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Land use scenarios for the development of a carbon-neutral energy supply – A case study from Southern Germany

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ABSTRACT

The Paris Agreement determined to limit global warming to below two degrees. National governments are now confronted with the challenge of taking action for climate protection. For Germany, this poses a major challenge, as the imminent phaseout of low-emission nuclear energy additionally increases the pressure to quickly advance the deployment of renewable energies. At the same time, their low energy density and the resulting high land requirements lead to severe conflicts in land use. The situation is aggravated by the fact that the diversity of societal actors leads to a diversity of energy strategies, which differ in terms of impacts on land use. We therefore want to analyse the impending restructuring of energy supply and the associated land use conflicts. We model potential scenarios of energy landscapes that can be derived from the two-degree target on the basis of Geographic Information Systems, by modifying the political guidelines and planning laws for the deployment of renewable energies. The analyses show that carbon-neutrality is attainable in principle. However, the spatial patterns of renewable energies differ considerably depending on the given legal framework. It also comes to show that land use policy must take greater account of the perspectives of those social groups that are confronted with the installation of renewable energies in the immediate vicinity of their own living environment.

1. Introduction

1.1. *Research gaps and questions*

Currently, national governments are facing the challenge of defining concrete measures to meet the target of the Paris Agreement to keep global warming below two degrees (UNFCCC, 2015, 3). The problem is that policy-makers have little knowledge on the spatial organisation of a carbon-neutral energy system. Therefore, we take up the inspiring idea of Van d. Horst (2017) – "energy landscapes of less than two degrees global warming" – and model energy landscapes that can limit global warming to below 2°C.

In line with this ambitious goal, we want to focus on the spatial dimensions of the Energiewende and its implication for land use policy, as we have identified the following research gaps in this field:

1) So far, there is no regionally transferable methodological approach to transforming the energy system that allows to directly align the speed and scope of the renewable energies expansion with international climate targets.
2) The land needed for the energy transition and the spatio-temporal patterns of renewable energies that take international climate policy into account have not yet been analysed in their land use complexity.
3) It is also unclear to what extent carbon-neutral energy landscapes lay the foundation for new social conflicts.
4) Furthermore, it is questionable to what extent current land use hinders the timely transformation of energy supply towards carbon neutrality and to what extent politics can successfully counter potential land shortages by adapting planning law.
5) Finally, there are no sufficient recommendations for action for a stringent and socially balanced regional energy transition that takes up the requirements of international climate policy.

Unfortunately, the vast landscape changes in rural areas, whose aesthetics and land use systems have been reshaped within only a few years by the technological intrusions of wind, solar, and bioenergy, have greatly reduced the acceptance of energy infrastructures (Bosch and Schmidt, 2020). In view of the urgency inherent in climate protection, this loss of acceptance significantly increases the pressure on

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policymakers to take action. This is exacerbated by Germany’s strategy to phase out nuclear energy, thereby relinquishing a carbon-neutral and reliable technology. Emissions are to be reduced by 65% in 2030 and by 88% in 2040 compared to 1990. Carbon neutrality is targeted by 2045, and by 2050 Germany’s greenhouse gas balance should even be negative (BMU, 2021, 5).

Due to the high land consumption of renewable energies, the numerous competing land uses, and the declining social acceptance (cf. Von Streit, 2021), Germany’s climate policy can only succeed if comprehensive analyses of potential carbon-neutral energy landscapes are carried out at an early stage. The government’s goals in the context of Germany’s National Sustainable Development Strategy to reduce land consumption, which still amounted to 52 ha per day between 2016 and 2019, to 20 ha by 2030 (UBA, 2021) are forcing society to achieve greater space efficiency, also in the context of the energy transition. We therefore address the following research questions:

1) How can a quantitative and spatially transferable methodological approach to transforming the energy system be designed that matches the expansion of renewable energies with international climate targets?
2) What land consumption would we have to anticipate in the course of this energy transition due to the expansion of renewable energies, what territorial-institutional framework conditions are decisive in this regard, and what alternative land use patterns are viable?
3) What requirements arise from these findings for a socially balanced regional land use policy?

For these reasons, we will **(1.)** model potential energy landscapes that can be derived from the two-degree target and visualise them on the basis of Geographic Information Systems (GIS). The German Energiewende will be linked to the Paris Agreement so that those spatio-temporal patterns of renewable energies are identified that make it possible to keep global warming below two degrees. To avoid excessive complexity, we focus primarily on the electricity sector. However, through sector coupling, we will include the mobility and transport sectors, whose complete electrification will lead to an increase in electricity demand of 30% in the modelling period 2022–2045.

The multitude of energy landscape options is **(2.)** mapped by means of scenarios, by varying the planning law requirements for renewable energies, which concern regional planning, nature conservation, tourism, and settlement as well ass distance areas. This makes it possible to analyse the extent to which the legal provisions for the expansion of renewable energies and the land use systems resulting from them can be reconciled with climate protection goals, and to what extent changes in planning law help to overcome spatial bottlenecks or exacerbate them. Based on these findings, **(3.)** potential social conflicts that could arise from the landscape changes are identified, critically assessed, and **(4.)** evaluated in the form of recommendations for action to build sustainable land use systems.

From a technological perspective, the focus of our study is on wind energy and photovoltaics, because although hydropower and bioenergy play an important role in the electricity mix, the potential of the former is largely exhausted and the latter is no longer politically desirable (Bosch et al., 2020; Bosch and Kienmoser, 2022). The fossil-nuclear capacities in the electricity mix will therefore be substituted by wind energy and photovoltaics in equal parts each year until 2045 (Fig. 1). This equal substitution seems appropriate because in an open competition, photovoltaics would prevail over wind energy at all locations in the study region due to the high regional global radiation. However, ensuring grid stability makes it necessary to develop both technologies, as they reach their respective optimum under completely different meteorological conditions (Heinemann and Lorenz, 2015; Mengelkamp, 2015). In addition, intermittent wind energy and photovoltaics are supported by the numerous base-load and peak-load capable biogas plants that have already been greatly expanded in the region.

1.2. Theoretical background

In the following, we will unpack the theoretical framework for the development of scenarios for building carbon-neutral energy landscapes and expound on the conceptual and normative premises underlying our modelling. In scientific literature, land use systems that are primarily related to the energy sector are referred to as energy landscapes (Apostol et al., 2017; Bosch and Schmidt, 2020; Calvert et al., 2019; Stremke and Picchi, 2017). If we want to delve deeper into the spatial dimensions of carbon-neutral energy landscapes, it is important to understand that this type of landscape can emerge from very different types of "human expression" (Berger and Luckmann, 2010, 36). Energy landscapes are consequently the "result of socially formed patterns of interpretation and evaluation" (Kühne, 2019, 69) and specific social constructions of reality. According to this understanding, we assume several possible "energy futures" (Rohde and Quitzow, 2021, 189), each of which has its origin in specific subjective feelings and actions that can be solidified

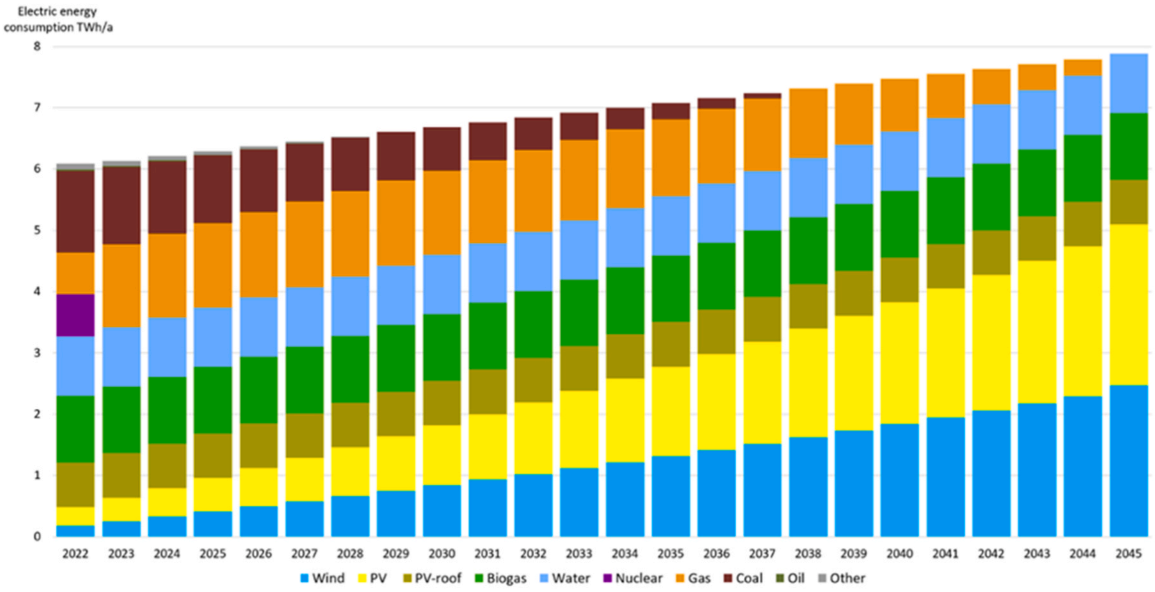


Fig. 1. Development of the regional electricity mix according to the two-degree target.

through repetition and institutionalisation into "typifications" (Berger and Luckmann, 2010, 36). This means that although we assume the successful realisation of a carbon-neutral society in the long term, the spatial planning designs that will lead us to this reality of a carbon-free everyday world are diverse and unclear in terms of their assertiveness (Bosch and Kienmoser, 2022). Therefore, we want to model and analyse different spatial-technological options that reflect the entire spectrum of societal goals and legal framework conditions. To this end, we will develop scenarios that are shaped by different objectives, e.g. with regard to planning law, legislation, and nature and species protection. We will analyse the relationship between restricted and unrestricted areas for the expansion of renewable energies as a dynamic structure of typifications that creates a "space of possibility" (Bruns and Kühne, 2013, 88).

