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Wind power deployment and the impact of spatial planning policies

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Abstract
Spatio-environmental externalities of renewable energy deployment are mainly managed through spatial planning policies, like regional expansion goals, zoning designated areas, or setback distances. We provide a quantitative analysis of how effectively spatial planning policies can steer RES deployment, using the example of onshore wind power expansion in Germany. Based on a novel georeferenced dataset of wind turbines and spatial planning policies, we use a dynamic panel data model to explain yearly additions in wind power capacities. Most importantly, we find a strong positive impact of zoning specific land areas for wind power deployment. An additional square kilometer of designated area leads to an increase of 4.6% of yearly capacity additions per county. Not only the amount of designated area matters, but also the size and shape of each individual designated area. Small and elongated areas are, on average, associated with more wind power expansion than large and compact areas. Moreover, we find that in states with an expansion goal, capacity additions are 2.6% higher. In contrast, increasing the setback distance between turbine sites and settlements by 100 m is associated with reductions of yearly capacity additions by about 3.1%. Our findings show that policymakers can resort to spatial planning instruments in order to effectively arrange wind power deployment with other land uses.

Keywords Environmental regulation · Multi-level governance · Panel data · Wind power · Spatial planning

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1 Introduction

Much of the debate on transforming energy systems to reach carbon neutrality is centered around the question of which policies effectively deliver CO_2 emission reduction, or almost equivalently, which policies deliver a vast expansion of renewable energy sources (RES). Arguing about the best incentive-based instruments (e.g. taxes, certificate trading, subsidies, standards, etc.), we seem to forget that merely making RES investments profitable does not necessarily result in actual RES deployment. Addressing profitability is only half the battle when it comes to large-scale RES plants. Wind power turbines and open space photovoltaic systems are technologies with considerable land requirements. How and where land for RES deployment is provided, or restricted, therefore also strongly affects RES investments.

Especially the siting of wind power turbines is accompanied by severe public debates. Many countries regulate construction sites of wind power plants—the amount and the spatial distribution—by means of spatial planning policies. Resorting to a toolbox of planning instruments, governments intend to provide some land areas for wind power usage while they exclude others. To understand which policies effectively steer wind power deployment—that is to successfully induce an intended increase or decrease in added power capacities at a certain place—we need to turn our attention to regulation through spatial planning policies. With this work we examine by which instruments and to what extent spatial planning policies impact onshore wind power deployment.

In principle, regulators make use of spatial planning instruments to regulate land-use decisions of private actors. Wind power projects require space and produce spatial externalities, like visual disamenities, noise emissions, or wildlife impacts (Zerrahn 2017). In order to address these spatial externalities and manage land-use trade-offs, regulators resort to spatial planning instruments. These planning instruments may comprise setback rules that require a specified distance between wind turbines and the closest residential area, or designating zones that earmark the installation of wind turbines. Such spatial planning instruments are in use in most countries with onshore wind power deployment, especially in Europe and the U.S. (Lerner 2022; Winikoff 2022; Dalla Longa et al. 2018; Oteri et al. 2018; Haugen 2011). Most commonly, competences for spatial planning policies are assigned to subnational levels, e.g. states, regions, or counties (Keenleyside et al. 2009; Söderholm et al. 2007).

We empirically analyze the role of spatial planning policies by exploiting panel data from Germany. Of course, the specifics of spatial planning instruments may differ slightly across countries: setback rules may relate to different objects (e.g. single houses, residential complex or property lines), or the zoning of designated areas may allow for other land uses or not. Still, these types of spatial planning instruments are very similar and well comparable to instruments applied in Germany, making the implications of this paper internationally relevant. We collect georeferenced data on the following spatial planning policies implemented in Germany at the state and regional level: (1) expansion goals for future wind power deployment, (2) forest bans for wind turbines, (3) setback distances to residential areas, and (4) the zoning of areas designated for wind power deployment. With this unique panel dataset including all 401 German counties and all years between 2000 and 2016, we are able to examine the effect of spatial planning policies on yearly additions of wind power capacity. We use a dynamic panel data model to account for unobserved heterogeneity and true state dependence. In particular, we include time lags of several years of all our policy variables since the development of wind power projects as well as spatial planning processes may span over years.

Our empirical results highlight the strong positive impact of zoning specific land areas for wind power deployment. By zoning designated areas, planning authorities effectively control the spatial allocation of wind turbines. An additional square kilometer of designated area leads to an increase of about 4.6% of yearly capacity additions per county. However, our results show that not only the total amount of designated area matters, but also the size and the shape of each individual designated area. Elongated areas are, on average, associated with more wind power expansion than compact areas. We also identify state-level expansion goals and setback rules as effective instruments. While introducing an expansion goal raises yearly capacity additions by 2.6%, increasing the setback distance between turbine sites and settlements by 100 m is estimated to reduce yearly capacity additions by 3.1%.

Our work is connected to four different strands of literature on wind power expansion.

The first strand of literature comprises studies which measure the spatial externalities of wind power deployment, and thereby explain the need for spatial regulation of wind power deployment. Constructing and operating wind turbines may cause negative impacts on the local scale. For instance, noise disturbances for residents or landscape changes emanating from wind power deployment find expression in lower property prices (Gibbons 2015), or a decline in life satisfaction (Krekel and Zerrahn 2017), and they are reflected by a positive willingness to pay for moving away wind turbines (Meyerhoff et al. 2010). However, this strand does usually not address the question how the observed spatial externalities can be addressed effectively by regulation.

This shortcoming is overcome in a second strand of literature by means of spatial modeling approaches (Reutter et al. 2023; Salomon et al. 2020; Drechsler et al. 2011). These papers simulate the application of spatial planning policies on the allocation of wind turbines. Commonly, they focus on minimizing economic and environmental costs of wind power deployment and assess welfare implications of differing policies, e.g. an increase in setback distances. While this literature simulates impacts of spatial planning policies (greenfield or ex-ante) given optimal siting decisions, we estimate actual (observed) impacts from real-world policy changes.

A third strand of literature concentrates on qualitative empirical (ex-post) analyses of spatial planning. Studies for the U.S. and Europe have described and emphasized the role of spatial planning policies in the siting of wind power projects (Cowell et al. 2017; Haugen 2011; Iglesias et al. 2011; National Research Council 2007; Pettersson et al. 2010; Power and Cowell 2012). They evaluate siting regulation enforced by federal, state, regional, and local authorities. Though this literature underlines the intuition that spatial planning policies steer wind power expansion, it lacks quantitative analyses, especially to verify the magnitude of their effect.

Here, a fourth strand of literature which comprises a number of quantitative studies for Europe and the U.S. has identified profitability and land availability as the two fundamental drivers for spatial allocation of wind power capacities (Ek et al. 2013; Goetzke and Rave 2016; Hitaj 2013; Lauf et al. 2020; Shrimali et al. 2015; Staid and Guikema 2013). Still, while these studies provide an advanced understanding of the impact of incentive-based instruments—mainly addressing profitability of wind power projects—it neglects the influence of (subnational) spatial planning policies.

To the best of our knowledge, the only empirical and quantitative analyses to include spatial planning policies thus far are Stede et al. (2020) and Lauf et al. (2020). Stede et al. (2020) solely focus on setback rules and apply a difference-in-differences approach to show for the German state of Bavaria that an increase in setback distance has a significantly negative effect on wind power deployment.[1] In a cross-sectional analysis, Lauf et al. (2020) use county- and region-wide aggregated data to examine the effect of total designated area on wind power deployment in Germany and Sweden. They find that zoning more designated areas promotes the installation of wind turbines.[2] For the first time and in contrast to the above-mentioned studies, we draw on a unique panel data set of detailed georeferenced spatial planning policies applied at different federal levels from 2000 to 2016 in the whole of Germany. Besides time series on state-specific policies (e.g. setback rules), we use information on time-varying geo-locations of all individual designated areas that were determined by regional planning authorities in this period. This allows us, for example, to identify how many wind turbines were placed within and outside of designated areas per county. By integrating zoning policies to this level of detail, we can provide new evidence on the impact of the details of spatial planning policies. By using a dynamic spatial panel, we can deal with unobservable spatial and/or time specific effects and better disentangle the impacts of various spatial planning policies.

In the following Sect. 2, we first explain the mechanism of spatial planning in Germany and depict the expected impacts of spatial planning policies on wind power deployment based on a simple theoretical model. In Sect. 3 we establish our empirical approach. Section 4 describes the dataset and unrolls how variables of interest are generated. Section 5 presents empirical results. Section 6 discusses policy implications and limitations. Section 7 concludes.

2 Spatial planning and the siting of wind turbines

Spatial planning policies can influence how much of technically suitable land areas are actually available for wind power deployment. In Sect. 2.1 we describe the division of competences and instruments of spatial planning within the German multi-level government system. The German spatial planning system may well represent the situation in the majority of federally structured countries. In Sect. 2.2 we set up a simple theoretical model which explains wind power allocation as a wind developer's private investment decision that is regulated through spatial planning policies. Thus, the theoretical model leaves us with various expected effects of different spatial planning policies (see Sect. 2.3) that are scrutinized in the empirical part of the paper.

[1] Stede et al. (2020) show that construction permits for wind turbines declined in response to a larger setback distance. This decline reflected the extent to which available land for wind power deployment was reduced due to the the increase in setback distance.

[2] In their study on wind power expansion in Sweden, Ek et al. (2013) include a dummy variable indicating whether municipalities have areas classified as national interest for wind power (NIAW). They find a positive effect for this NIAW classification. Since the NIAW classification is their only proxy for good wind resources the positive effect cannot be attributed to potential facilitation of planning and permit processes.

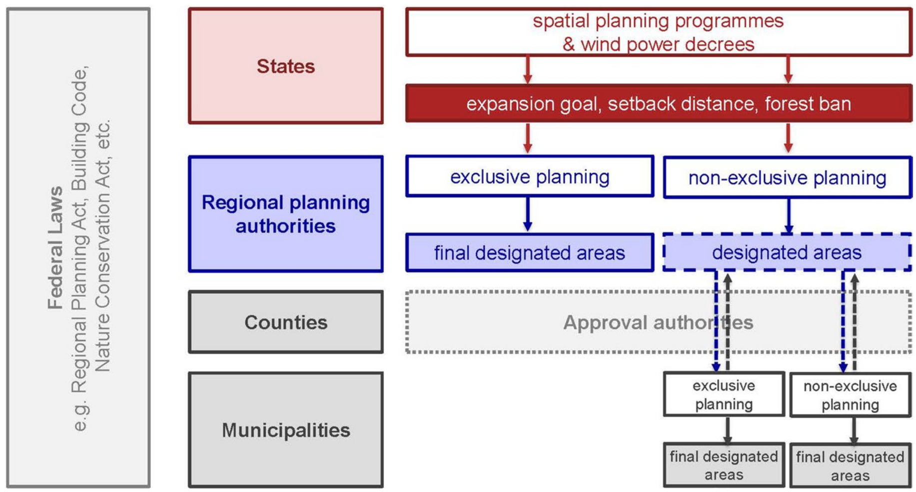


Fig. 1 Spatial planning system in Germany. *Notes:* The amount of final designated areas specified at the regional or local level may be also zero

2.1 Spatial planning policies in Germany

In Germany, competences on spatial planning are structured within the federal political system.[3] Though the federal government holds some critical legislative powers that affect wind power allocation (e.g. Federal Control of Pollution Act, Federal Nature Conservation Act), the realm of spatial planning lies within the original responsibility of the German states ("Bundesländer"). The states are subdivided into regional planning authorities ("Regionale Planungsverbände") which in turn comprise a number of counties ("Kreise") and municipalities ("Gemeinden"). Among these three subnational levels (i.e. states, regions, and counties), policy making is mainly a hierarchical process. States decide on how far-reaching and detailed they set rules and prescriptions for subsequent regional planning authorities. Regional planning authorities then set up regional plans which are lastly adopted and concretized by local development plans (see Fig. 1). Since no data on the local level (i.e. counties and municipalities) is accessible, we only consider state-level and regional policies in our empirical analysis.

2.1.1 State level

State governments establish their spatial planning policies mainly via state development plans ("Landesentwicklungsplan") or guidelines for planning and permitting authorities ("Windenergieerlasse").[4] There are three key policy instruments that largely define wind power related spatial planning decisions at the state level, and which we consequently

[3] For an extensive description of the spatial planning system in Germany see Pahl-Weber and Henckel (2008).

