significantly reduces the number of wind turbines, which in turn leads to concentrated PV areas. The wind potential thus only extends until 2026. In the case of reduced nature conservation in the *Nature Conservation Minus* scenario, the number of wind turbines increases significantly in certain parts. This means that the wind potential extends until 2033. As a result, a smaller PV cluster is sufficient to cover the remaining demand.

The study has shown that a combination of a GIS-based approach (relying on comprehensive input data) and a siting algorithm can be a powerful tool to model energy landscapes within spatial constraints in order to achieve carbon-neutral electricity production. It has been revealed that the current planning regulations pose major obstacles for the wind energy in the Allgäu region, while large areas are available for PV energy. The results further indicate that the energy transition would be accompanied by massive changes to the landscape due to the large amount of space required by RE technologies. Depending on the scenario, these changes vary in their scope. The results also show that changes in planning law restrictions can significantly reduce or increase the space available for RE site deployment.

In future studies, the siting algorithm could be applied to other regions, possibly at the level of higher spatial units or even whole countries, assuming reliable input data.

CRediT authorship contribution statement

Dragan Petrovic: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology. **Friederike Schrade:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Stephan Bosch:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Harald Kunstmann:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used *DeepL Translator* and *DeepL Write* services in order to translate and rephrase text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Funding

This work was supported by the German Research Foundation [project number 509460539].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Acknowledgments

We thank the editor and the reviewers for their helpful and constructive comments.

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