Different social processes can thus be inscribed in the material design of carbon-neutral energy landscapes, while it is currently still unclear 1. to what extent the reconfiguration of social relationships around energy supply establishes new spatial-technical systems (Bridge, 2018; Häußling, 2019), 2. which interests will prevail in the process, and 3. where the new energy landscapes will extend according to these interests. Consequently, the question of where the energy landscapes should emerge is followed by a reflection on the underlying social implications and conventions (Schweiger et al., 2018, 432). The central territorial-institutional framework conditions that are used to develop carbon-neutral energy landscapes are the three planning levels of federal spatial planning, state or regional planning, and communal urban land use planning (Bosch, 2021, 160 f.). According to the constitution, spatial planning must create the spatial prerequisites for the expansion of renewable energies (BMJV, 2021). In this context, the economic, social, and ecological functions of spaces are to be coordinated, as required by the guiding principle of sustainable spatial development. Spatial planning must mediate between renewable energies and any competing land claims by weighing up public and private interests and specify the results of this process in the regional plans. Furthermore, the Federal Building Code (BMJV, 2017a) should be mentioned, which designates wind energy as privileged projects, as long as there are no conflicting public concerns, such as monument, soil, and water protection. The Renewable Energy Sources Act (EEG) also exerts a spatial steering effect (BMJV, 2017b), as it pushes the expansion of wind and solar energy towards pre-burdened sites, such as residential, commercial, infrastructural, or military brownfields (BMJV, 2020). Finally, the siting patterns of energy landscapes are shaped by ecological factors, as the aim of nature and species conservation is to protect ecologically sensitive areas from mechanisation (Job et al., 2016, 483).

Apart from these official planning guidelines, the exercise of social power has a decisive influence on how future energy landscapes will be shaped (Mulvaney, 2017, 155). Quantitative spatial modelling needs to capture this influence on territorial-institutional frameworks, as it is not foreseeable in which directions societies will develop in the long run. In a reference scenario, we will therefore show which spatial corridors are currently open to renewable energies within the existing power structures or territorial-institutional frameworks. The current planning-law reality behind this scenario is to be seen as the result of "socially developed, mediated, and preserved knowledge" (Berger and Luckmann, 2010, 3) and in this sense has a great persistence. Nevertheless, this knowledge can be transformed by overarching social processes (external shocks, megatrends, arbitrary stops in discourses) or basic innovations in niche areas (Geels, 2011), so that alternative objectivations become more likely in the context of permissible land uses. All further scenarios we will model therefore assume significant power shifts in the context of societal negotiation processes for the spatial organisation of carbon-neutral energy landscapes and are to be considered as potential "specific conglomerations of reality and knowledge" (Berger and Luckmann, 2010, 3).

With regard to our project, we derive the following premises from the theoretical background:

1) The territorial-institutional frameworks on which our modelling is based (e.g. planning law, land use policy, spatial restrictions, distance areas) are the preliminary result of a powerful social negotiation process and primarily reflect the land use interests of specific actors. The theoretical framework enables us to explore possible energy futures by varying the territorial-institutional frameworks (e.g. strong or weak nature conservation) and the resulting variabilities in the relationship between restricted and unrestricted areas.
2) If we vary the territorial-institutional structures in the modelling and deviate from the current paradigms in planning law, legislation, and nature protection, we bring to the fore the interests of actors whose ideas of a carbon-neutral society have been marginalised so far. From the theoretical framework, we therefore derive the necessity of using quantitative methods to contribute to the debate on more energy justice and, in this sense, to refer to the procedural dimension of the energy transition.

2. State of research

2.1. Bringing together GIS and social sciences

The application of quantitative methods has a long tradition in social sciences, because according to Black (1999) modelling the world on the basis of social science theories opens up the possibility of extrapolating various probable social situations and states. Ritchie and Ormston (2014, 28) emphasise that applied sciences and theoretical approaches fit well into one another, since 1. all research should always be based on theoretical assumptions and 2. all forms of social science research should contribute to building theory by helping to better understand the "social world". In this sense, the development and application of scenarios can be an important component, as social systems are path dependent and unfold along specific trajectories that are strongly influenced by institutional frameworks and power constellations (Berkhout and Hertin, 2000, 166). The knowledge, perception, and actions of people are thus in a "locked in" state, as the authors underline. Energy futures can therefore be reduced to an ensemble of possible scenarios and show options for regional planning and policy. The limited time frame for humanity to do something about excessive global warming forces us to look into the future with the tools of science. In the context of environmental change, "futurizing" with the help of scenarios is a way of "thinking about tomorrow" (Pulver and Van Deveer, 2009, 1).

This quantitative approach, which Stephens (2022, 83) calls *climate isolationism*, is by no means free of criticism. The article by Niedzwetzki (1984, 66), in which the author compares the limits and possibilities of qualitative and quantitative methods, emphasises that the ability to forecast by means of quantitative research suffers above all from the fact that the technical possibilities have been developed more than the theoretical understanding of social contexts. Almost forty years after this criticism, in the field of GIS-based modelling, there is still a large gap between technical possibilities and theoretical relevance. Although GIS-based studies attempt to capture the social compatibility of the energy transition (Sunak et al., 2015), they do not go beyond simplified distance calculations (Höfer et al., 2016). Unfortunately, power asymmetries that dominate the territorial-institutional framework as well as alternative energy futures that can be derived from a constructivist perspective are not considered. Our study can be understood as an attempt to connect the socially abstract but spatially accurate GIS-based approaches with significant social science findings. Conversely, the study also pursues the goal of building a bridge from theory to applied sciences, since the social science theories remain very vague in practical spatial planning. The methodological-conceptual focus is therefore on the connection of two disciplines that so far have hardly converged, but whose linkage is of great importance for minimising land use conflicts at the background of climate protection measures.

2.2. A new approach

Due to the great social importance of the energy transition, a growing number of GIS-based approaches for the spatial optimisation of renewable energies have been developed over the last two decades (Amador and Domínguez, 2006; Zhu et al., 2023). Surprisingly, although the social, technological, and legal dimensions of renewable energy development are always recorded and visualised in great detail, this is done without proper regard to the overarching political and social objectives (Harper et al., 2019, 160 f.). Hence, in order to address the climate emergency more effectively, the existing planning law and planning culture will need to change. In our view, the urgency imposed on the Energiewende by climate change must therefore lead to a new hierarchisation of influencing factors within spatial planning. The question of "spatial compatibility" (Sward et al., 2021, 3) must undoubtedly be asked, but first and foremost, it must be ensured that the climate goals are achieved. For this reason, all our scenarios on the planning law of renewable energies fulfil the internationally defined climate targets and thus also allow for a debate on the most compatible spatial corridor for the implementation of the Paris Climate Agreement. Compared to all previous GIS analyses, our study re-prioritises for the first time all social, technological, and planning considerations with the timely realisation of carbon neutrality being the central premise.

Our study differs from previous approaches in that we do not mix the different factors influencing the expansion of renewable energies, as they develop their impact at different scales (Sward et al., 2021, 3). In particular, it is the controversially discussed social parameters that elude an exact regional assessment, as they are strongly tied to local contexts (Bosch and Schmidt, 2020). The course of municipal planning processes, civic engagement, or changes in property relations result from complex social interactions at the local level (Harper et al., 2019, 167). According to Klok et al. (2023, 9), there is not always enough geodata of sufficient quality available for regional potential analyses. An explicit survey of these data would take great empirical effort (Peri et al., 2020; Petrova, 2016). Zaunbrecher and Ziefle (2016, 312) even claim that these profound insights into the social acceptance of the Energiewende can not at all be operationalised for large-scale quantitative approaches and thus point to a "theory/practice divide". Sward et al. (2021, 6) consider the parameters of participation, environmental impact, equity, return on investment, power distribution, local culture, and planning history as the central social implications of the Energiewende, which can be understood solely through the collection of primary data (interviews, local surveys). For our analyses, this does not mean that we focus exclusively on economic or technological criteria and ignore the socio-technical dimensions of the energy transition, as for example Raillani et al. (2022). Instead, we take up central leitmotifs from the societal debates on the spatial limits and possibilities of renewable energies that are conducted throughout the country and the federal state (e.g. importance of nature conservation and species protection, stimulation of regional economic cycles, export opportunities for peripheral regions) and incorporate them into scenarios in the form of socio-technical trends. The unique selling point of our study is therefore that we keep the GIS analyses of regional energy systems (meso level) free of "subjective" (Sward et al., 2021, 3), locally specific social considerations and draw up potential spatial expansion corridors for renewable energies based on overarching social objectives (e.g. carbon neutrality). In further studies, specific social contexts (micro level) can then be discussed in greater depth.

The GIS analyses on renewable energies carried out so far also suffer from the fact that instead of producing various spatial options, all economic, ecological, and social implications lead to one final spatial cartographic statement. Thus, the risk is high that an improbable spatial path is presented to the actors of the energy transition (Harper et al., 2019, 161). Our approach is therefore to show the spatial diversity and planning range of a carbon neutral energy system by means of scenarios, each of which strengthens or weakens the significance of a specific parameter. In this way, we want to ensure that the climate goals can also be achieved under changing social conditions. If we were to focus only on a possible spatial corridor for the expansion of renewable energies, it is unlikely that a carbon-neutral energy supply could be established by the middle of the 21st century, given the low level of acceptance, as Klok et al. (2023, 1) point out.

2.3. Limitations of GIS-based approaches

According to Sward et al. (2021, 6), GIS-based approaches often give the impression that public opposition must be overcome and complete acceptance for the infrastructure measures of the Energiewende must be established. However, a local discourse around the advantages and disadvantages of the Energiewende is a necessary and constructive process within a democratic order, which we cannot and do not want to undermine with our study. Klok et al. (2023, 1) actually doubt the possibility of being able to influence the local acceptance of the energy transition on the basis of GIS.