[4] Of course, there are many further ways how state governments can regulate wind power deployment, e.g. by means of the state planning act, the state building law, or their nature conservation law. Equally, there are further important policy decisions taken by state governments, e.g. the specification of setback distances between wind turbines and aeries of threatened bird species.

include into our empirical analysis. First, state governments may set *expansion goals* that define a level of wind power deployment which shall be reached at a certain point in the future. Expansion goals may formulate an amount of wind power capacities (in MW), an amount of electricity produced from wind turbines (in GWh), or a total area designated for wind power deployment (in km^2). By setting expansion goals, state governments can force subsequent planning levels to comply with their targets or at least to take them into account.[5] Second, state governments may implement *forest bans* such that the construction of wind turbines in forest areas is principally not authorized. Via provisions in the state forest act ("Landeswaldgesetz") or via abovementioned regulations (e.g. state development plans, guidelines for planning authorities), all or certain forest areas (e.g., depending on their size or type of forest) are excluded from wind power deployment. Third, *setback distance* rules are applied in order to keep a certain distance between turbine sites and residential settlements. For example, the German states choose setback distances ranging from 500 m up to 2000 m.[6] Also sometimes called 'minimum distance rules', setback distances are part of spatial planning policies in almost all European and many other countries with wind power installations (Dalla Longa et al. 2018; Oteri et al. 2018).

2.1.2 Regional level

Within the German spatial planning system, the regional level is the highest level at which spatial plans contain a map with explicit demarcations for certain land uses, e.g. settlements, industrial zones, or wind power deployment. In general, regional planning authorities have to carry out requirements prescribed by state governments when mapping which areas are excluded from and which areas are designated for wind power. However, to some extent it is the responsibility of the regional planning authorities where exactly these designated areas are drawn in. For example, a state government may predefine that a certain amount of power generation shall be produced from wind turbines, but the regional planning authorities within that state transfer this requirement into concrete georeferenced designated areas (see Fig. 2). Accordingly, *designated areas* for wind power deployment are the key policy instrument at the regional level. Similarly, also in other countries regional or local planning authorities—more or less autonomously—apply the zoning of designated (or priority) areas (Lauf et al. 2020; Dalla Longa et al. 2018).

The zoning of designated areas is conducted at two administrative levels—the regional and the local level—and it may be designed in one of two ways—through *exclusive planning* or through *non-exclusive planning*. Under exclusive planning at the regional level, regional planning authorities exclude any (outskirt) area from wind power deployment that is not specifically marked as a designated area. Simultaneously, exclusive planning means that regional planning authorities make the final decision on zoning designated areas leaving no scope for decision-making to the local level (see Fig. 1). In contrast, under non-exclusive planning, all area that is not specifically marked as designated by the regional planning authorities is still available as a potential turbines site (exemplary, see wind turbine sites outside designated areas in Fig. 2). Non-exclusive planning also leaves some

[5] As *expansion goals* we refer to specified target marks that may have the legal form of goals or principles of spatial planning ("Ziele oder Grundsätze der Raumordnung"), or the form of sectoral planning decisions ("Fachplanung") or administrative provisions ("Verwaltungsvorschrift").

[6] Setback distance rules can be defined with respect to different aspects. They can refer to the height of wind turbines or the type of settlement.

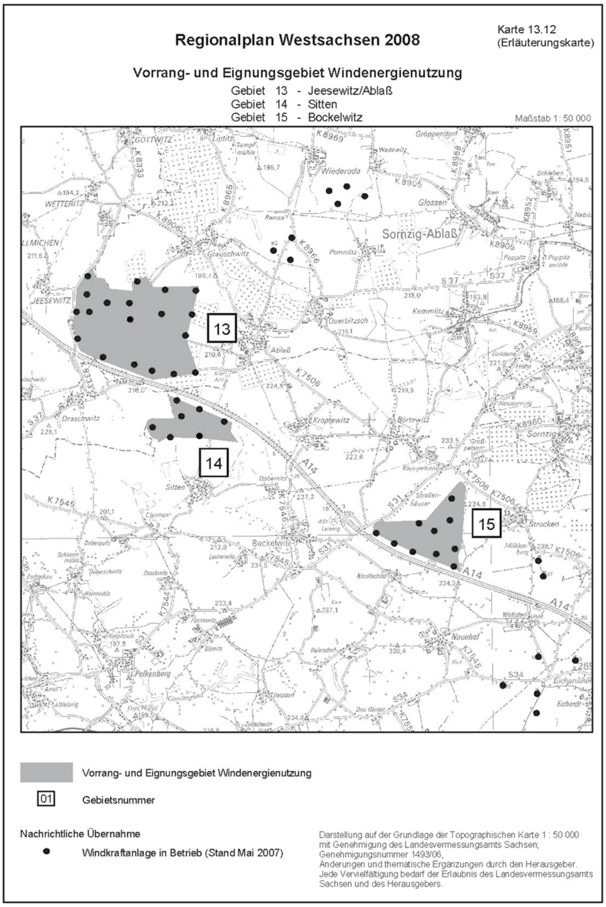


Fig. 2 Regional plan. *Notes:* The figure shows an exemplary section from a regional plan. Designated areas are plotted in gray. Wind turbine sites are illustrated by black dots. All three individual designated areas contain existing wind turbines. Further wind turbines are constructed outside of the designated area, meaning that at the time of their building approval non-exclusive planning was in place

leeway to the subsequent local level. Here, local planning authorities can decide whether to introduce exclusive or non-exclusive planning and they can mark further designated areas.[7] Nevertheless, regardless of the type of planning—exclusive or non-exclusive planning—authorities increase the probability of success for wind power projects by zoning designated areas. Within designated areas wind power plants more likely receive building permission because here wind power deployment is legally favored over other land uses.[8]

[7] In general, regional and local planning authorities have to take into account the respective others' zoning decision. The Federal Spatial Planning Act prescribes this 'mutual feedback principle' in order to ensure consistent spatial planning.

[8] Precisely, the Federal Spatial Planning Act (FSPA, "Raumordnungsgesetz") sets three types of designated areas: priority areas, restricted areas, and suitable areas (§7 Para. 3 FSPA). Utilizing one of these types of designated areas or a combination of them regional planning authorities de facto implement what we denote as *exclusive* and *non-exclusive* designated areas.

2.2 A simple model of wind power deployment

We set up a simple theoretical model that reflects how spatial planning policies expectedly influence wind power deployment, or more precisely, *yearly additions of wind power capacities per county* which is our dependent variable in our regression model. Whether to construct a wind turbine at a certain location is a private investment decision by wind developers. Accordingly, the model explains wind power expansion coming from the wind developers' perspective. We first define the wind developer's profit function and its deployment decision before deriving its expected response to spatial planning policies. Within the model, spatial planning policies impact profitability of and land availability for wind power deployment. They affect costs and revenues of wind power deployment on site and determine the amount of currently available building sites for wind turbines.

2.2.1 Wind developer's profit function

Let us assume that a representative wind power developer decides on how much wind power capacity to build in each county.[9] Additional wind power capacity installed in county i and year t is denoted by $y_{i,t}$ (which is the dependent variable in the empirical analysis). We assume the wind developer to solely consider costs and benefits originating from decisions in the current year. This is equivalent to an investment decision being based on the net present value of wind power projects. The representative wind developer's profit function $\pi_t(.)$ in county i and year t reads as follows:

$$\pi_t(y_{i,t}) = s_{i,t}\, e_{i,t}(y_{i,t}) - c_{i,t}(y_{i,t}). \tag{1}$$

Total revenues (first term on rhs) depend on the level of remuneration per unit of electricity $s_{i,t}$ and the amount of electricity $e_{i,t}$ produced from newly installed wind power capacities in county i and year t.[10] Total costs of constructing and operating the amount of newly installed wind power capacities are denoted by $c_{i,t}(y_{i,t})$ (second term on rhs).

We can further specify the components in eq. (1) that determine the wind developer's total revenues and total costs. First, remuneration $s_{i,t}$ is specified through the federal RES support scheme that in Germany varies with the productivity of wind turbine sites $w_{i,t}$ and over time t (Hitaj and Löschel 2019).[11] We write $s_{i,t} = s(w_{i,t}, t)$. In turn, site-specific productivity $w_{i,t}$ itself is a function of geographical characteristics $\mathbf{x^c_{i,t}}$ (e.g. wind conditions) and policy variables $\mathbf{x^p_{i,t}}$ (e.g. forest ban) in county i and year t. Policies can change the site productivity function in a county by excluding certain locations (e.g. forest area) from wind power usage, thus altering the functional shape of the site productivity curve. We comprise geographic and policy variables in vector

[9] This is a valid assumption since most sites are allocated to wind developers in a first-come, first-served manner. Commonly, wind developers attempt to secure suitable locations as early as possible, e.g. by contacting land owners and concluding user contracts. Over time, land owners (most of them are farmers) professionalized in leasing their land, such that price competition over land use rights emerged among wind developers. In model terms, assuming a representative wind developer per county versus perfect competition among many wind developers is equivalent as long as the representative firm optimizes the net present value of those profits that originate from current but not future decisions.

[10] Precisely, $e_{i,t}$ represents the expected sum of electricity produced from wind power capacities over their life time.

[11] See Appendix H for more information on the details of the federal RES support scheme.

$$\mathbf{x_{i,t}} = \begin{pmatrix} \mathbf{x^c_{i,t}} \\ \mathbf{x^p_{i,t}} \end{pmatrix}.$$

In addition to geographic and policy variables, site productivity $w_{i,t}$ also depends on the stock of already installed wind power capacity $Y_{i,t-1}$ and time t. Productivity of new wind power plants may vary with $Y_{i,t-1}$ because existing wind turbines may cause wake effects, meaning that an upwind wind turbine generates decreases in downwind wind speeds and thus lowers a downwind wind turbines power generation (see Lundquist et al. 2019). Site productivity may also vary with t because technological progress allows higher yields per unit of capacity (e.g. development of weakwind turbines). We write $w_{i,t} = w(\mathbf{x_{i,t}}, Y_{i,t}, t)$ and thus $s_{i,t} = s(w(\mathbf{x_{i,t}}, Y_{i,t}, t), t)$.

Second, the function of total costs of electricity production $c_{i,t}$ is defined through the same, above-mentioned variables, hence we write $c_{i,t}(y_{i,t}) = c(y_{i,t}, \mathbf{x_{i,t}}, Y_{i,t-1}, t)$. Their influence on the cost function is briefly explained as follows. County-specific geographic and policy variables $\mathbf{x_{i,t}}$ affect costs of electricity production in a number of ways. Geographic characteristics like topographic conditions lead to higher or lower construction costs of wind turbines. Spatial planning policies can cause or avoid additional transaction costs for wind developers when preparing and undergoing the permission process for wind power projects. Installed wind power capacities $Y_{i,t-1}$ may bring about synergy effects because necessary grid infrastructure already exists and can be shared (e.g. converter substation, access roads), and thus construction and operation costs for additional turbines are lower. With time *t*, cost components may change due to trends in the economy or wind energy sector, as was observed with comparatively strongly falling financing costs over the last two decades (Egli et al. 2018).[12]

Third, by defining site productivity as the ratio of electricity production per installed capacity, we write $e_{i,t} = w_{i,t}\, y_{i,t}$. That is, for county i and year t site productivity $w_{i,t}$ indicates how much electricity $e_{i,t}$ is produced from added wind power capacities $y_{i,t}$.[13] Altogether, we can rewrite the wind developer's profit function as follows:

$$\pi_t(y_{i,t}) = s(w(\mathbf{x_{i,t}}, Y_{i,t-1}, t), t)\, w(\mathbf{x_{i,t}}, Y_{i,t-1}, t)\, y_{i,t} - c(\mathbf{x_{i,t}}, Y_{i,t-1}, y_{i,t}, t). \tag{2}$$

2.2.2 Wind developer's deployment decision

In order to maximize their profits wind developers decide on the amount of added wind power capacities $y_{i,t}$. The profit-maximizing level $y^*_{i,t}$ is defined through the wind developers' first-order condition. Differentiating eq. (2) w.r.t. $y_{i,t}$ and setting $\frac{\partial \pi_t}{\partial y_{i,t}} = 0$, we obtain:

$$\forall i, t: \quad \frac{\partial c(y^*_{i,t}, Y_{i,t-1}, \mathbf{x_{i,t}}, t)}{\partial y_{i,t}} = s(w(\mathbf{x_{i,t}}, Y_{i,t-1}, t), t)\, w(\mathbf{x_{i,t}}, Y_{i,t-1}, t). \tag{3}$$

While wind developers strive to install $y^*_{i,t}$, their decision on wind power additions is constrained due to restricted land availability. By $\bar{Y}_{i,t}$ we denote the maximum amount of total

[12] Again, this is discounted total cost over the operating time of a wind turbine. However, from a wind developer's perspective 90–95 % of total costs of wind power projects are upfront, e.g. turbine price, project planning, etc. (Wallasch et al. 2015).

[13] Site productivity $w_{i,t}$ has unit h. Site productivity indicates the amount of full-load hours, i.e. the period of time the wind turbine is operating at full capacity.

wind power capacities that can be installed in county i and year t, given no wind turbines are built yet (greenfield approach). Thus, $\bar{Y}_{i,t}$ reflects greenfield land availability for building wind turbines by indicating an upper limit of overall installable capacities. $\bar{Y}_{i,t}$ is determined through socio-geographic land-use characteristics $\mathbf{x_{i,t}^c}$ (e.g., residential or protection areas) as well as through state, regional and local policies $\mathbf{x_{i,t}^p}$ (e.g., spatial planning). Land availability also directly depends on t because land-use efficiency, expressed in wind power capacity per area, changes over time (e.g., through the development of new wind turbine types). We write $\bar{Y}_{i,t} = \bar{Y}_{(}\mathbf{x_{i,t}}, t)$.

When we ask for the maximum amount of wind power additions in a given year, we have to consider wind power capacities already installed in previous years $Y_{i,t-1}$. Existing wind turbines occupy a part of the available land, such that the remaining area for maximum additional wind power capacities per county and year, denoted by $\bar{y}_{i,t}$, is defined as:

$$\forall i, t: \quad \bar{y}_{i,t} = \bar{Y}(\mathbf{x_{i,t}}, t) - Y_{i,t-1}. \tag{4}$$

Thus, wind developers face a constrained optimization problem, where their choice of yearly added wind power capacities, denoted by $\hat{y}_{i,t}$, is capped $\forall i, t: \ \hat{y}_{i,t} \leq \bar{y}_{i,t}$. The resulting function of $\hat{y}_{i,t}$ is defined as:

$$\forall i, t: \quad \hat{y}_{i,t} = \min[y^*_{i,t}, \bar{y}_{i,t}]. \tag{5}$$

Following eq. (5), we can interpret yearly wind power capacity additions as a linear-limitational function. One limiting factor is the profit-maximizing amount of additional wind power capacities. The other limiting factor is the maximum amount of possible wind power additions in county i and year t. This implies that increasing profitability or land availability may lead to more wind power additions, but does not necessarily do so since the respective smaller value of $y^*_{i,t}$ and $\bar{y}_{i,t}$ limits the value of $\hat{y}_{i,t}$.

2.3 Expected effects of spatial planning

Based on the above model, we formulate which effects of spatial planning we are expecting to find. With respect to each policy variable $x^p_{i,t}$ with $p = p1, \dots, p7$, we explain which effect on actual wind power deployment $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}}$ the model predicts. Hereby, $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}}$ is always composed of an effect on profitability $\frac{\partial y^*_{i,t}}{\partial x^p_{i,t}}$ and land availability $\frac{\partial \bar{y}_{i,t}}{\partial x^p_{i,t}}$.[14]

Profitability: With regard to the profit maximizing capacity level $y^*_{i,t}$ the influence of spatial planning policies is composed of its impact on revenues $s_{i,t} w_{i,t} y_{i,t}$ and its impact on costs $c_{i,t}$. Based on our model, we derive the expected effect of each policy by differentiating eq. (3) w.r.t. $x^p_{i,t}$ with $p = p1, \dots, p7$ and solving for $\frac{\partial y^*_{i,t}}{\partial x^p_{i,t}}$:

[14] As both of them are latent variables we cannot observe the effect of spatial planning policies on them directly. $y^*_{i,t}$ is at least to a certain extent private information of the wind developer, and $\bar{y}_{i,t}$ is not clearly definable because technical and legal restrictions for potential wind turbine sites are not conclusively assessable. Still, on the basis of our model we can hypothesize which effects on $y^*_{i,t}$ and $\bar{y}_{i,t}$ we are expecting, and which overall effect on $\hat{y}_{i,t}$ is expected.

$$\forall i,t: \quad \frac{\partial y^*_{i,t}}{\partial x^p_{i,t}} = \frac{1}{\frac{\partial^2 c}{\partial y^2_{i,t}}} \left((s + w\frac{\partial s}{\partial w})\frac{\partial w}{\partial x^p_{i,t}} - \frac{\partial^2 c}{\partial y_{i,t} \partial x^p_{i,t}} \right). \tag{6}$$

The sign of the policy effect defined by eq. (6) depends, first, on the impact on site productivity $w_{i,t}$, and second, on the impact on marginal deployment costs $\frac{\partial c_{i,t}}{\partial y_{i,t}}$.[15] If the policy impact on site productivity is positive $\frac{\partial w}{\partial x^p_{i,t}} > 0$ and the policy impact on marginal deployment costs is negative $\frac{\partial^2 c}{\partial y_{i,t} \partial x^p_{i,t}} < 0$, then the expected policy effect on the profit-maximizing level $y^*_{i,t}$ is positive $\frac{y^*_{i,t}}{\partial x^p_{i,t}} > 0$, and vice versa.[16] Otherwise the expected effect on the profit-maximizing level is ambiguous.

Land availability: With regard to the maximum level of additional wind power capacity $\bar{y}_{i,t}$, the influence of spatial planning policy is equivalent to its impact on land availability $\bar{Y}_{i,t}$. Based on our model, we derive the expected effect of each policy by differentiating eq. (4) w.r.t. $x^p_{i,t}$ with $p = p1, \dots, p7$ and solving for $\frac{\partial \bar{y}_{i,t}}{\partial x^p_{i,t}}$:

$$\forall i,t: \quad \frac{\partial \bar{y}_{i,t}}{\partial x^p_{i,t}} = \frac{\partial \bar{Y}}{\partial x^p_{i,t}}. \tag{7}$$

According to eq. (5), we expect that the overall effect on actual wind power expansion $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}}$ is always determined through the effect on the binding factor, either on profitability or on land availability. Subsequently, we propose the expected effects for all policy variables included in the empirical investigation. We briefly give an intuition for each policy effect and afterwards summarize them in Table 1.

2.3.1 Expansion goal: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \geq 0$

Introducing a state-level expansion goal for wind power deployment is expected to have a positive effect and may influence actual wind power additions via different channels. On the one hand, states likely pursue the goal by means of various measures which we otherwise do not consider, e.g., by improving building permit processes and consulting services, and thus costs of wind power projects are lowered (effect on profitability). On the other hand, an expansion goal also indirectly fosters or even directly prescribes to regional planning authorities to make land available for wind power usage, e.g., requiring a sufficiently large amount of designated areas (effect on land availability).

2.3.2 Forest ban: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \leq 0$

We expect a strictly negative effect of implementing a state-level forest ban. Banning wind turbines from forest areas mainly reduces land availability. If potential locations with high

[15] Deployment cost comprise construction as well as operation costs linked to deploying wind power capacities. $c_{i,t}$ has unit € /*MW*.

[16] This rests upon the realistic assumption that $s + w\frac{\partial s}{\partial w} > 0$, which means that the RES support scheme is designed such that the marginal revenue of an additional unit of wind power capacity $s_{i,t}w_{i,t}$ increases with site productivity. This is true for the German RES support scheme, see Appendix H.

productivity are thereby excluded, this also reduces site productivity such that the profit maximizing level decreases.

2.3.3 Setback distance: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \leq 0$

We expect that increasing the setback distance decreases wind power additions. The rationale is similar to the expected effect of a forest ban.

2.3.4 Designated areas: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \geq 0$

According to our model, the expected effect of designating additional areas for wind power deployment on land availability is always non-negative. Under exclusive planning, more designated areas enlarge the number of available locations for wind turbines. Under non-exclusive planning, more designated areas do not change the number of available wind turbine locations. The same applies for the profitability of wind power because adding more designated areas does not worsen site productivity or deployment costs, but may instead lower the latter. This is due to the fact that in the course of selecting designated areas regional planning authorities already prepare future wind power projects, and thereby some of the project costs and uncertainties are reduced and the procedure of building permission is facilitated.

2.3.5 Average size of individual designated areas: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \geq 0$

The total amount of designated areas per county may consist of many small individual designated areas or just a few large ones (see the three individual designated areas plotted in gray in Fig. 2). Ceteris paribus, changing the average size of individual areas does not necessarily change the mere amount of available construction area for wind turbines (in km^2). However, holding the total designated area constant, but increasing the average size of individual designated areas likely leads to a decrease in deployment costs because larger individual wind farms can be built and fixed cost (e.g., expert reports, grid connection, access routes, etc.) can be spread over more wind power plants (economies of scale).

2.3.6 Average shape of individual designated area: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \lesseqqgtr 0$

Though altering the average shape of the individual designated area does not change the mere amount of available construction area for wind turbines (in km^2), it may in fact change the number of wind turbine locations that fit into this area. Ceteris paribus, a more elongated area can likely contain more turbine sites than a more compact area. That is, more compact shaped areas, e.g., circles or squares, provide less turbine sites than more elongated areas, e.g. narrow rectangles. Let us look at the following example: if we change an individual square-shaped designated area into a narrow rectangle (by doubling two sides and halving the other two sides), while leaving its size (in km^2) unchanged, this can create additional turbine sites within the designated area (see illustration in Appendix F). Thus, designing designated areas less compact is expected to increase land availability. Whether the shape of designated areas also affects the profitability of wind power projects is unclear and depends on very local conditions. For example, due to wake effects an elongated area may provide higher (lower) site productivity in comparison to a compact area, if it is placed orthogonal (parallel) to the main wind direction.

Table 1 Expected effects of changes in policy and control variables

Variable	Effect on profitability $\frac{\partial y^*_{i,t}}{\partial x^p_{i,t}}$	Effect on land availability $\frac{\partial \bar{y}_{i,t}}{\partial x^p_{i,t}}$	Expected effect $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}}$
$\mathbf{x^p_{i,t}}$			
Expansion goal	≥ 0	≥ 0	≥ 0
Forest ban	≤ 0	≤ 0	≤ 0
Setback distance	≤ 0	≤ 0	≤ 0
Total designated area	≥ 0	≥ 0	≥ 0
Size of designated areas	≥ 0		≥ 0
Shape of designated areas	$\lesseqqgtr 0$	≥ 0	?
Exclusive planning	$\lesseqqgtr 0$	≤ 0	?
$Y_{i,t-1}$	$\lesseqqgtr 0$	-1	?
s	> 0		> 0
w	$\lesseqqgtr 0$		?
t	> 0	$\lesseqqgtr 0$	?

The upper part shows the expected effects of changes in policy variables. The lower part shows the expected effects of changes in control variables

2.3.7 Exclusive planning: $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}} \lesseqqgtr 0$

Non-exclusive planning does not restrict installations of wind power, whereas exlcusive planning restricts installations exclusively to designated areas. When regional planning authorities switch from non-exclusive planning to exclusive planning, our theoretical model does not predict a clear effect sign. Even though the productivity of available sites can only decline $\left(\frac{\partial w}{\partial x^{p,1}_{i,t}} \leq 0\right)$, marginal power production costs of available sites may increase or decrease $\left(\frac{\partial^2 c}{\partial y_{i,t} \partial x^{p,1}_{i,t}} \lesseqqgtr 0\right)$. For example, marginal power production costs may decrease, e.g., if exclusive planning would lower project costs through more well-founded and legally watertight regional plans. Hence, the expected effect on the profit-maximizing level is ambiguous $\frac{\partial y^*_{i,t}}{\partial x^p_{i,t}} \lesseqqgtr 0$. By contrast, the expected effect on land availability is very clear and negative $\frac{\partial \bar{y}_{i,t}}{\partial x^p_{i,t}} \leq 0$. However, its effect size depends on how many areas are designated for wind power, since designated areas are still available for wind power usage while all other areas drop out under exclusive planning.

Table 1 summarizes which overall effect of each explanatory variable we are expecting to find based on our theoretical model. We cannot directly observe whether a change in actual wind power additions $\hat{y}_{i,t}$ originates in a change in profitability (second column) and/or in a change in land availability (third column). For some variables the model predicts an unambiguous sign of the overall effect $\frac{\partial \hat{y}_{i,t}}{\partial x^p_{i,t}}$ (fourth column). Nevertheless, effects on profitability and land availability are not always aligned such that the empirical analysis must show which one of them dominates the other.

2.4 Time frames

Regulating and realizing wind power deployment is a matter of years. The impact of regulation on wind power deployment may only be recognized after years. In 2015, a business survey among wind developers found an average project length of about five years, starting with preliminary checks and closing with the initial operation of a wind turbine (FA Wind 2015).[17] According to own interviews of the authors with wind developers and other experts in the field, a project length of five years can be regarded as a conservative (respectively high) estimate with respect to the whole period from 2000 to 2016. Unlike today, during our investigation period there were less legal requirements in place that imposed time-consuming preparations on wind power projects.[18]

Multi-annual time frames are also common in spatial planning processes. Policies at the state level can take effect in the short and long term. For example, new setback rules or an introduced forest ban for wind power can be implemented within months. Nonetheless, these policies may contain transitional arrangements, e.g. provisions to safeguard ongoing projects and existing approvals, such that policy effects on actual wind power deployment can be delayed up to some years. Spatial plans at the regional level may exert influence as soon as they come into force. However, the wind power projects planned on their grounds may also materialize with delay. In conclusion, for most of the policies examined in our analysis we expect their impacts to be delayed at maximum by up to five years. In the next chapter we expound how to account for this by including lagged variables in our regression model.