Chassin et al. (2022) point out that the application of digital tools can only mobilise certain parts of the population. As a result, there is a danger that planning will only reflect particular interests. The combination of several planning tools that address different target groups (Çöltekin et al., 2017) might therefore increase the variety of actors included in GIS-based planning. Furthermore, it is important to note that planning tools that work within a specific social, political, and economic context cannot be easily transferred to other contexts and regions (Zhang et al., 2019). Moreover, the planning options offered by GIS tools are limited and do not provide the same analytical depth for all societal perspectives. The preferences of the developers and users of GIS-based approaches as well as the type of visualisation techniques offered by the GIS must therefore always be taken into account. Both determine what is representable in planning terms within the virtual landscapes and which parameters are underrepresented (Raaphorst et al., 2017).

It is also foreseeable that new planning methods and tools will break the linearity of former decision-making processes and destabilise existing power relations within the traditional planning hierarchy (Wallin et al., 2012). On the one hand, this can be seen as an opportunity to rob encrusted and destructive planning structures of their dominance. On the other hand, there is the danger that the established and democratically legitimised institutions will be deprived of social legitimacy. GIS technologies are consequently not good, bad, or neutral per se, but interact with the respective socio-political contexts in different ways (Kranzberg, 1986). McQuire (2021, 2) speaks of a state of "in-betweeness" in which digital tools are situated. Their value depends largely on the policies, principles, rules, guidelines, and methods of those who implement the technologies. In this context, Silva (2010) points out that there is no generalisable understanding but many visions of what planning is and who should benefit from it. Hence, the decisive factor for the transformative power of renewable energy planning are therefore not the GIS-tools themselves, but the intention with which they are developed and used (Horelli, 2013).

3. Method

3.1. Study region

The international community's goal of limiting global warming to below two degrees can only be achieved with the contribution of all regions world-wide. Therefore, we want to develop a methodology that can be applied to other regions if the respective ecological, social, and economic contexts are taken into account when selecting parameters that are fed into the modelling (e.g. distance areas, exclusion areas). To generate an initial experience with this methodological approach, we will illustrate its application by the example of the planning region of Augsburg (4063 km^2). In this region, the expansion of renewable energies will be confronted with special challenges, which will open up an interesting field of experimentation for geographical energy research from a socio-technical perspective.

Located in the heart of Bavarian Swabia, this economically powerful study region is of great interest because the Bavarian state government has launched the Bavarian Energy Programme, in which numerous measures for the further implementation of the energy transition have been specified, such as the additional expansion of 300 wind turbines and the expansion of 3.2 GWp of PV capacity (StMWi, 2019). The region is strongly affected by the phase-out of carbon-neutral nuclear energy, which is why the expansion of renewable energies is not only significant in terms of climate protection, but also to secure the high quality for industrial development (Stratmann and Kersting, 2022).

Another unique characteristic of the region is the concern about the cultural landscape changes ensuing the energy transition. The great importance attributed to an aesthetic and thus recreation-promoting landscape has become a central argument in the spatial planning of renewable energies and has severely restricted the use of wind energy in particular by stipulating long separation distances (i.e. between wind turbines and properties). The region has numerous special cultural landscape elements that are intensively marketed by tourism stakeholders. The extent to which the Bavarian tourism industry restricts the spatial possibilities of wind energy through planning law has been shown in detail by Tatu (2019).

3.2. Multi-criteria approach

Our innovative approach to modelling energy landscapes is described in detail in a process chart (Fig. 2). It can be divided into data collection, modelling, and result processing and distinguishes between a theoretical (physical), a technical (efficiency), an economic (yield), and

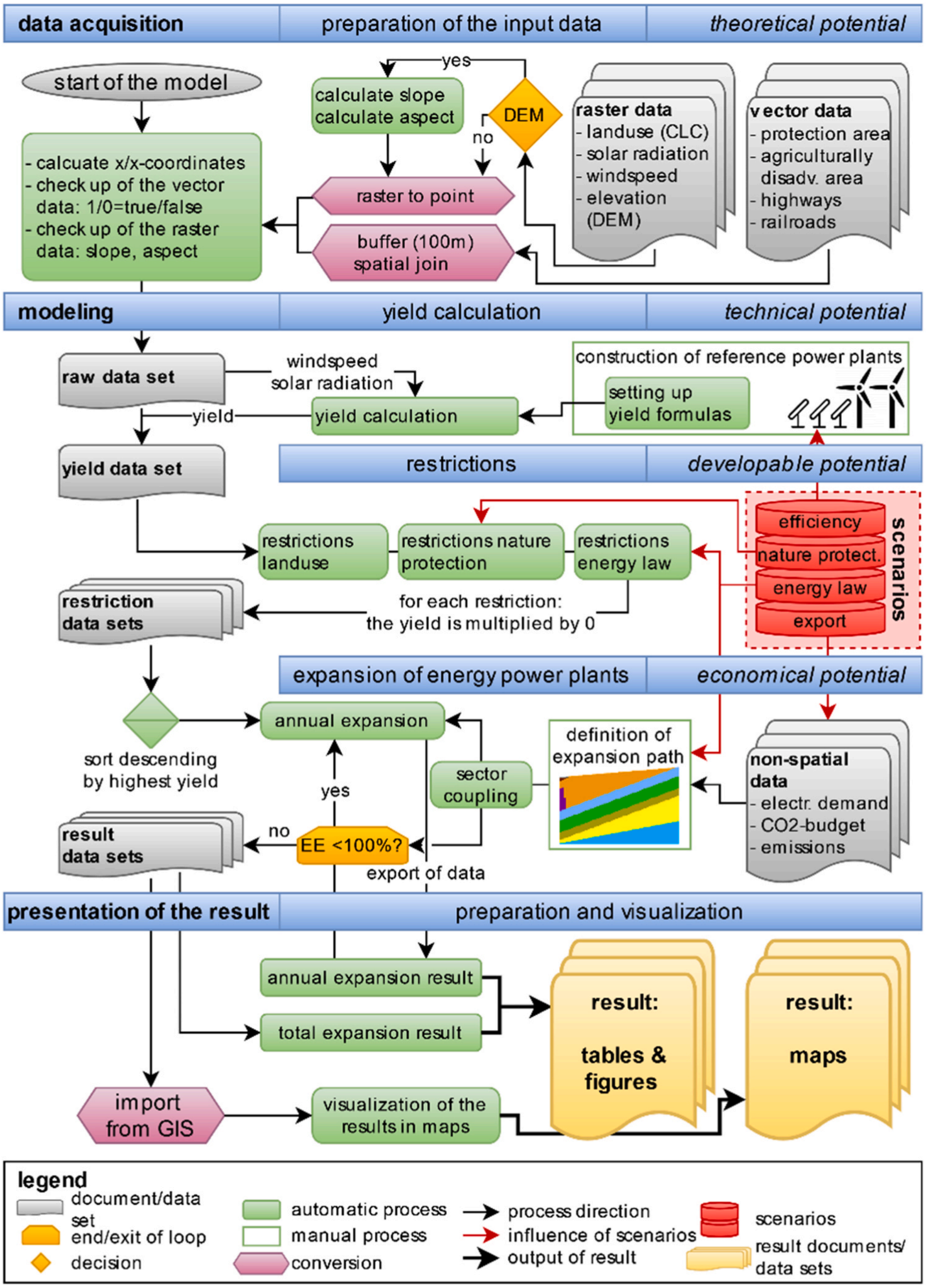


Fig. 2. Methodology for the modelling of carbon-neutral energy landscapes.

a developable (planning law) potential. The core natural site factors with regard to wind energy – cf. Bremen and Wessel (2015), Emeis (2015), Mengelkamp (2015) – are the mean annual wind speed, its temporal variations, the frequency distributions of mean wind conditions, the turbulence intensities, the extreme values, the spatio-temporal variabilities, and the wind profiles over complex terrain. When modelling wind potential, we assume site-specific average values for reasons of complexity reduction. Yield-relevant site factors for PV ground-mounted systems – cf. Müller (2015), Heinemann and Lorenz (2015) – are global radiation (direct and diffuse radiation), temperature (influence on efficiency), humidity and cloud formation, extreme values, and spatio-temporal variability. With regard to yield, it is particularly necessary to identify locations with high global radiation. For this reason, the focus of our modelling is on this parameter.

From a methodological point of view, it is a multi-criteria decision analysis (Shao et al., 2020). Exclusion criteria are used to determine the areas that are inaccessible for renewable energies (e.g. buffer zones, protected areas, recreational areas, settlement areas). For the restriction-free areas, further criteria - evaluation criteria - must be used to assess which technology is best suited for a particular location (e.g. yield). Since the criteria can occur in the form of numerical values and/or qualitative characteristics, they must be processed for the quantitative analyses (criteria value normalisation) in a further step. Subsequently, the different geodata can be overlaid and intersected with each other in the form of individual layers (overlay analysis). In the context of this intersection of geodata, we weight the individual data equally (equal weighting), as there is great uncertainty about the impact that individual parameters actually have in certain regions. By means of scenarios, however, we want to explore to what extent the variation of exclusion citeria will lead to significant changes in the land use patterns of renewable energies.

3.3. Spatio-temporal pattern of renewable energy expansion

The spatio-temporal pattern concerning the expansion of the carbon-neutral power supply, which is based on a GIS analysis of raster cells automated in Python (raster grid approach) (Bosch et al., 2020; Bosch and Kienmoser, 2022), is as follows: The restriction-free locations of the regions are filled with wind power or PV ground-mounted systems in descending order of the highest yield until the electricity gap created within one year by the dismantling of the fossil power plants is closed. Only that technology can be placed on a site (grid cell 100 m) that achieves the highest electricity yield there in accordance with the natural potentials (wind speed, global radiation) and for which, moreover, no exclusion criteria (e.g. nature conservation, water bodies) apply. In the modelled period (2022–2045), this substitution mechanism takes place until the complete supply with renewable electricity is achieved. The current stock of renewable energy plants, whose share of the electricity mix in the study region is already 54%, is integrated into the modelling. This means that an expansion of 46% is to be modelled.