3 Empirical strategy

In order to unravel the effects of spatial planning policies on yearly wind power additions, we apply a dynamic panel data analysis. Our empirical approach addresses three challenges: 1) time lags of potential policy effects, 2) unobserved individual heterogeneity, and 3) possible state dependence. First, we take into account that policy effects are likely observed with some delay (see Sect. 2.4). Therefore, we lag policy variables by the most suitable time period based on economic theory, test statistics, and auxiliary regressions with different time lags (see the impact response analysis in Appendix D). Second, unobserved (time-invariant) county-specific effects cause omitted variable bias if they are correlated with regressors. To remove this unobserved heterogeneity we use first-difference (and within) estimators. Third, we include the lagged dependent variable respectively the stock of installed wind power capacities as a regressor because it is likely that wind power additions in preceding years affect wind power additions in the current year. Thus, our

[17] The project length can be divided into the earlier 'time-to-plan' (TTP) period and the later 'time-to-build' (TTB) part of wind power projects. With regard to wind power projects the TTP period accounts for most of the project length. For our investigation period, the maximum length of the TTP phase is about four years (FA Wind 2015). In general, the TTP period plays an important role for commercial construction projects (Millar et al. 2016).

[18] Nowadays, wind developers have to provide e.g. formal environmental impact assessment, run public participation procedures, or order expert reports concerning monument protection, visual axes, etc. Furthermore, data on the realization period of wind power projects between 2000 and 2016 underpins that this phase of wind power projects was considerably shorter compared to today. The realization period spans from the day the building permission was issued to the day of inital operation. Between 2000 and 2016 average realization period was among ten to 15 months (Fachagentur Windenergie an Land 2021). Exceptional cases are the years 2008 and 2009 when average realization period was above 20 months.

model specifies that the dependent variable is directly affected by its own lag (true state dependence).

3.1 Regression model

Our dependent variable is the natural logarithm of additions of wind power capacity per county i and year t, denoted by $ln(y_{i,t})$. The estimated effect sizes β_l^P and β_l^C are semi-elasticities since all but one regressor enter the regression equation in level terms. The only regressor in log terms is the stock of installed capacities $ln(Y_{i,t-1})$, hence its coefficient λ reports an elasticity. The stock of installed capacities is equal to the sum of all lags of the dependent variable $Y_{i,t-1} = \sum_{s=t-1}^{T} y_{i,s}$. Our variables of interest are state-level and regional spatial planning policies that have been in place in each county, denoted by the vector $X_{i,t-l}^P$. Control variables $X_{i,t-l}^C$ comprise geographic and socio-economic features of counties, e.g. green votes and population density, but also county-specific remuneration through the national RES support scheme. The individual-specific effect α_i captures all constant and unobserved variables that are county-specific and affect $y_{i,t}$. These may be physical characteristics (e.g. topographic and climatic conditions), institutional properties (e.g. human resources of planning and licensing authorities, attitude of officials working at approval authorities), or population-oriented attributes (e.g. social capital, etc.). Finally, ξ_t depicts yearly time effects that are common across all counties, e.g. technological development of wind turbines. $\epsilon_{i,t}$ is the idiosyncratic error term that is assumed to be serially uncorrelated.

Equation (8) describes our regression model:

$$ln(y_{it}) = ln(Y_{i,t-1})\lambda + X_{i,t-l}^P\beta^P + X_{i,t-l}^C\beta^C + \alpha_i + \xi_t + \epsilon_{it} \tag{8}$$

Depending on the specification of l, the regression model in eq. (8) accounts for different time lags until policies impact yearly wind power additions. Our main regression model is specified by policy-specific lags that we regard as suitable based on our knowledge on time frames of wind power projects and policy implementation, on the AR(1) and AR(2) tests as well as the incremental Sargan-Hansen test (see Sect. 3.2). The choice of the lag structure is underpinned by an auxiliary analysis that looks at the time span of impact responses (Appendix D). Regressing the change in the stock of wind power capacities in $t-1$ versus in $t+h$ for all values of $h = 1, \dots, 8$ on our regressor variables shows us how impact responses vary across policies. While we observe a quick response to the zoning of designated areas, we see larger time delays for setback rules and total remuneration. As explained in Sect. 2.4, the planning of wind power projects may span over years, while five years of project length can reasonably be assumed as a maximum project length for our period of investigation. Accordingly, we limit our time lags to a maximum of five years (as chosen for the variable setback distance).

Including the stock of installed capacities (i.e. the sum of all lags of the dependent variable) as a regressor means that wind power additions in preceding years affect current wind power additions, expressed by the coefficient λ. We also include two modifications of $Y_{i,t-1}$ as controls, i.e. the overall capacity density of installed wind turbines $\frac{Y_{i,t-1}}{A_{i,t-1}^{county}}$ (see Sect. 4.3) and the capacity density of installed wind turbines within designated areas $\frac{Y_{i,t-1}^{designated}}{A_{i,t-1}^{designated}}$ (see Sect. 4.2.2). There are several reasons why future wind turbine constructions may depend on the existing stock of wind power capacities. For example, the amount of past capacity additions may reflect how many potential turbine sites are already exploited respectively left over or how local people get accustomed to the presence of wind farms and create less resistance.[19] Equally, it may represent infrastructure that was developed for existing wind turbines and that reduces marginal deployment costs of additional turbines.

3.2 Estimation method

We use a first-difference (FD) estimator that removes the unobserved county-specific effect α_i. The first-difference transformation of the dynamic model reads as follows:

$$\triangle\, ln(y_{i,t}) = \triangle\, ln(Y_{i,t-1})\lambda + \triangle\, X^P_{i,t-l}\beta^P_l + \triangle\, X^C_{i,t-l}\beta^C_l + \triangle\, \xi_t + \triangle\, \epsilon_{i,t} \tag{9}$$

However, the OLS estimator is inconsistent because $\triangle\, ln(Y_{i,t-1}) = ln(Y_{i,t-1}) - ln(Y_{i,t-2})$ is correlated with the (first-differenced) error term $\triangle\, \epsilon_{i,t} = \epsilon_{i,t} - \epsilon_{i,t-1}$ (Cameron and Trivedi 2005; Baltagi 2021). To address this endogeneity, we apply the Arellano-Bond estimator which uses second or higher lags of the variables as instruments for $\triangle\, ln(Y_{i,t-1})$ (Arellano and Bond 1991). The Arellano-Bond estimator uses the generalized method of moments (GMM) and is suitable for panel data with a dynamic process, few time periods (small T), and a large number of individuals (large N); see Roodman (2009).

Setting up the moment conditions to estimate the first-differenced equation, we also consider potential endogeneity of state and regional policy variables. While state-level policies are less likely prone to endogeneity since state-wide policy decisions are rarely tailor-made for a single county, there could be the case that wind developers exert influence on the zoning of designated areas. Wind developers might anticipate the zoning of certain areas and try to act on spatial planning authorities in order to finalize the envisaged areas as designated for wind power. This, however, would rather speed up project realization for wind developers than increasing the amount of total designated areas. Yet, as a conservative assumption, we treat all policy variables as endogenous. As mentioned above, we can use second and higher lags of the policy variables as instruments. This is defined by the following moment conditions[20]:

$$E[y_{i,t-s}, \triangle\, \epsilon_{i,t}] = 0, \tag{10}$$

$$E[x^P_{i,t-s}, \triangle\, \epsilon_{i,t}] = 0, \quad \text{with} \quad s = 2, \ldots, t \quad \text{and} \quad t = s, \ldots, T. \tag{11}$$

If the selection of lagged regressors accounts for all dynamics (e.g. delayed feedback of the dependent variable), we should not find any serial correlation in the resulting error term. To check this, we apply the tests for first- and second-order serial correlation by Arellano and Bond (1991), denoted by *AR(1)* and *AR(2)*.[21] Under the assumption of serially

[19] Of course, the argument could also work the other way around.

[20] We assume that *population density*: and *GDP per capita* are strictly exogenous, while *green votes* and all federal and state policy variables are defined as predetermined variables. Predetermined variables are not strictly exogenous as they are potentially correlated with past and current error terms (Roodman 2009).

[21] Errors of the first-differenced regression model should have negative first-order serial correlation and zero second-order serial correlation to reasonably assume no serial correlation of error terms in levels (Kiviet 2020). We use postestimation statistics of the STATA-command *xtdpdgmm* to implement AR(1) and AR(2), see Kripfganz (2019).

uncorrelated errors, the lagged regressors, as defined by Eqs. (10) and (11), can constitute valid instruments for the first-differenced equation. In order to test the validity of (a subgroup of) instruments, we use the Sargan-Hansen test of overidentifying restrictions (in tables reffered to as *Hansen's J-statistic*) (Hansen 1982). If lagged regressors turn out to be invalid instruments this may imply that the regression model has not yet been specified adequately and requires additional explanatories (Kiviet 2020). When comparing the suitability of different lag specifications, we additionally consider the model and moment selection criteria (herein referred to as *MMSC*) for panel data models, developed by Andrews and Lu (2001), which resemble the widely used Akaike and Bayesian information criteria (*AIC* and *BIC*).

We further run a fixed-effects (FE) and random-effects (RE) model. The latter also allows us to estimate coefficients of time-invariant variables, e.g. wind power potential or technical potential. It should be noted that both suffer from a bias in the estimate of λ approximately of magnitude $1/T$ (Nickell 1981).[22] Still, as the standard approach to account for unobserved heterogeneity, the FE and RE model serve as proper basis for comparison. Moreover, we change the dependent variable from log-transformed (measured in ln(MW)) to level terms (measured in MW and MW/km^2) and account for the censored data structure by running conditional fixed-effects Poisson regressions. Finally, we run regressions on the subsample of rural counties only since urban counties see very little wind power installations over the 17-year sample period.

4 Data

Our dataset comes entirely from administrative sources. We first describe our dependent variable before turning to policy variables and control variables. Our sample covers yearly observations for all 401 German counties from 2000 to 2016.[23] We choose counties as the observational unit because this allows us to account for county-specific effects, e.g., when local authorities are in charge of building permit issuance. At the same time, as a spatial unit it is large enough to avoid the cutting of designated areas that would impede an examination of features of designated areas.

4.1 Dependent variable

The dependent variable is the natural logarithm of the amount of additional wind power capacity installed per county and year ln(MW). Data of wind turbines built between 2000 and 2016 with technical and geo-referenced information on each turbine is based on Manske et al. (2022).[24] Figure 3 shows the development of the stock of installed wind power capacities per county. Until 2000, existing wind power capacities were concentrated in a

[22] When estimating FE and RE models the within estimator is always inconsistent since the demeaned regressor is correlated with the error term (Cameron and Trivedi 2005).

[23] We treat county mergers that took place between 2000 and 2016 as if they had occurred at the beginning of our period of investigation. Only 29 of 401 counties (7.23 %) were restructured due to administrative reforms, almost all of them (28 counties) are in Mecklenburg-Western Pomerania, Saxony, and Saxony-Anhalt.

[24] The data set by Manske et al. (2022) is open access and provides the most accurate picture of the spatial and temporal distribution of wind power expansion in Germany.

few counties in the northern half of Germany. In subsequent years, wind power expansion mainly proceeded in northern counties, and only a little share went to southern parts.

4.2 Policy variables

4.2.1 State-level policies

State-level policy variables are coded based on a broad review of all relevant state development plans, laws, decrees, acts, etc. that have been in place between 2000 and 2016.

Setback distance: The variable *setback distance* (measured in km) incorporates state-level specifications by law (e.g., in Bavaria) as well as state-level guidelines for permitting the construction of wind turbines or for designating areas for wind power. We consider setback rules with regard to residential areas. Further sub-rules, for example with regard to single housings, may determine different setback distances that are not reflected by this variable. For a first overview of the development of setback rules in German states see Fig. 4. Throughout the observation period almost all states introduced setback distance rules (see also Appendix I).

Forest ban: The variable *forest ban* is a binary variable indicating that the deployment of wind power is prohibited in forest areas. It varies across states which type of forest the state-specific statutory ban is referring to. We define *forest ban* to be equal to 1 if state regulation generally prohibits wind power in forested areas following Bunzel et al. (2019). As you can see in Fig. 5, several states introduced a forest ban (see also Appendix I).

Expansion goal: The binary variable *expansion goal* is equal to 1 if state governments have implemented a goal that determines future targeted wind power deployment. The goal may be specified in terms of electricity amounts, capacity amounts, or an amount of area provided for wind power. While in 2000 only two states had set an expansion goal, by the end of 2015 all states had implemented such a policy, see Fig. 6 (see also Appendix I).

4.2.2 Regional policies

Regional policy variables are generated from geo-referenced data on regional plans of all regional planning authorities from 2000 to 2016. While recent regional plans are partly accessible via public websites, we reached out to regional planning authorities to collect all regional plans that have been in place since 2000.

Total designated areas: The variable *total designated area* reports the total amount of all legally effective designated areas in km^2 per county and year. If a regional plan loses its validity (e.g., due to jurisdiction), all designated areas within the corresponding counties of the regional planning authority are disregarded. Accordingly, the value of *total designated area* may rise and fall over time. As Fig. 7 shows, especially within the first half of our observation period more regional planning associations specified designated areas.[25]

Average size of individual designated areas: This variable specifies the average size of all individual designated areas within a county, where $N_{i,t}$ is the number of individual designated areas in county i in year t. For each county and year it is calculated by dividing

[25] The variable *total designated areas* includes all designated areas independent from the type of planning—exclusive or non-exclusive planning. However, by interacting the variables *exclusive planning* and *total designated areas* in our regression analysis, we account for potential differences of the effect of zoning designated areas under one or the other type of planning.

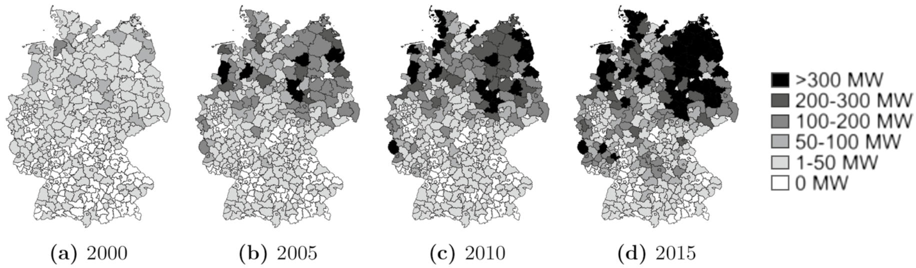


Fig. 3 Development of installed wind power capacities per county (in MW)

the *total designated area* by the number of all individual designated areas (e.g., in Fig. 2 there are three individual designated areas). That is $Size_{i,t} = \frac{\sum_{s=1}^{N_{i,t}} A_{s,t}}{N_{i,t}}$.

Average shape of individual designated areas: This variable indicates how compact individual designated areas are on average. It is computed as the average ratio of the size of all individual designated areas A to the squared perimeter of these designated areas P^2 per county and year. Hence, the ratio is $Shape_{i,t} = \sum_{s=1}^{N_{i,t}} \frac{A_{s,t}}{(P_{s,t})^2}$. For example, a more elongated designated area has a larger perimeter than a circular designated area of same size. Accordingly, in counties where designated areas are more elongated, the variable (*average shape of individual designated areas*) is lower than in counties with more circular designated areas. See also Appendix F.

Average capacity density: This is another variable which shall shed light on the impact of designated areas. To assess the availability of vacant designated areas, the variable *average capacity density* within designated areas measures the average amount of installed wind power capacities per total designated area per county and year (MW/km^2). It is computed as the quotient of wind power capacities installed within designated areas and the *total designated areas*. Thus, it indicates how much of the total designated area per county and year is already exploited. Strictly speaking, it is rather a control variable, but we use it to study the policy effect of zoning designated areas.

Exclusive planning: This is a binary variable which indicates by value 1 that the corresponding regional planning authority applies exclusive planning. It takes value 0 where non-exclusive planning is in place. As explained before, exclusive planning means that the regional planning authorities make the final decision on the zoning of designated areas, and turbine constructions on all other areas are not permitted. Exclusive planning leaves no leeway to local planning authorities. In contrast, non-exclusive planning means that the regional planning authorities may preset designated areas, but local planning authorities can concretize, deviate and expand the final zoning of designated areas. Hence, under non-exclusive planning the regional planning authorities do not exclude areas from wind power deployment.[26]

Figure 8 shows the development of total designated areas in aggregate terms under exclusive and non-exclusive planning. The aggregated total designated areas under *both*

[26] Usually, the state level decides which type of planning is in place. Though state governments prescribe the type of planning, we subsumed the variable *exclusive planning* under regional policies because it describes the actions by regional planning authorities.

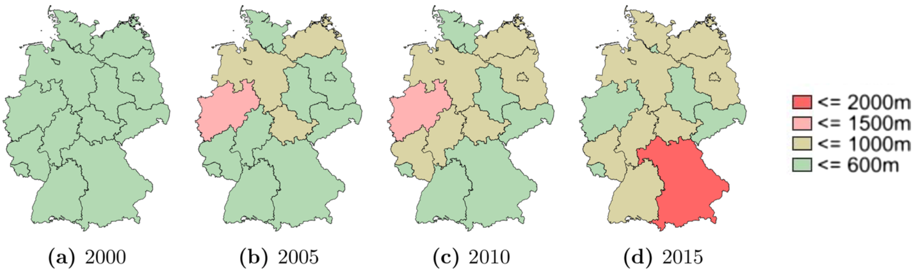


Fig. 4 Development of state-level setback distances

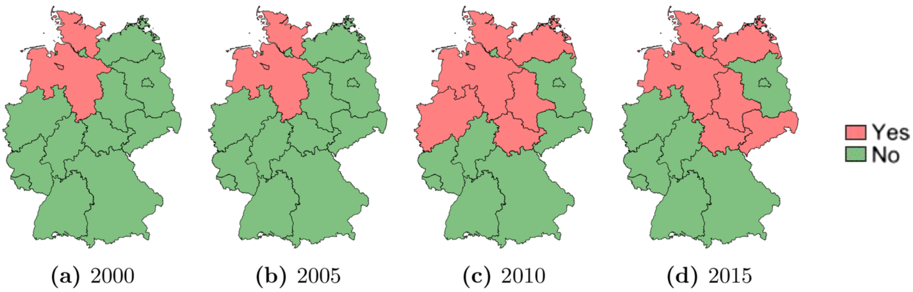


Fig. 5 Development of State-level Forest Bans

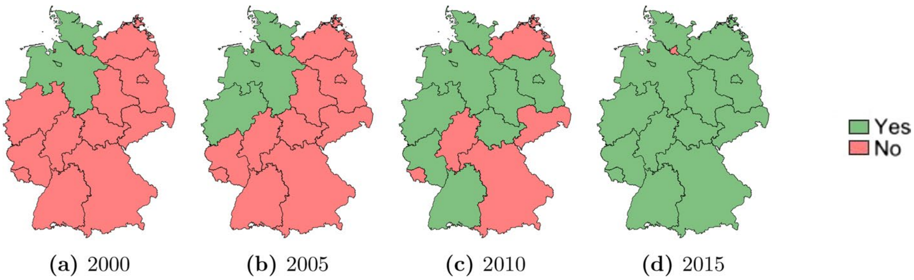


Fig. 6 Development of state-level expansion goals

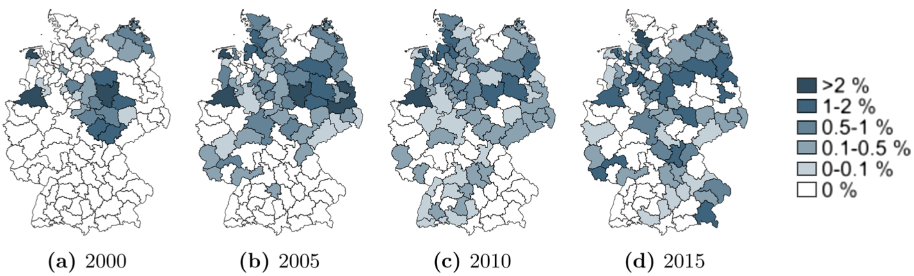
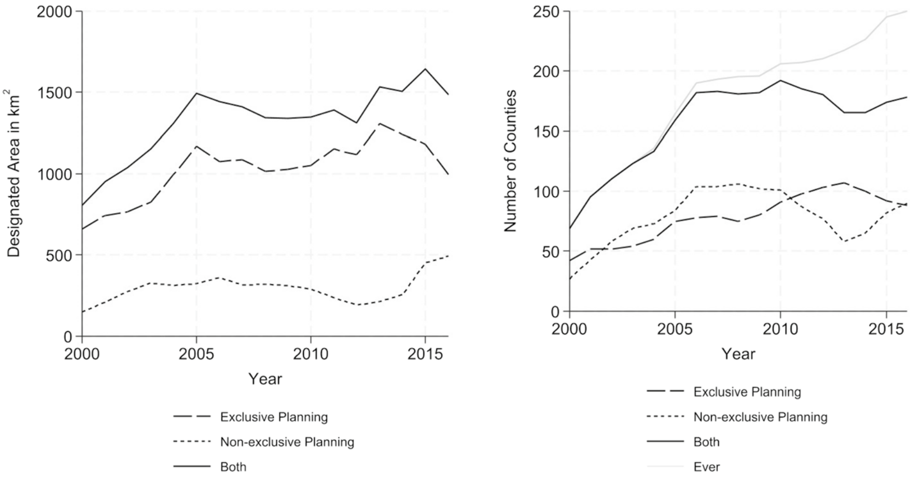


Fig. 7 Development of total designated areas per regional planning association (in % of the territory)



(a) Aggregated Total Designated Areas (b) Counties with Designated Areas

Fig. 8 Development of designated areas and the corresponding type of planning

planning types rose mainly within the first five years of our investigation period (see Fig. 8a). This increase was driven by an increase in exclusive designated areas. While the difference in the aggregate amount of total designated area remained large, the number of counties with a positive amount of total designated area under exclusive and non-exclusive planning followed a comparable trend (see Fig. 8b). By 2016, at the end of our investigation period 250 out of 401 counties have *ever* had designated areas.

4.3 Control variables

Data on area sizes and land use is obtained from the Federal and State Statistical Offices (Federal and State Statistical Offices 2021). The *county area* and its land use naturally constitute the maximum amount of available land. While settlement, transport, or water areas rule out the building of wind turbines, technically wind turbines can be constructed on agricultural and forest areas. We combine agricultural and forest areas to approximate the *technical potential* for wind power deployment per county.[27]

We include the *stock of installed capacities* using the data set by Manske et al. (2022). This variable is defined as the sum of yearly added wind power capacities since 1990 up to the year of observation $Y_{i,t-1} = \sum_{r=1990}^{t-1} y_{i,r}$. Existing wind power capacities can point to existing infrastructure (e.g. grid connection, access routes) which can be utilized by newly added wind turbines, and existing infrastructure can reduce marginal deployment costs for additional capacities. Whereas this can enhance profitability, existing wind power capacities likely reduce land availability since turbines sites are exploited. The latter should be

[27] A more detailed number of technical potential for wind power deployment is provided by Masurowski et al. (2016). His data on technical potential even takes into account the legal lower bound of setback distances. However, his data also incorporates some state rules which in our analysis comes within the policy variables. Using the data by Masurowski et al. (2016) results does not change.

covered by the variable *density of installed capacity*. This variable is calculated as the ratio of the *stock of installed capacities* and the *technical potential* measured in MW/km^2.

Discounted *total remuneration* per wind power capacity depends on site-specific power production and RES support payments (cf. first term in the profit function, eq. (1) in Sect. 2). To calculate this variable, we assumed the deployment of the following standard wind turbines within the following time periods: Enercon E-70 with 2.30 MW from 2000 to 2004, Enercon E-82 with 2.30 MW from 2005 to 2011, Enercon E-101 with 3.05 MW from 2012 to 2016. In combination with the data from the German Meteorological Service ("Deutscher Wetterdienst (DWD)") we obtain the annual power production of standard wind turbines in all counties. Finally, we apply the corresponding RES support scheme to compute the average amount of discounted revenues for each county and year. The steps of calculation are presented in Appendix H in more detail. Moreover, we consider the productivity of a turbine site which is determined through its *wind power potential* measured in W/m^2. Based on data from 1981 to 2010 from the DWD we calculate the average wind power density at 80 m height for all counties (DWD Climate Data Center 2014). This variable may have an extra impact on wind power additions—aside from its indirect impact through *total remuneration*—e.g., because profitability is more robust to changes in the RES support scheme.

Further control variables are socioeconomic variables drawn from Federal and State Statistical Offices (2021). The *GDP per capita* may affect both profitability and land availability, if for example there are more resource for spatial planning and infrastructure in wealthy regions. The variable *green party votes* captures the share of votes for the green party in national elections. The expansion of renewable energy usage is a key concern of the German green party, such that many green party votes may represent a stronger local support for wind power projects. From Hermes et al. (2018) we use estimates on landscape aesthetic quality. They assess *landscapes attractiveness* by a standardized method referring to landscape diversity, naturalness and uniqueness. This variable can approximate the public costs of changing the landscape, and may thus indicate the potential for local resistance against wind turbines.