The time limits for the transformation process are the regional CO_2-budgets that may not be exceeded. Consequently, the expansion of renewable energies is reciprocally linked to the dismantling of fossil-nuclear power plants. This exnovation of the old energy system does not have to take place as quickly as possible. However, it is important to keep an eye on the cumulative emission quantities of the longer active fossil power plants: As long as fossil power plants continue to generate electricity in the respective region, the resulting CO_2-emissions per kilowatt hour produced are deducted from the respective current total regional CO_2-budget (Fig. 3). In doing so, we are guided by Statista (2022a), which gives the CO_2-emissions per kilowatt hour depending on the type of power plant (e.g. lignite = 1153 CO_2/kWh, hard coal = 949 CO_2/kWh). Depending on how long certain fossil power plants remain on the grid (variable), they continue to emit carbon dioxide and reduce the region's CO_2-budget. This is unproblematic as long as the budget is not exceeded.

3.4. Calculating the limiting CO_2-budget

In calculating the total regional CO_2-budgets, from which the power plant-specific emissions are subtracted, we refer to the data of the IPCC (2021, 38) that has outlined that global warming can be limited with a probability of 83% to 1.5°C, 1.7°C, and 2.0°C respectively if, starting in 2020, no more than 330 Gt, 550 Gt, and 900 Gt respectively are emitted. Our modelling is therefore based on the value of 900 Gt, which results in a global CO_2-budget of 825 Gt for the year 2022 (start of the modelling period), if the CO_2-emissions already consumed in 2020 and 2021 (75 Gt) are included (Statista, 2021). The focus of the modelling must therefore always be on the available regional CO_2-budget.

To determine the study region's CO_2-budget, the burden-sharing principle is used, in which the CO_2-budget still available per nation is distributed proportionally to the global population (Friedlingstein et al.,

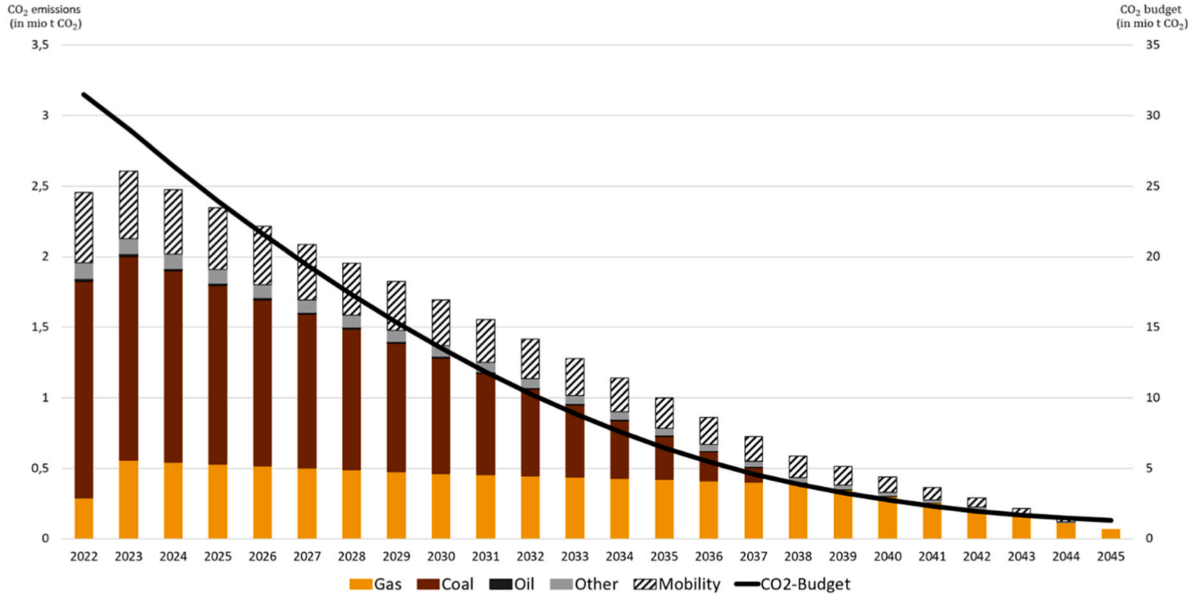


Fig. 3. Development of the regional CO_2-budget according to the two-degree target.

2019; Raupach et al., 2014). It must be taken into account that the share of the German population in the world population changes during the modelling period (Statistisches Bundesamt, 2022). For this reason, the methodology averages the current share of the world population and the share at the end of the modelling period (2045) to determine the total budget for Germany. The share of the population of the study region in Germany remains roughly the same during the modelling period (Statistisches Bundesamt, 2022). Currently, Germany and the study region contribute 1.8% to global CO_2-emissions (Statista, 2020), while their share of the global population is only 1.1% (Statista, 2022b; Statistisches Bundesamt, 2022).

Given an average world population during the modelling period of 8.685 billion, this results in an absolute per capita budget of 95 t CO_2. From this, a regional CO_2-budget of 90 Mt is derived if an average population of 946,500 is taken as a basis for the Augsburg region. The shares of the fuel and heating sectors are then subtracted from this total regional budget, leaving a CO_2-budget of 31 Mt for the electricity sector (Fig. 3). At this point, however, it is important to consider sector coupling (transport and mobility). We assume an increase in electricity demand of 30% in the long term, which is why we add this additional amount to the current electricity demand. Therefore 4 Mt of the CO_2-budget of the fuel sector must be transferred to the regional budget of the electricity sector.

3.5. Data and scenarios

The CORINE Land Cover dataset forms the major data basis of our spatial modelling. It divides the earth into 44 land use classes (Copernicus, 2018). This allows us to define which areas are to be excluded for the expansion of renewable energies. An overview of the criteria, datasets, and sources is given in Table 1. Of particular importance are the vector data on protected areas provided by the Federal Agency for Nature Conservation (BfN, 2021) and data on slopes based on the Digital Terrain Model of the Official Topographic Cartographic Information System (ATKIS) of the Bavarian Survey Administration (LDBV, 2018). Through the latter, slopes of more than 10 degrees can be excluded for PV-systems, as installation costs would be too high and resulting in too low profitability (UBA, 2013, 12; Zaspel-Heisters, 2015, 545). In addition, south-exposed sites with slopes between 5 and 10 degrees are preferred against north-exposed terrain. Slopes with an inclination of 10 degrees or more are also excluded for wind projects for reasons of installation costs. Furthermore, it should be noted that 30% of the PV-module area is to be designated as an area of ecological compensation and thus part of the mapped PV-landscape. The data that form the basis of the transport corridors – preferred sites vor PV – are also provided by the ATKIS of the Bavarian Surveying Administration (LDBV, 2018). Special cultural landscapes that need to be protected from mechanisation and from which distance areas must be kept are provided as spatial information, e.g. via the Digital Base Landscape Model (Basis-DLM) and by the State Office for the Preservation of Monuments. Finally, in order to be able to carry out the analyses, numerous data on the study region are required, such as population size, regional electricity consumption, shares of fossil and regenerative sources in energy consumption, CO_2-emissions of the heat, fuel and electricity sectors, the plant technology (e.g. efficiency) as well as the locations of the energy plants that have already been expanded. In particular, our modelling is based on data on natural site factors and energy infrastructure obtained from the Energy Atlas of Bavaria (StMWi, 2021) and from the Federal Network Agency.

Table 1
Datasets, attributes, and sources of the modelling.

Dataset	Attribute	Source
Land uses	Agriculture, forests, artificial areas, water bodies, settlement areas, transport infrastructure	CORINE Land Cover-Dataset (Copernicus), OpenStreetMap (OSM)
Protected areas	Biosphere reserves, nature reserves, national parks, bird sanctuaries, landscape conservation areas, Flora Fauna Habitat directive (FFH)	Geoservice of the Federal Agency for Nature Conservation
Natural site factors	Global radiation (kWh/m^2/a), wind speed (m/s at hub height)	German Weather Service (DWD), Energy Atlas Bavaria
Cultural landscape elements	Castles, fortresses, monasteries, chruches, orchards	State Office for Monument Preservation
Cultural landscapes, recreational areas	Areas of high/low landscape quality (official classifications), geotopes	Digital Basic Landscape Model (Basis-DLM) of the Federal Agency for Cartography and Geodesy, WebGIS applications
Terrain, topography	Slope, aspect, accessability	Digital Terrain Model (DTM) of the Official Topographic Cartographic Information System (ATKIS), OpenStreetMap (OSM)
Energy infrastructure	Electricity grids, existing power plants	Energy Atlas Bayern
Regional energy system	Regional energy demand (TWh), 6.25 TWh/a	Energy Atlas Bayern
Regional population development	Average regional population size (2022–2045), 900,000 inhabitants	Energy Atlas Bayern, Federal Statistical Office (Destatis), Federal Agency for Civic Education (bpb)
Global population development	Average global population size (2022–2045), 8750,000 people	Statista - Business Data Platform
Two-degrees-target (global)	Global CO_2-Budget (t), 1000 Gt	Intergovernmental Panel on Climate Change (IPCC)
Two-degrees-target (regional)	Regional CO_2-Budgets (t), 0,1 Gt	Own calculation
Climate-impacting emissions	CO_2-emissions energy sector (t), CO_2-emissions type of power plant (CO_2/kWh), coal 1153 g CO_2/kWh, oil 815 g CO_2/kWh, gas 428 g CO_2/kWh	Energy Atlas Bayern, Statista - Business Data Platform
Plant technology photovoltaics	Efficiency (%), capacity (kWp), Hanwha Q.Plus BFR-G4.1; module table: 3 m (35°), power installed: 285 Wp, land consumption: 8.9 m^2/ 1 m^2 pv module * slope of terrain	Hanwha Q CELLS GmbH
Plant technology wind turbine	Efficiency (%), capacity (MW), Enercon E-147 EP5 – rotor diameter: 147 m, power installed: 5 MWp, land consumption: 24.5 ha	Enercon GmbH

Following the preparation of the data, the Augsburg region is subdivided into a grid with a resolution of 100 m. For each grid cell, the following information is allotted: type of land use, the associated legal restrictions for wind energy and photovoltaics, infrastructural conditions, and the potential electricity yield per plant resulting from plant technology and natural conditions. For wind energy, the Enercon E-147 EP5 turbine (5 MW) is used, while the Q.Plus BFR-G4.1 turbine (285 Wp) developed by Hanwha Q.Cells forms the technical basis for photovoltaics. The wind speeds are recorded at hub height and given in m/s, the global radiation arriving at the ground in kWh/m^2. Both data sets are available in a 200 m grid. They are therefore processed for modelling by interpolation into a 100 m grid.