4.4 Summary statistics

We present overall summary statistics in Table 2. In Appendix A we also report between and within summary statistics as well as summary statistics only including rural counties (for both see Table 6).[28]

5 Results

Our results ascribe a major role in steering wind power deployment to state-level and regional spatial planning policies. Table 3 presents the estimates of our main regression model.[29] Tables 8 and 9 show results for further specifications including interaction terms at the state and regional level. We first explain the estimated effects of state-level policies

[28] Table 7 in Appendix A presents the correlation matrix.

[29] Table 11 in Appendix C presents regression results when using wind power additions measured in MW respectively MW/km^2 as the dependent variable.

(Sect. 5.1), then describe the results on regional policies (Sect. 5.2), and finally present the estimated impacts of further variables (Sect. 5.3).

A first look at Table 3 reveals that across estimators, almost all coefficients are of similar sign. Our empirical results generally confirm the policy effects that were expected based on our theoretical model (see Table 1) and provide insights into the quantitative extent of policy effects and the varying time lags of policy impacts. Estimates from the Arellano-Bond (A-Bond) estimation (column 1 in Table 3) are regarded as our main findings. While the FE model (column 2) and the RE model (column 3) underestimate the coefficient of *log stock of installed capacity* approximately by order 1/T (see Sect. 3), estimates still range within comparable magnitude to the A-Bond estimates.[30]

5.1 State-level policies

At the state level, the three policies under investigation—expansion goals, forest bans, and setback rules—exhibit different effect sizes. In states that have introduced an ***expansion goal***, yearly capacity additions are, on average, 26.3% (A-Bond estimate) higher than in states where no expansion goal is in place.[31] We include the second lag in our main regression model as supported by the Arellano-Bond and the incremental Sargan-Hansen tests as well as the impact response analysis in Appendix D. Results from the impact response analysis suggest that the implementation of an expansion goal has an immediate impact that lasts up to five years (see Fig. 10a). The introduction of an expansion goal not only signals the government's intention to foster wind power expansion, it may also point to more detailed and concurrently adopted policies that directly enhance wind power deployment which we could not grasp in our analysis. Furthermore, expansion goals work indirectly via spatial planning regulation that subsequently adjust to these goals and translate them into more tangible measures. Though our binary variable *expansion goal* does not capture any differences in design, ambition nor stringency, the various effect mechanisms may explain the quantitatively meaningful and robust effect we find throughout all specifications.

Spatial planning instruments which entail the categorical banning of wind power deployment are expected to have an unambiguously negative effect. This is true for ***setback distances*** which exclude any potential turbine sites that are closer to residential areas than the specified distance. We find that yearly wind power additions decrease by 3.1% when increasing the setback distance by 100 *m*. The variable *setback distance* is lagged by five years which is indicated by our impact response analysis (see Fig. 10c). There may be two reasons for such a large time delay. Firstly, setback rules need to be considered at the very start of a wind power project, since they determine whether a potential turbine site is legally developable or not. Due to the long realization period of wind power projects the effect of implementing a setback rule will only be observable in deployment figures years later. Secondly, changes in setback distances are usually set out with some transitional arrangements. This means that those wind power projects which already applied for a building permit are exempted from newly introduced rules.

30 If we assume the true value is $\lambda = 0.35$, then the FE estimate $\hat{\lambda}^{FE}$ approximately deviates by $-\frac{1+\lambda}{T-1} = -\frac{1+0.35}{12-1} = -0.13$ as $N \to \infty$ (Nickell 1981).

31 We apply a log-linear model (see Sect. 3) such that a one-unit change in a regressor variable induces a $100 \times \beta\%$ change in the (not transformed) dependent variable.

Table 2 Summary statistics

Variable	Observations	Mean	Std. Dev	Min	Max
Added capacity (MW)	6817	6.1	18	0	593
Expansion goal (0/1)	6817	0.602	0.489	0	1
Forest ban (0/1)	6817	0.261	0.439	0	1
Setback distance (in km)	6817	0.731	0.349	0.5	2
Exclusive planning (0/1)	6817	0.195	0.396	0	1
Total designated area (km^2)	6817	3.3	9.1	0	73.8
Avg. size of ind. designated areas (km^2)	6817	0.254	0.541	0	5.93
Avg. shape of ind. designated areas (A/P^2)	6817	0.0258	0.0217	0	0.0774
Avg. capacity density (MW/km^2)	6817	2.88	7.2	0	173
Stock of installed capacity (MW)	6817	45.6	100	0	1605
Density of installed capacity (MW/km^2)	6817	5.52	14.4	0	309
Population density ($1000/km^2$)	6817	.522	.675	0.036	4.71
GDP per capita (T€)	6817	29.2	13.3	11.2	180
Total Remuneration (Mio. €/MW)	6817	1.26	0.383	0.425	2.89
Green Party votes (%)	6817	7.96	3.4	2.1	28.7
County area (km^2)	6817	891	721	35.5	5495
Technical potential land ($100\ km^2$)	6817	7.33	6.29	0.0938	45.2
Wind power potential (W/m^2)	6817	185	54.4	82.7	526
Aesthetic landscape quality (0–100)	6817	56.3	9.62	27.4	78

Our estimates for the effect of implementing a ***forest ban*** are statistically not significant. Though this is surprising since this policy measure can only reduce the area of potential turbine sites, there is a good reason why we do not find evidence for a negative effect in our sample: While our variable is binary and solely captures if a ban is in place or not, forest ban regulation implemented by German states differs in its extent (e.g. regarding the type of forest that is involved, see Bunzel et al. 2019). On average, our binary variable overrates the severity of forest bans because even if state regulation solely excludes distinct types of forests our binary variable is indicating a forest ban. Therefore, we expect the estimated effect of *forest ban* to be underestimated in our model.

As both policies, *setback distances* and *forest ban*, refer to specific areas of land we extend the main model by two interaction terms. The extended specification includes the interaction of *setback distance* with *population density* as well as the interaction of *forest ban* with *forest area* (see Table 8 for all estimates). In both cases, higher values of the interaction term reflect more land area being excluded from wind power deployment. Expectedly, their estimated coefficient should have a negative sign. This would imply that the negative effects of *setback distances* and *forest ban* become stronger for more densely populated and more forested counties. However, we cannot find significant marginal effects for either of the two policy variables in the extended specification. As mentioned before, this is likely due to the simplified coding of the variable *forest ban*. The lack of statistical significance of the marginal effect of *setback distance* conditional on *population density* may be due to the fact that the *population density* only roughly reflects the spatial settlement structure that determines the scope of the exclusive buffer zones around residential areas.

Table 3 Main policies

Log capacity additions (ln(MW))	Main policies		
	(1)	(2)	(3)
	A-Bond	FE	RE
L2.Expansion goal (0/1)	0.263**	0.123**	0.085
	(0.130)	(0.056)	(0.057)
L.Forest ban (0/1)	0.038	−0.042	−0.051
	(0.180)	(0.078)	(0.078)
L5.Setback distance (in km)	−0.308*	−0.187**	−0.194**
	(0.162)	(0.078)	(0.076)
L.Exclusive Planning (0/1)	−0.014	0.167	0.033
	(0.322)	(0.103)	(0.077)
L.Total designated area (km^2)	0.046*	0.021***	0.015***
	(0.026)	(0.007)	(0.004)
L.Avg. capacity density (MW/km^2)	−0.002	−0.017***	−0.014***
	(0.014)	(0.006)	(0.005)
L.Log Stock of installed capacity (ln(MW))	0.349*	0.116**	0.309***
	(0.188)	(0.053)	(0.023)
L2.Density of installed capacity (MW/km^2)	−0.019***	−0.011*	−0.005**
	(0.006)	(0.006)	(0.002)
L4.Total Remuneration (Mio. €/*MW*)	3.440***	3.080***	2.505***
	(0.920)	(0.579)	(0.457)
L.Green Party votes (%)	0.039	0.060*	0.006
	(0.110)	(0.033)	(0.009)
L5.Population density ($1000/km^2$)	0.838	0.861	0.019
	(0.765)	(0.534)	(0.053)
L.GDP per capita (T€)	−0.007	−0.007*	−0.002
	(0.007)	(0.004)	(0.001)
Technical potential land ($100\ km^2$)			0.033***
			(0.005)
Wind power potential (W/m^2)			−0.026***
			(0.004)
Wind power potential (W/m^2) × Wind power potential (W/m^2)			0.000***
			(0.000)
Aesthetic landscape quality (0–100)			−0.007*
			(0.003)
Year dummies	Yes	Yes	Yes
Observations	4812	4812	4812
Counties	401	401	401
R-squared		0.096	0.506
AR(1)	0.000		
AR(2)	0.386		
Hansen's J-statistic	0.546		
MMSC-AIC	−13.194		

Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

For RE and FE regressions we applied clustered standard errors at the county level. Compare Table 10 for the subsample of rural counties

5.2 Regional policies

At the regional level, policies predominantly intend to control wind power expansion through the planning of designated areas. In the following, we report results for those policy variables that were included to represent regional wind power specific spatial planning.

First, the estimated effect of the ***total designated area*** emphasizes the importance of zoning specific areas designated to wind power deployment. We find that an extra 1 km^2 of designated area per county raises yearly wind power additions by 4.6%.[32] Since the response to new designated areas seems to be delayed by around one year (see Fig. 10d), we include the first lag of all variables concerned with regional planning policies. The quick impact of new designated areas is well explained by the regional planning process that precedes and prepares the zoning. Due to the transparent and participatory process of setting up spatial plans, wind developers can anticipate which areas are likely designated for wind power deployment and initialize wind power projects in advance.

Second, the type of planning—***exclusive planning*** versus non-exclusive planning—does not have a significant effect on wind power expansion. Remember that our variable refers to the planning type at the regional level. If a regional planning authority pursues non-exclusive planning, then lower-level local planning authorities can still resort to exclusive planning. Our data does not cover this information. Equally, under non-exclusive planning at the regional level, we cannot observe whether and how much area is designated to wind power deployment by local planning authorities. This may largely explain why we find different marginal effect sizes when interacting *total designated area* with *exclusive planning* (see Table 9, column 1). We find a strongly positive marginal effect of zoning designated areas under exclusive planning (10.1%, see Table 13) and an insignificant estimate of total designated area under non-exclusive planning.[33] Also, we see that the effect of *exclusive planning* itself is increasing in *total designated area*, telling us that in counties with a large supply of designated areas this planning type is advantageous (see Fig. 13).

Third, the impact of the ***average capacity density*** within designated areas is not statistically significant. While the FE and RE regressions find a significant negative effect, the Arellano-Bond estimate for our main model specification (see Table 3) is not significant. This is likely because existing wind power installations have two countervailing effects. On the one hand, existing wind turbines occupy turbine sites supplied through designated areas, thus reducing available space for further installations. On the other hand, existing wind turbines establish infrastructure which can be used for the construction and operation of further capacities, thus lowering the costs of adding more wind turbines. In the end, the first effect should prevail since, at some point, all potential turbine sites within the

[32] We find a similar magnitude of the effect of zoning an additional 1 km^2 of designated area per county when using the change of absolute capacities (MW) and applying the conditional FE-Poisson estimator. The estimated coefficient indicates a rise of 2.8% (see Table 11). Likewise, when using the change of capacity density (MW/km^2) as the dependent variable, the estimated effect of an increase in the share of designated area by 1 percentage point is an increase in yearly capacity additions per km^2 by 28.1% (see Table 11). By the regression results of our main specification we need to add 6.1 km^2 to achieve a 28.1% rise in yearly capacity additions. Given the average county area of 890.8 km^2 adding 6.1 km^2 of designated area corresponds to 0.7 percentage points.

[33] As depicted by Fig. 10f, the impact response to the implementation of exclusive planning is rather delayed by more than one year. Since we interact *exclusive planning* with *total designated area* and *avg. capacity density* we include the first lag of exclusive planning also in our main model specification. Lagging *exclusive planning* by more years does not change its estimated coefficient neither the other estimates.

designated area are exploited. In fact, this is reflected by our results when including the interaction term of *total designated areas* and *avg. capacity density*. At a value of 0 MW/km^2 for *avg. capacity density* the marginal effect of *total designated areas* under exclusive planning is estimated to induce an increase of yearly wind power additions by 6.6%. While this estimate is significant, effect size and statistical significance diminish with the average capacity density rising. At a value of 30 MW/km^2 the marginal effect is equal to zero and statistically insignificant. We interpret this result as one square kilometer of designated area being exploited after 30 MW of wind power capacities have been installed. This threshold is also mirrored by descriptive statistics on the average capacity density of designated areas discussed in Sect. 6.2.

We further include two attribute variables in our extended regression model in order to additionally characterize the zoning of individual designated areas. While the type of planning and the amount of total designated areas are generally predefined by political decision makers (e.g. state governments or regional assemblies), the zoning of individual areas is an original planning task that is carried out by regional planning authorities. Principally, it is at their discretion to decide on the exact size and shape of each individual designated area.[34] Our regression results suggest that these zoning details play an important role. We find empirical evidence for both size and shape of individual designated areas to affect wind power expansion.

When interacting ***avg. size of individual designated areas*** with *total designated area* we find a significant negative average marginal effect (AME) of the average area size (see Table 4, column 1). The total amount of designated area being equal, demarcating many small areas is associated with more wind power additions than demarcating few large areas. In numbers, enlarging the average size of individual areas from 0.5 to 0.6 km^2 reduces yearly capacity additions by 5.2%. Likewise the AME of the ***avg. shape of individual designated areas*** is negative indicating that designating more compact areas is associated with fewer wind power additions than designating less compact areas (column 2). For example, re-designing the average shape from a square area (compact) to an elongated rectangle area (non-compact) is reflected by a change in the shape value from 0.0625 to 0.04 (see Fig. 17). Such an exemplary change from more compact to less compact areas is associated with an increase in capacity additions by 93.4%.[35]

When including all interactions among the three variables that capture the total amount, the average size and the average shape of designated areas, the AME of the *avg. size of individual designated areas* loses statistical significance while the estimate of *avg. shape*

[34] In Germany, regional planning authorities follow a planning procedure by which, first, those areas have to be excluded from the pool of possible designated areas which meet so called "strict taboo criteria" (e.g. settlement areas) and, second, further areas can be excluded which meet "soft taboo criteria". Depending on regional socio-geographic conditions, this leaves differing leeway for regional planning authorities. Also, there can be vague requirements for the zoning of designated areas that need to be considered by regional planning authorities. These intend to ensure that planning authorities select sites where the deployment of wind turbines is technically and economically realizable. However, the very reason and need for spatial planning in the first place, namely coordinating and trading-off multiple public and private interests that demand for land use, must leave—at least to some extent—discretionary leeway to the regional planning authority.

[35] As explained by means of the theoretical example in Appendix F, ceteris paribus, changing square-shaped areas to form narrow rectangles changes the value of the variable *average shape of individual designated areas* by $\frac{1}{25} - \frac{1}{16} = -\frac{9}{400}$. Hence, the effect on yearly capacity additions is equal to 93.4 % = −41.5% $\times -\frac{9}{400}$

of individual designated areas remains almost unchanged (column 3 in Table 4). This is likely due to some collinearity of the size and shape variable that are by construction correlated because the *avg. shape of individual designated areas* is composed as the ratio of the size to the perimeter squared (see Sect. 4.2.2).

In order to further scrutinize the effect of each zoning detail—size and shape—we run a complementary regression at the level of individual designated areas. We regress *capacity density per individual designated area* in log-transformed (ln(MW/km^2)) as well as in level terms (MW/km^2) on the size and shape of each area. Thereby, we estimate to what extent the *size* and *shape* affect how much a designated area is exploited in terms of wind power installments per square kilometer.[36] For this area–level regression, we again find empirical evidence that points to an impact of both zoning details (see Table 5). Still, while the shape variable is significant in the log-transformed OLS regression (column 1), it is not significant in the level-terms Poisson regression (column 2), and the size variable vice versa.

Together, our regression results at the county level and at the level of individual designated areas indicate a negative impact of increasing the size of designated areas, although the result is not robust to all model specifications. This may be reasoned by two countervailing effects. On the one hand, larger individual areas are expected to offer economies of scale because wind developers can realize larger wind farms and thereby achieve lower deployment costs per capacity installed. Fixed costs due to planning activities, grid connection, preparation of access routes, etc. can be shared across a number of wind turbines. On the other hand, reaching the same capacity density within a large area as compared to a small area may imply that wind developers face higher transaction costs and performance risks, e.g., in negotiating with multiple land owners, coordinating with other developers that hold construction permits for parts of the area, or positioning new turbines around existing turbines. Moreover, wake effects in larger wind farms may require wider spacing between wind turbines. Otherwise, upwind wind turbines would decrease downwind wind speeds and thus lower power generation of downwind wind turbines (Lundquist et al. 2019).

The negative effect of zoning a rather compact instead of a non-compact area is in line with our theoretical explanation on the amount of available turbine sites within areas of different shapes. As depicted by our theoretical and our real-world examples in Appendix F, a non-compact area likely provides more available turbine sites than a compact area. Yet, negative effects, e.g., wake effects, presumably occur to a lesser extent within non-compact areas (because less turbines are placed downwind of others) such that the positive effect of more turbine sites prevails.[37]

5.3 Further variables

Among the control variables, we particularly emphasize the impact of financial incentives by the federal RES support scheme (REA). Discounted *total remuneration* has a significantly positive effect. An increase of 10,000 € in discounted total remuneration per MW is associated with a 3.4% rise in yearly wind power additions (see A-Bond estimate in Table 3). Equally, we highlight the impact of past wind power installations. The

[36] We control for the profitability of the site by including *total remuneration* and only consider the capacity density five years after a designated areas came into effect. Five years after the zoning of areas available sites are usually used up. See also Fig. 9.

[37] We do not track whether regional plans allow that the rotor blades of wind turbines may cross the boundaries of designated areas or not. If this is forbidden by the regional planning authority, the effect should be less negative respectively larger.

Table 4 Average marginal effects (AME) of zoning details

Log capacity additions (ln(MW))	Regional Policies + Zoning Details		
	(1)	(2)	(3)
	A	B	C
L.Avg. size of ind. designated areas (km^2)	−0.518*		−0.094
	(0.285)		(0.561)
L.Avg. shape of ind. designated areas (A/P^2)		−41.506*	−48.765*
		(24.126)	(25.056)
Observations	4812	4812	4812
Counties	401	401	401
AR(1)	0.000	0.000	0.000
AR(2)	0.336	0.267	0.251
Hansen's J-statistic	0.191	0.317	0.464
MMSC-AIC	−7.186	−9.350	−15.170

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

Average marginal effects are evaluated at the means of all regressor variables. The columns A, B, and C correspond to the estimations presented in Table 9

Table 5 Complementary regression: zoning details

	OLS	Poisson
	(1)	(2)
	ln(MW/km^2)	MW/km^2
Shape of ind. designated area (A/P^2)	−8.043***	−3.762
	(2.939)	(6.327)
Size of ind. designated area (km^2)	0.001	−0.200***
	(0.024)	(0.059)
Total Remuneration (Mio. €/MW)	−0.059	−0.150
	(0.240)	(0.210)
State fixed effects	Yes	Yes
Time fixed effects	Yes	Yes
Observations	2181	2181
Regional planning associations (RPAs)	78	78
R-squared	0.219	
Log-likelihood		−17594.5

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

Estimates are based on OLS and Poisson regressions with standard errors clustered at the regional level. The observational unit is the individual designated area per year. The samples include all individual designated areas 5 years after coming into effect

positive estimate of the *log stock of installed capacity* reflects a strong state dependence of wind power expansion. A 10% increase in the stock of capacities is associated with a 3.5% increase in yearly wind power additions. As expected, past wind power additions improve conditions for future expansion, e.g. in terms of existing grid infrastructure, institutional performance of planning and permitting processes, or probably also people's attitude towards wind energy.

At the same time, however, past wind power expansion implies that some turbine sites from the pool of potential turbine sites, i.e., the *technical potential land* approximated by the amount of agricultural and forest land, are already exploited. In line with that, the estimate of the *density of installed capacity* says that one more MW installed per technical potential land reduces annual wind power additions by 1.9%. In other words, jumping from 0 to 52.6 MW/km^2 would stop any further wind power expansion because all potential sites were used up (as $-1.9\% \times 52.6 = -100\%$).

Finally, we can derive some insights on the impact of time-invariant factors from the estimation of the RE model (see Table 3, column 3). Corresponding to the negative effect of the *density of installed capacity*, the RE estimate of *technical potential land* exhibits a positive effect. Counties that have 100 km^2 more of agricultural and forest land also have on average 3.3% more yearly capacity additions. Furthermore, according to the RE model there is a negative impact of *wind power potential* meaning that counties with bad wind conditions do better than counties with favorable wind conditions. We think that this estimate captures some part of the effect of *total remuneration* which is lower in the RE model than in the Arellano-Bond estimation. Thus, the marginal effect of wind power potential shown in Fig. 15 likely mirrors the fact that the federal subsidy scheme compensates for bad wind conditions.

6 Implications and discussion

The empirical analysis draws a clear picture of the main drivers of wind power deployment in Germany. It shows how strongly federal, state-level, and regional planning policies are influencing wind power expansion. In this section, we discuss the main implications from our regression results.

6.1 Key spatial planning policies

We find a crucial impact of land availability in principle, but we especially point out to the influence of spatial planning policies. Of course, technically available area for wind power deployment is a principle precondition. This is confirmed by the negative coefficient of the overall *density of installed capacity* on technically suitable land.[38] It tells us that the more wind turbines are already installed, the less turbine sites are available for additional wind power plants.[39] In this regard, such a saturation effect is in line with the finding of the existing literature that land availability substantially affects wind power expansion (Hitaj 2013; Hitaj and Löschel 2019; Lauf et al. 2020).

On top of that, our study adds the main finding that spatial planning policies have been highly effective in steering de-facto land availability in Germany. Our results highlight three effective means in order to increase or decrease wind power deployment: setting an expansion goal, adjusting setback distances, and zoning designated areas for wind power

[38] Equally, the positive estimate of *technical potential land* from the RE model reflects this.

[39] The negative effect of the overall density of existing wind turbines further suggests that also turbine sites outside from designated areas are used up. It should be noted that we have no data on designated areas that are specified at the local level. Therefore, wind turbines which are constructed outside of regionally planned designated areas may lie within locally planned designated areas.

deployment. First, our results support the view that by implementing state-level *expansion goals* the mix of wind power related policies at the state and regional level is accordingly aligned. Presumably, state-level expansion goals take effect via indirect channels and by influencing the whole policy mix. Within the complex system of spatial planning, expansion goals require a certain degree of coordination of all policies such that planning and permit decisions are compatible with the overarching expansion target. In Germany, the new federal law passed in 2022 takes this line and prescribes that all states need to reserve two percent of their land area for wind power. While this two-percent-target is designed as a mandatory requirement, our analysis does not differentiate which level of commitment, ambition or stringency is established by an expansion goal. In examining these differences future research can provide further valuable insights.

Second, our estimated impact of setback rules confirms the finding by Stede et al. (2020). It is still remarkable that we find a negative effect of increasing setback distances in our study because our data set does not entirely contain the effects of the largest increase in setback distances that ocurred in Germany. This increase was implemented by the Bavarian state government in 2014, but mainly took effect years later (e.g. due to transitional arrangements). Thus, already smaller increases in setback distances have also led to less wind power expansion in other German states (cf. Figure 17). This once again emphasizes the inhibiting respectively unleashing effect of changes in setback distances.

Third and most notably, our empirical results stress the crucial role of designating specific areas for wind power deployment. Zoning *designated areas* proves to be an effective way to provide available turbine sites. By using this planning instrument, regulators are able to spatially allocate the deployment of wind power. Regulators may even foster or hamper wind power deployment through their way of zoning designated areas (see next section). We are the first to use georeferenced data on the zoning of designated areas. Thus, we provide much more detailed and more robust inference on the importance of zoning decisions than previous studies that are based on aggregated spatial data (Lauf et al. 2020).

Furthermore, we argue that the positive effect of designated areas not only expresses increased land availability, but also reflects that planning authorities screen all potential turbine sites and select those that are (most) suitable for wind power deployment. During the process of setting up regional plans, regional planning authorities analyze their territory thoroughly with regard to many issues that matter for the permission of wind turbines. That is, regional planning authorities account for gross of the environmental externalities of the envisaged wind power projects, and consider concerns regarding immission protection, species protection, landscape conservation, and other public interests. Thus, substantial obstacles for wind power projects are identified in advance and are effectively avoided when zoning designated areas. In this respect, spatial planning not only manages land availability, but also filters turbine sites with less project risks. In addition, planning authorities at least partially consider wind conditions of designated areas in order to avoid the accusation of preventing wind power deployment in principle.[40]

[40] The weak positive correlation of *total designated areas* and *wind power potential* may reflect this (see Table 7).