In different scenarios, the spatial exclusion criteria are varied. From a typological point of view – cf. Börjeson et al. (2006) – all scenarios are normative scenarios, since concrete societal goals, such as carbon neutrality and the two-degree target, are aimed for and thus specific value systems are represented. Apart from the base scenario, one could also speak of explorative scenarios, as the main drivers of the energy transition are varied and therefore different energy futures are explored.

The first scenario, which we will present in the following, is also a predictive scenario that is based on the extrapolation of trends, hence depicting a very probable development.

- **Reference scenario:** In this scenario, the analysis inquires the extent to which carbon-neutral energy landscapes are feasible within the current legislation and planning law. This regards technology, land uses, and planning law (priority areas, distance areas, Renewable Energy Sources Act, restriction areas, etc.). For example, national parks, nature reserves, and core zones of biosphere reserves are categorical exclusion areas for wind power and PV plants. For the former, bird sanctuaries also represent inaccessible areas. Furthermore, ground-mounted PV plants may only be erected along motorways and railway lines within a 200-metre corridor. In addition, a maximum of 200 PV plants per year (regardless of the individual plant's size) can be planned on agriculturally disadvantaged sites. Regarding to photovoltaics, we will distinguish between 1. a complete expansion on the open landscape and 2. an expansion that, in terms of energy quantity, takes place 50% on the open landscape and 50% on the roof tops of settlements. This procedure is maintained in all scenarios in order to be able to better assess the spatial effects of building-integrated concepts.

- **Scenario nature conservation:** The representatives of nature conservation try to prevent strong technological interventions in the environment in order to secure the diversity of species, genetic endowments, and ecosystems (Job et al., 2016; Zaspel-Heisters, 2015). Therefore, on the one hand, we will simulate a tightening of nature conservation by blocking technological access to nature parks, flora-fauna habitat areas, landscape conservation areas, and bird sanctuaries (also for PV). For Blaschke et al. (2013), however, there is a risk of spatial discrimination if planning law divides rural areas into those worthy and those unworthy of protection. This stigmatises seemingly inferior areas in a landscape-ecological hierarchy. Such assignments declassify energy landscapes to "non-landscapes", as Schöbel (2012) puts it, thus contradicting the constitutional requirement of the German Spatial Planning Act (BMJV, 2021) to establish balanced land use patterns in Germany's rural subspaces. On the other hand, it is therefore also analysed how the opening of certain protected areas - nature conservation areas, bird sanctuaries, biosphere reserves - for the expansion of renewable energies affects the feasibility of the energy transition. Both sub-scenarios hence take into account the difficult relationship between nature conservation and climate protection.
- **Scenario energy act:** This scenario is primarily about the land interests of actors who can be assigned to agriculture or project development and who advocate providing more space for renewable energies. For this reason, the legal regulations that only grant access to photovoltaics within a 200-metre corridor along transport infrastructure and that also only allow a maximum of 200 PV project developments per year on agriculturally disadvantaged land (StMELF, 2021), are lifted. From the analysis, we hope to gain deeper insights into the dimensions of land use competition between agriculture and solar energy production. For wind energy, the current provisions on distance areas will be eased. Specifically, this concerns the 10 H-regulation, which requires a distance between turbine and settlement that corresponds to 10 times the height of the turbine. Under these circumstances, projects can hardly be realised. Therefore, it is important to analyse to what extent the goal of a climate-neutral energy supply is facilitated when modelling the distances of 800 m that applied before the 10 H-regulation, which is a minimum requirement of the Federal Emission Control Act (BImSchG). In this way, it is possible to analyse the quantitative significance of changes in the distance areas in general.
- **Scenario export:** This scenario is designed for regional policy, whose tasks include harnessing endogenous potentials of a region. Therefore, this scenario is based on the findings of the economic theory of comparative cost advantages, which states that trade between regions with different endowments of production factors (e.g. energy resources) brings economic advantages for both sides (Praetorius, 2019, 47). The supplying region can better exploit its renewable energy potential and thus boost regional economic cycles. The receiving region is able to meet its electricity needs without having to mechanise its own landscape. For this reason, we assume that one third of the electricity production of the Munich planning region is taken over by the Augsburg region. To do so, Augsburg's electricity production would have to be increased by 55%.

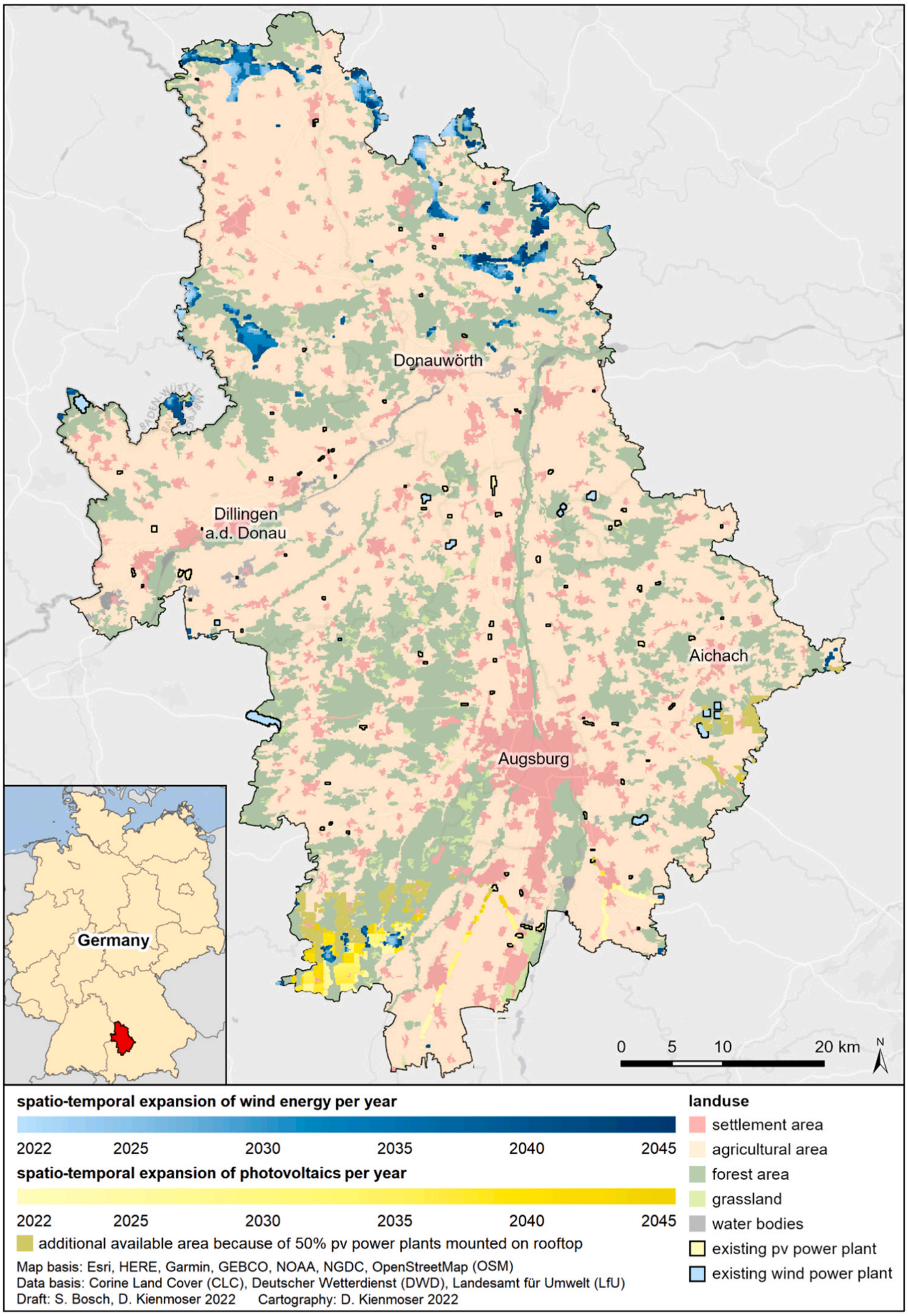
4. Results

The analyses show that it is possible to develop carbon-neutral energy landscapes in time. However, depending on the underlying assumptions in planning law and land use, there are significant differences in the expansion of renewable energies.

Reference scenario: The reference scenario shows that the focus of wind energy expansion is in the north of the region, with several spatial clusters (Fig. 4). The even more concentrated expansion of photovoltaics, on the other hand, unfolds mainly in the south. A total of 105,090 ha are available for expansion, with wind energy accounting for 38,141 ha and photovoltaics for 66,949 ha. 5641 ha are needed for wind energy and 4677 ha for photovoltaics. This corresponds to 1.4% and 1.2% of the area of the study region, respectively. So, according to our modelling, the land consumption of the transformation of the electricity sector deviates significantly from the values calculated by Matthes et al. (2018, 21) in their study on the regionalisation of the Energiewende for the whole of Germany. They arrive at a total land take of 1.7% for wind energy and 0.2% of the federal area for photovoltaics. On the one hand, these differences from our study are due to the fact that we have taken into account current developments in energy policy, such as the passing of the Federal Climate Change Act and the amendment of the Renewable Energy Sources Act 2021. On the other hand, our modelling is based on a much greater spatial accuracy, which is due to the GIS-based procedures we use and our methodological concept that combines many geodata in high spatial resolution. Undoubtedly, the difference in the size of the study regions also plays a role, as the natural and legal conditions for the expansion of renewable energies in the Augsburg region are not consistently comparable with the average conditions for the whole of Germany.

The map also shows which spaces in rural areas would be spared from the expansion of photovoltaics if 50% of the required amount of solar energy were installed on roof tops. This would affect a total of 53% of the open landscape. These areas, mapped as "additional available area" (cf. Fig. 4), could then be used for other functions. In the reference scenario, there would be a considerable technical relief in the area of the Western Forests Nature Park. The building-integrated expansion of photovoltaics would thus correspond to the interests of regional tourism that aims to protect recreational landscapes from excessive mechanisation.

Scenario nature conservation: In this scenario, the first step is to analyse how a weakening of nature conservation affects the spatial patterns of renewable energies. The differences to the reference scenario are visualised cartographically (Fig. 5). In contrast to the first scenario, bird sanctuaries, nature reserves, and biosphere reserves are included in the energy landscapes. National parks remain excluded. The area available in principle for wind energy compared to the base scenario increases by 315 ha (+0.8%) and by 8326 ha (+12%) for photovoltaics. In total, 113,731 ha (+8%) are available for expansion (wind energy: 38,456 ha, PV: 75,275 ha). 5641 ha are required for wind energy (+/-0%) and 4677 ha for photovoltaics (+/-0%). This reveals that the reduction of nature conservation-related restrictions does not lead to any changes in the areas actually required compared to the reference scenario, as the most productive sites hardly overlap with the areas



Map basis: Esri, HERE, Garmin, GEBCO, NOAA, NGDC, OpenStreetMap (OSM)
Data basis: Corine Land Cover (CLC), Deutscher Wetterdienst (DWD), Landesamt für Umwelt (LfU)
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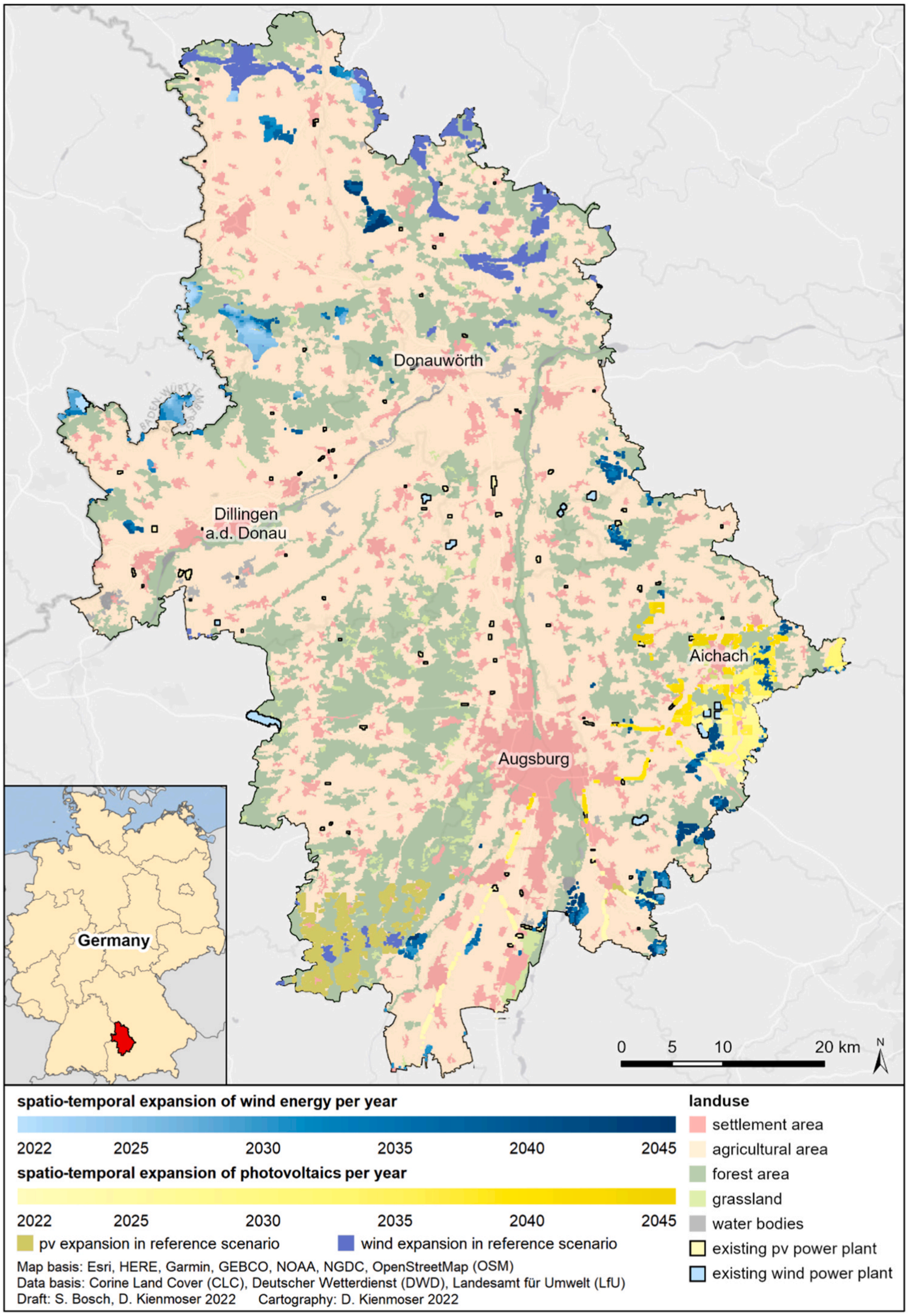
Fig. 4. Carbon-neutral energy landscape (base scenario).

worthy of protection. This is remarkable insofar as advocates of renewable energies often regard too much nature conservation as an obstacle to the energy transition (Leibenath, 2014, 126 ff.).

In a second step, we model how land uses change if nature conservation is expanded. This scenario takes into account the conflicting relationship between climate protection and biodiversity (Jackson, 2011). The assumption here is that nature parks and landscape conservation areas are no longer accessible for renewable energies. The spatial changes compared to the reference scenario are striking (Fig. 5). Not only does the composition of the wind energy clusters in the north of the region change, but completely new areas for wind energy are created in the south, east, and west. The focus of photovoltaics also shifts remarkably towards the east. In total, only 46,856 ha are still available, which corresponds to a reduction of 55% (wind energy: 18,859 ha = -51%, PV: 27,997 ha = -58%). 6121 ha are needed for wind energy (+9%) and 4693 ha for photovoltaics (+0.3%). This implies that the tightening of nature conservation specifically pushes wind energy expansion towards lower-yield sites, resulting in significantly higher land consumption. Increased nature conservation would consequently lead to greater landscape interventions overall, thus in a sense counteracting its own goals. If half of the required amount of solar energy were to be provided by rooftop photovoltaics, there would be a spatial relief in open landscape of 57%, which would be conducive to the interests of nature conservation. However, experts anticipate an increased expansion in open landscape (Grefe, 2022).

Scenario energy act: In this scenario, we leverage the fundamental



Map basis: Esri, HERE, Garmin, GEBCO, NOAA, NGDC, OpenStreetMap (OSM)
Data basis: Corine Land Cover (CLC), Deutscher Wetterdienst (DWD), Landesamt für Umwelt (LfU)
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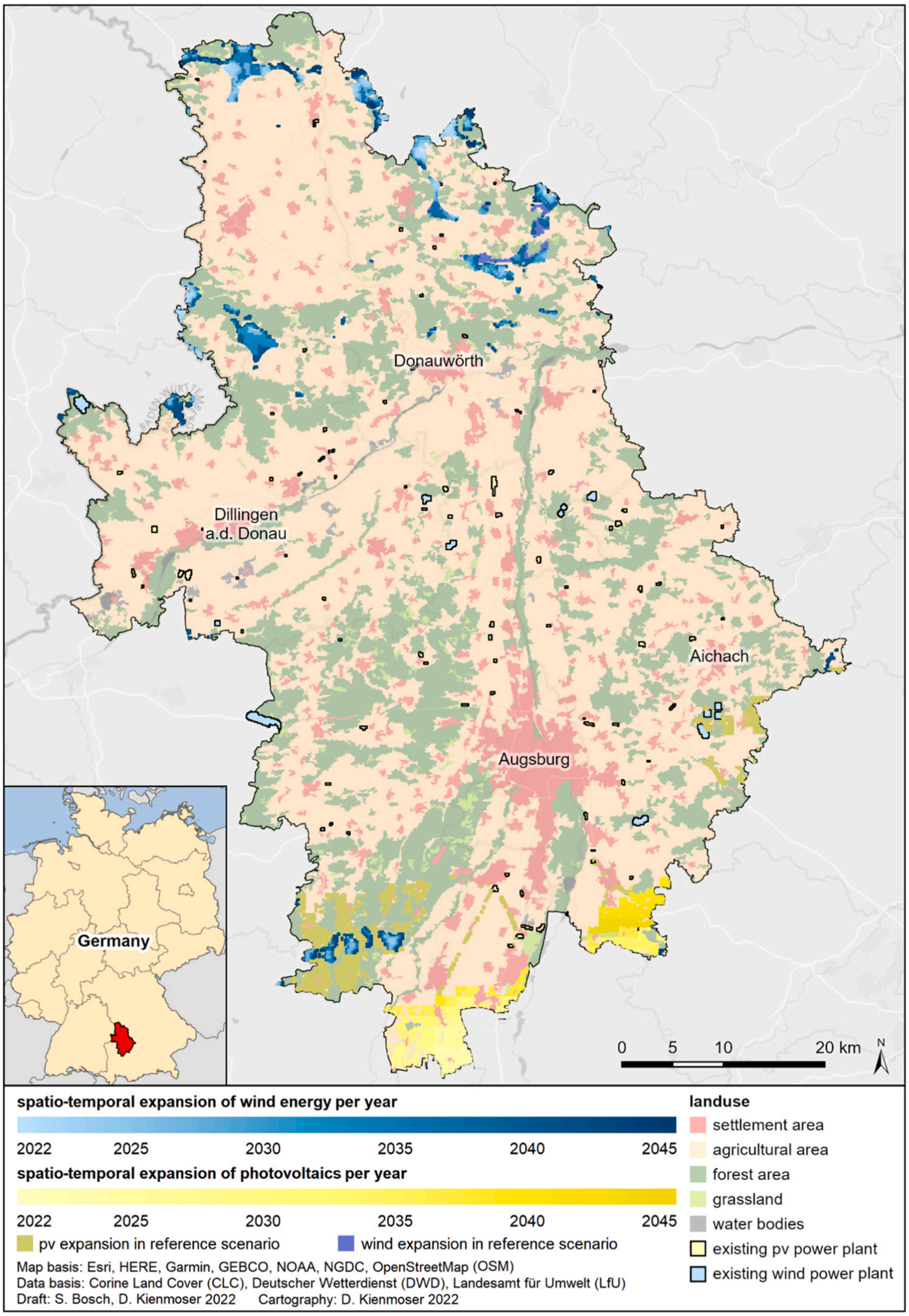
Fig. 5. Carbon-neutral energy landscape (scenario nature protection).

spatial principle of current land use policy, which aims to shift the expansion of renewable energies towards pre-burdened areas. According to Bosch and Schmidt (2020), this principle hinders a socially just energy transition, as it only mechanises those locations that are already industrially shaped and thus ecologically burdened. Cowell (2010, 222) refers to this as a selective, remotely controlled planning rationality that determines "acceptable locations" for renewable energies on the basis of a few environmental factors and detached from local social contexts. Our analyses therefore provide an initial basis for the question of which spatial implications are associated with a renunciation of the category of "pre-burdened space".

The spatial changes in this scenario compared to the reference scenario are as follows (Fig. 6): A total of 373,487 ha (+355%) are available for expansion (wind energy: 168,097 ha = +340%, PV: 205,390 ha = +207%). For the actual transformation, 5319 ha are needed for wind energy (-6%) and 4648 ha for photovoltaics (-1%). The integration of rooftop photovoltaics would lead to a reduction in ground mounted photovoltaics of 51%.

It can be concluded that abandoning the category "pre-exploited space" leads to lower land consumption overall, reducing the mechanisation of landscape. A more socially just expansion would thus also be more ecologically compatible. Nevertheless, spatial concentrations of energy technologies also occur in this scenario; for photovoltaics, these are now located mainly in the south of the region, where the high global radiation offers excellent natural conditions for solar power production. In contrast to the previous scenarios, this time the concentration zones



Map basis: Esri, HERE, Garmin, GEBCO, NOAA, NGDC, OpenStreetMap (OSM)
Data basis: Corine Land Cover (CLC), Deutscher Wetterdienst (DWD), Landesamt für Umwelt (LfU)
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Fig. 6. Carbon-neutral energy landscape (scenario energy act).

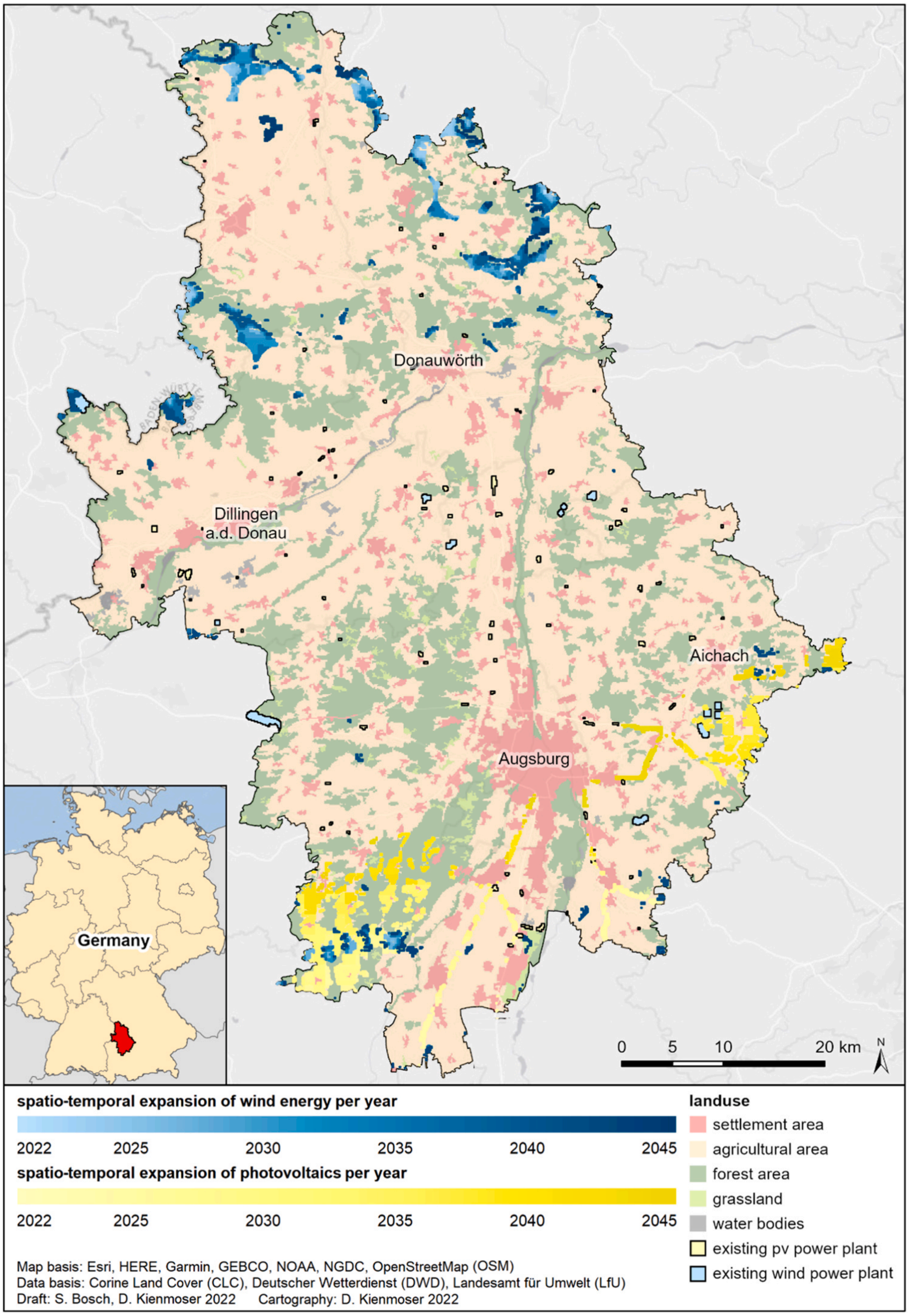
are the result of natural conditions and not the product of an institutionally legitimised spatial marginalisation of sub-regions.

Scenario export: In this scenario, the study region not only supplies itself with renewable electricity, but also a neighbouring region. Such interregional alliances make sense, as both regions would benefit. To model this, we have assumed that the Augsburg region takes over one third of the electricity production of the Munich region. The expansion of wind energy and photovoltaics is therefore considerably expanded. The basic spatial-technological dichotomy remains unaltered (Fig. 7). Compared to the reference scenario, the same sites are occupied, but due to the greater demand for energy, the demand for land is even much higher. Of the total available 105,090 ha (+/-0%) (wind energy: 38,141 ha, PV: 66,949 ha), now 8636 ha are needed for wind energy (+52%) and 8273 ha for photovoltaics (+76%). The export surplus is consequently accompanied by a massive encroachment on the landscape, e.g. high land consumption, increased visibility of power plants, and aesthetic changes. The integration of rooftop photovoltaics would require 56% less ground mounted photovoltaics.

5. Discussion

5.1. Spatial impacts, transferability, and technological progress

The scenarios have shown that the energy transition can lead to considerable changes in land use patterns. Yet there are notable exceptions: surprisingly, the weakening of nature conservation regulations



Map basis: Esri, HERE, Garmin, GEBCO, NOAA, NGDC, OpenStreetMap (OSM)
Data basis: Corine Land Cover (CLC), Deutscher Wetterdienst (DWD), Landesamt für Umwelt (LfU)
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Fig. 7. Carbon-neutral energy landscape (scenario export).

does not lead to any changes compared to the base scenario. This is of particular interest, as the spatial competition between climate protection and nature conservation is seen as a major obstacle to achieving a carbon-neutral society. The reason why sustainable energy production interferes so little with nature conservation objectives are the specific land use conditions of the Augsburg region, where the most productive sites are primarily located outside protected areas. The existing legal framework for nature conservation thus offers sufficient options for the energy transition. However, this finding cannot necessarily be transferred to other regions where protected areas may be more extensive. This regional case study nevertheless weakens the arguments of project developers who blame nature conservation for a hampering energy transition.

The second variation of the nature conservation scenario has shown that the feasibility of climate protection strategies in the region is made more difficult if nature conservation is strengthened. Wind projects would then hardly be possible, especially in the north-east of the region, so that there would be a spatial shift towards the north-west and partly to the south-east. Any strengthening of nature conservation should therefore be done with great sensitivity to the impacts on the overall land use patterns. The extent to which societal discourses are moving towards a relaxation (anthropocentric discourse) or tightening (physiocentric discourse) of nature conservation is currently impossible to predict.

One example of a massive influence of altered regulations on the spatial pattern of the energy transition is that of allowing photovoltaics on inferior agricultural land: almost the entire expansion would shift to the south of the region, where the sunniest sites are found. As in the scenario nature protection, this variation in land use can likewise only be applied to certain regions, namely those that are characterised by a similar endowment in terms of agriculturally disadvantaged areas and whose land use policies allow for the integration of these areas into the energy transition despite land competition with the food and feed industry. Currently, a trend of adopting this spatial practice of integrating agricultural land into the energy transition can be observed in Germany. This is primarily due to the Ukraine conflict, which has massively driven up electricity costs, leading to a gold-rush in the PV-sector. The eased planning regulations reinforce this process, which directs the market's gaze towards "land for future solar development" (Grefe, 2022, 35). Powerful investors such as businessmen, banks, and food companies have recently been securing more and more agricultural land and converting it into industrial land. The digitalisation of society and the electrification of mobility are leading to millions of solar panels being installed in rural areas. This could lead to rising rental prices for agricultural land and thus to a disadvantage for food and fodder production. Furthermore, the low-yield and hitherto extensively used soils, which are in the focus of the PV-industry, are also of great importance in the context of biodiversity and nature protection. In terms of transferring findings to other regions, it can be derived that short-term price shocks due to profound changes in the international energy markets can have a significant impact on land use patterns. This is especially the case when plant operators no longer need state subsidy, which is only guaranteed for certain areas, and push the deployment of renewable energies beyond the state-defined spatial corridors due to high financial returns.

Moreover, we assume that technical advances will be achieved during the modelling period. This could have major effects on the spatial patterns of the energy transition. We think about energy storage, which offers the possibility of better coordinating the weather-dependent technologies with energy demand. In addition to chemical energy storage (hydrogen, methane), the industry is focusing on the expansion of mechanical storage technologies (pumped storage, compressed air storage). A better match between production and consumption could also be achieved through optimised demand-side management, which helps to shift energy demand into times of higher energy production. Both would reduce the need for renewable energy and consequently the land consumption. In order not to exceed CO_2-budgets prematurely and to be able to operate fossil power plants longer, research and development have also been working for years on technologies for greenhouse gas reduction (carbon dioxide removal, enhanced weathering). It can be assumed that a lucrative market for negative emissions will emerge in the coming decades that can remove gigatonnes of carbon dioxide from the atmosphere (Probst and Schmitt, 2022, 33 f.). Such developments could be integrated into the modelling as part of a further study.

5.2. *Method – criteria weighting*

In all scenarions, the deployment of renewable energies is characterised by strong spatial concentrations and spatial-technological polarisations, with wind energy having its spatial focus in the north and photovoltaics in the south of the region. This may result from our method of including the most productive sites first and foremost in the expansion concept in order to keep the land consumption as low as possible in accordance with the federal government's objectives to increase land efficiency (UBA, 2021). In a further study, it could be analysed whether, if the focus of regional planning is more on the ecologically or socially compatible expansion of renewable energies, a suboptimal electricity yield can be overcompensated by other criteria (e.g. environmental impact, acceptance, landscape aesthetics). This would mean that the economically best locations are not necessarily primarily included in establishing a carbon-neutral society. The stronger weighting of social or ecological criteria (rank-order weighting), however, must be based on expert knowledge, which should be obtained in the course of expert interviews with local stakeholders. This opens up scope for qualitative research. What we already know is that the plant operators in the Augsburg region have so far shown little interest in the economic optimisation of energy projects (Bosch and Schwarz, 2019). That is why the existing wind and PV plants are located between the two poles of expansion calculated by our models. This entrepreneurial behaviour is due to the fact that the once strong financial support by the government, which especially the older plants experienced and which has now gradually been replaced by market mechanisms, did not force plant operators to choose the most profitable locations. Despite the increasing economic pressure, we know from economic science that entrepreneurs often make economically suboptimal site decisions. Therefore, a weighting of criteria based on the specific spatial contexts of energy supply, in which social and ecological factors are emphasised, appears plausible. It should be noted, however, that the actual spatial options of renewable energy planning are primarily linked to the specific local, regional and national power relations. These multi-scalar power structures cannot be broken up so easily (Cowell and De Laurentis, 2023). The weighting of criteria must therefore consider current power structures.

5.3. *Social balance of land use*

Looking at the actors who have created the planning law requirements, we can see a substantial influence on the part of state bodies (federal ministries, state ministries, nature conservation, and licensing authorities), which prescribe a narrow spatial corridor for renewable energies. Above all, the requirement to concentrate the expansion on pre-burdened, already technologised or industrialised areas must be viewed critically if "acceptable locations" (Cowell, 2010, 222) are the result of a top-down procedure in which only particular interests are expressed. In order to be able to establish alternative concepts for achieving the climate goals, the energy transition must therefore be seen as a political struggle in which the current dominant energy regime is to be destabilised (Burke and Stephens, 2018, 78). However, this is not about a comprehensive social revolution, but a redistribution of power and opportunities for more participation of marginalised social groups. This could be seen as a form of "renewable energy (in)justice" (Pellegrini-Masini et al., 2020), because the acceptance of the energy transition is at risk if certain social groups are marginalised by the siting decisions. In our opinion, the category "pre-burdened space", which was explicitly addressed in the context of the scenario energy act, should therefore be abandoned. This would also lead to some ecological advantages, as the energy transition would cause less land consumption. It is also necessary to think about how planning laws can be revised so that the technological burdens of the transformation process are distributed more evenly and fairly. In our estimation, this could be done via lower distance regulations and relaxed restrictions in those sub-regions in which infrastructure measures for the energy transition are completely excluded under the current legal framework. This includes protected areas where wind energy development has been prevented, for example, for reasons of bird protection. The latest turbine technologies with radar devices can now locate flocks of birds and switch off at an early stage (BfN, 2020). Consequently, this kind of land use conflict could be minimised and possibly more regions could be exempted from a too strong machanisation, if bird sanctuaries were integrated more into energy transition planning.

Despite all criticism of the spatial concentration of renewable energies, it should be pointed out that it is precisely the economically peripheral regions that could seize the opportunity to emerge as exporters of the energy transition and boost regional economic cycles.

6. Conclusions

The aim of the study was to develop a GIS-based approach for the spatial transformation of regional energy systems. The expansion of renewable energies was linked to the temporal and quantitative objectives of national and international climate strategies. In this context, the question arose as to what land consumption the complete development of a carbon-neutral energy system would require, what regional changes in land use would result and which land use categories would be most affected. Finally, it was of interest which territorial-institutional framework conditions would define this transformation, which spatial interests would be addressed by this framework, and how the transformation of the energy supply could be made more socially balanced.

Regarding the Paris Agreement and the objectives of the German Federal Government, the study revealed that it is in fact possible to realize a carbon-neutral regional energy system by the 2050 deadline. The innovation of our approach was that we did not only assume a single possible spatial development. Rather, we created an ensemble of potential spatial corridors in which carbon neutrality was achieved under completely different legal frameworks or scenarios. This was implemented by varying planning law. In line with our theoretical background, we see these variants as alternative objectifications that have the potential to replace the current legal foundations of land use. This could happen, for example, if changing social discourses or external shocks erode hegemonic narratives and the power relations based on them.

Currently, the spatial requirements are primarily defined by state actors (ministries, nature conservation, and licensing authorities). The result of these conceived energy spaces can be seen in the reference scenario: it became clear that to achieve carbon neutrality, 1.4% of the study area would have to be designated for wind energy and 1.2% for photovoltaics. Our analyses, which included the current planning law, therefore deviate from the results of an earlier Germany-wide regionalization of the energy transition, which estimated the area required for wind energy to be slightly higher and that for photovoltaics to be significantly lower (Matthes et al., 2018). Our calculations have also shown that an increased expansion of building-integrated photovoltaics would contribute to the technological relief of protected areas (Augsburg Western Forests) and thus correspond to the land use interests of regional tourism. What was surprising about the second scenario was that the reduction of spatial restrictions of nature conservation had no effect on the spatial pattern of renewable energies. This is due to the regional peculiarity that the most profitable locations for wind and solar energy are outside the ecologically sensitive areas. Consequently, competition for space between the energy transition and nature conservation, which is often described as an obstacle to a comprehensive energy transformation, cannot be confirmed with regard to our study area.

In contrast, even a slight tightening of nature conservation would result in a completely new spatial pattern. Wind energy in particular would be displaced from high-yield locations, thereby significantly increasing the land consumption of the energy transition. A tightening of nature conservation should therefore be carried out with consideration for the location options of a carbon-neutral energy system. Our analyses have also shown that removing the category of "pre-polluted sites" within legal planning would massively reduce land consumption. In addition, a valuable contribution to a socially balanced energy transition could be made if renewable energies were distributed more evenly across rural areas. However, concentration zones should not be ruled out per se if economically peripheral regions attempt to boost regional economic cycles in this way, as shown in the last scenario. Still, this should be done on a voluntary basis and not be predetermined by planning law. The relaxation of restrictions in areas that currently still have many exclusion zones is also important in this context. Bird sanctuaries could play a central role here, as the latest wind turbines offer the possibility of detecting flocks of birds at an early stage via radar, thus stopping in time to prevent collisions.

The value of both our study and the scenarios within it becomes visible when considering how frequently the Renewable Energy Sources Act and planning law have been adjusted in recent years, drastically changing the spatial prerequisite for renewable energies. Many studies have relied on the production of a single final outcome map and have quickly lost validity (Klok et al., 2023). By analysing scenarios with different spatial conditions, we prevent a short half-life period of our cartographic visualisations. Furthermore, our scenarios revealed that the variation of individual parameters can lead to significant changes in the spatial potential of renewable energies. Yet our study has limitatons: the method used in the study reveals the locations of energy landscapes based solely on economic yield, leading to densely concentrated clusters of energy installations in certain areas. For example, photovoltaic installations are predominantly found in the southern part of the planning region, occupying nearly all available open spaces. However, a comparison with existing installations shows significant differences, mainly due to the method's lack of consideration for civic land ownership.

Finally, for further studies we recommend including the perspectives of those people who are directly affected by renewable energies. For reasons of complexity, these local social contexts were not examined. The study instead focused on the meso-level of site planning and on more general, supra-local social discourses on the spatial integration of renewable energies (e.g. role of nature conservation, importance of economic cycles, unequal spatial development). Further case studies could analyze the extent to which local social contexts influence the restructuring of the energy supply and to what extent parameters such as acceptance, participation, local planning structures, and landscape aesthetics make a deviation from the most profitable locations appear reasonable to implement a sustainable energy supply. Qualitative research based on expert interviews with local stakeholders may be one approach of further investigations. Furthermore, participatory mapping methods could be used to investigate what ideas the local population has about a spatially balanced expansion of renewable energies, which locations they would exclude, and where residents can imagine the deployment of wind and solar plants.

CRediT authorship contribution statement

Stephan Bosch: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Dominik Kienmoser:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare no conflict of interests.

Data Availability

Data will be made available on request.

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