6.2 Details matter: fine–tuning in spatial planning

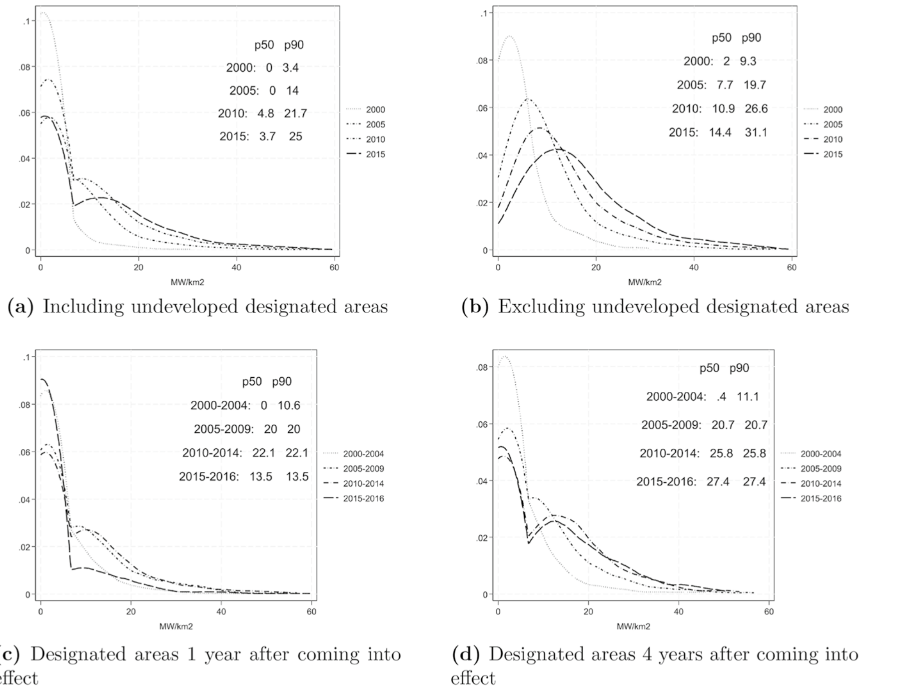
Spatial planning always requires some discretionary leeway for planning authorities, otherwise there is no need to mandate regional and local authorities to balance public and private land-use demands. Our empirical results reveal that details of the decisions taken by the regional planning authorities can strongly influence the success and amount of wind power projects on site. More precisely, through fine-tuning the layout of designated areas—i.e., their size and shape—planning authorities may to some degree pursue their own agenda. This is true, even if prescriptions by higher administrative levels (e.g., state government) demand for a fixed targeted amount of total designated areas (e.g., an expansion goal in the form of an area target). Our regression results point out that the very details of individual designated areas, in particular their size and shape, determine the effect of designating areas for wind power deployment. Some studies which examine the technical as well as legal potential for wind power deployment already consider this when simulating an optimal exploitation of available construction areas (Bons et al. 2019; Masurowski et al. 2016). However, our study is the first that provides empirical evidence for this effect and quantifies its magnitude.[41]

Since planning authorities decide on this fine-tuning of designated areas, policymakers could consider more specific guidelines for planning authorities (e.g. targeting a rather scattered allocation of individual designated areas or areas that stretch orthogonal to the main wind direction, etc.). At the same time, the more detailed prescriptions are set by federal or state governments, the more they reduce the regional and local planning authorities' scope to optimally weigh and balance all public interests—which exactly is their original task. Except from rather inflexible prescriptions, governments could also resort to soft instruments that require some kind of score for the aggregate of designated areas or stick a signaling price tag on them. Likewise, financial benefits, which are provided to those counties or municipalities where wind power plants are constructed, can set positive incentives to design designated areas in a wind power-promotive way. Purportedly, financial benefits are more likely to be taken into account by regional and local planning authorities than soft instruments. For example, in Germany in 2021 the federal government implemented such payments that benefit those municipalities which have wind turbines installed on their territory.

Matters of fine-tuning are clearly under-represented in the public discussion. For example, in Germany a long-running debate revolves around the sufficient amount of total designated areas that is needed to reach national wind power deployment targets (Meier et al. 2019). While the debate and the law that resulted from it solely focus on the mere targeted amount of total designated areas, it neglects the importance of the layout of individual designated areas. Our study is the first to empirically show that the layout of areas affects how much wind power capacity is installed within these areas. Since actual wind power deployment varies with the size and shape of designated areas, a target on total area alone (as implemented in Germany in 2022) may not lead to the amount of wind power installations envisaged by the government.

Matters of zoning details are also under-represented in the scientific literature. The impact of the size and shape is fundamental when predicting the amount of total designated areas needed to reach a wind power deployment target. Few simulation studies incorporate this relationship by means of siting algorithms (Ryberg et al. 2019; McKenna et al. 2015; Bons

[41] Optimization studies usually apply a siting algorithm that ensures the optimal exploitation of available land in terms of maximally installable wind power capacities.



(a) Including undeveloped designated areas

(b) Excluding undeveloped designated areas

(c) Designated areas 1 year after coming into effect

(d) Designated areas 4 years after coming into effect

Notes: *Figures show the probability density of the capacity density of individual designated areas. The probability density functions per year are estimated by kernel with bandwidth 3.*

Fig. 9 Development of Capacity Density over Time

et al. 2019). However, by using siting algorithms and optimizing wind power capacity per land area, these studies do not consider a possibly inefficient siting of wind turbines, e.g., due to sequential additions over time. Moreover, they do not take into account other real-world obstacles that often reduce actual capacity density, e.g. the necessary consent of landowners.[42] Indeed, our empirical values of capacity densities lie below values that are used by simulation studies[43] and at the same time confirm earlier statistics that also estimated actual capacity densities (Enevoldsen and Jacobson 2021; Miller and Keith 2018). Yet, we are the first to provide numbers on the actual utilization rate of areas made available for wind power deployment, i.e., designated areas.[44] Fig. 9 summarizes these numbers. Although capacity density has increased over time, both in its median value (p50) as well as its 90th percentile

[42] Winikoff (2021) highlights the role of landowners in influencing the deployment of wind power. They show that in areas with fragmented landownership less wind turbines are installed than in areas with concentrated landownership.

[43] For their analysis Bons et al. 2019, p.66 f.) assume an average value of capacity density of 25.64 MW/km^2 for Germany.

[44] Enevoldsen and Jacobson (2021) study existing wind farms and draw geometric areas around wind turbine clusters to derive estimates of capacity density with mean values of 19.8 MW/km^2 for operational wind farms in Europe, and 20.5 MW/km^2 outside of Europe. For European onshore wind farms they find a median value of 13.9 MW/km^2.

value (p90), there is still a wide variation of wind power capacities installed per km^2.[45] We think it is essential for policymakers to consider these variations in capacity density when translating expansion goals in terms of wind power capacities into expansion goals in terms of designated areas.

6.3 Exclusive versus non-exclusive planning at the regional level

There are good reasons to argue for both positive as well as negative effects from exclusive instead of non-exclusive planning. Exclusive planning may exert a negative effect since all non-designated areas are excluded from wind power deployment. Wind developers cannot receive building permits outside of designated areas, and local planning authorities cannot add to or change the zoning of designated areas. In contrast, under non-exclusive planning regional planning authorities do not exclude any area from wind power deployment, but they leave further planning decisions open to the local level. This allows local planning authorities to expand but also to reduce the zoning of designated areas. Moreover, local planning authorities may still implement exclusive planning within their municipalities in order to yet exclude all non-designated areas.[46] Thus, the effect of (non-)exclusive planning is ambiguous ex ante.

In fact, our empirical results do not find a significant average marginal effect of exclusive planning itself. The abovementioned pros and cons offer a valid justification for this. However, the marginal effect of exclusive planning is turning positive and statistically significant when the amount of total designated areas is increasing (see Fig. 13a). This could be explained by the 'planning performance' by regional compared to local planning authorities. Regional planning authorities likely have more resources and specialized capacities than the much smaller local planning authorities to meet complex and challenging zoning tasks. Therefore, one can argue that under exclusive planning the zoning of designated areas is of higher quality, in the sense that legal planning requirements are technically better addressed (e.g. issues relating to species protection), and designated areas achieve more legal certainty. This 'planning performance', in turn, mostly depends on financial resources provided as well as the ambition and statutory planning provisions prescribed by the state level. At the same time, a more ambitious state policy will lead to more designated areas. Hence, the positive marginal effect of exclusive planning rising with the amount of total designated area could well reflect a superior planning performance that is facilitated by wind power supportive state policies.

6.4 What is the limiting factor: Profitability or land availability?

Our analysis offers an approximate estimate of the cost of (under)providing land availability. As the main regression results show, increasing *total remuneration* by 13,500 € per MW is on average equivalent to increasing *total designated areas* by 1 km^2 per county. At the aggregate level (inter-county level), this ratio can be considered as the rate of

[45] The variation of capacity density is also illustrated by the development of the average capacity density across German states, see Fig. 19 in Appendix G.

[46] The lack of county-level data leaves more work for further research. For example, an interesting question is whether exclusive or non-exclusive planning at the regional level leads to more total designated areas. Since under exclusive planning all relevant matters are weighed at the regional level and conflictual issues are resolved by the regional planning authority, allegedly there might be less blocking opportunities for local planning authorities that intend to avert wind power deployment on their territory.

substitution between two input factors of the wind power deployment function. Both, raising nationwide applicable remuneration by 13,500 € per MW or expanding designated area in each county by 1 km^2 increases yearly wind power additions by 4.6%.

In contrast, from an intra-county perspective profitability and land availability cannot be regarded as substitutes. Referring to our theoretical model in Sect. 2.2, note that either profitability or land availability constrains county-specific wind power additions. That is, in each county wind power additions are either equal to the *profit-maximizing amount of wind power additions* or equal to the *maximum amount of possible wind power additions* (cf. eq. 5). Accordingly, raising total remuneration (respectively profitability) only increases wind power additions in those counties where profitability is the limiting factor. Likewise, enlarging designated areas (respectively land availability) only augments wind power additions in those counties where land availability is the limiting factor. Against this background, we can interpret the abovementioned effect size as a shadow price. For the average county, we find that the shadow price of relaxing the land availability constraint by enlarging the designated area by 1 km^2 is equal to the financing costs of raising total remuneration by 13,500 €/MW.

However, when looking at the RE model, the effect of relaxing one limiting factor—profitability or land availability—varies across counties and regions. For example, the limiting factor differs between an average Northern and an average Southern German county. An increase in the total designated area has a stronger positive effect in Southern Germany than in Northern Germany (see Fig. 16a in Appendix E.5). This tells us that in Southern Germany compared to Northern Germany land availability is more often the limiting factor. In contrast, the influence of profitability did not significantly differ between Northern and Southern German counties. An increase in total remuneration is on average associated with a similar rise in wind power additions in Northern and Southern Germany (see Fig. 16b). This suggests that in Northern counties, where land availability was less often binding, the effect of an increase in total remuneration was smaller, while in the few Southern counties, where land availability was not binding, the effect of an increase of total remuneration was higher. Only in this case, the average effects of an increase in total remuneration in Northern and in Southern Germany turn out to be equal.

Interestingly, in our area-level regression in Sect. 5.2 we find no significant effect of total remuneration on the exploitation of designated areas (see Table 5). This suggests that once land was made available for wind power deployment, i.e. through the zoning of designated areas, profitability is not a limiting factor for the exploitation of turbine sites. One reason may be that planning authorities primarily zone designated areas in windy areas. Another reason is that the German subsidy scheme compensates for less windy conditions such that the development of designated turbine sites seems to be sufficiently profitable at most available sites. Again, this reinforces that spatial planning policies are just as important and effective as market-based regulation.

7 Conclusion

The vast expansion of renewable energies requires a lot of space. Concerned about the financial support for RES technologies, the economic literature and public debate primarily circle around incentive-based policies like carbon pricing or subsidy schemes. In contrast, planning and permission policies are often neglected, though they are frequently used to regulate the deployment of large-scale RES plants, like wind turbines or open-space solar power plants.

We provide the first comprehensive quantitative analysis on how effectively spatial planning policies can steer wind power deployment. To do so, we compile a unique dataset on spatial planning policies in Germany covering all years from 2000 to 2016. We apply a dynamic panel model to account for unobserved heterogeneity and true state dependence. Drawing on georeferenced data of wind turbines and spatial planning policies, we are able to assess the impact of various policies that intend to steer wind power expansion.

Our results highlight the strong positive impact of zoning specific land areas for wind power deployment. By zoning designated areas, planning authorities can effectively control the spatial allocation of wind power plants, and they can promote additional wind power expansion while at the same time properly managing environmental externalities from wind turbines. We find that an additional square kilometer of designated area leads to an increase of about 4.6% of yearly capacity additions per county. However, our results show that not only the total amount of designated area matters, but also the size and shape of each individual designated area. Elongated areas are associated with more wind power expansion than compact areas. Since the zoning of designated areas is a competence held by regional and local planning authorities, their planning decisions can have an important impact on the exploitation of designated areas, in terms of wind power capacity installed on 1 km^2 of designated area (i.e., capacity density, MW/km^2). When governments set planning guidelines and prescribe area targets in order to achieve wind power deployment goals they need to take into account the varying rate of exploitation of designated areas.

Our empirical analyses further points to a negative impact of setback rules. The effect of increasing the setback distance between turbine sites and settlements by 100 m is estimated to reduce yearly capacity additions by about 3.1%. We also find that expansion goals exert a supportive effect on wind power expansion, presumably, by coordinating and aligning subnational planning policies and permit procedures. Following on from this, a worthwhile quest for future research is to examine the drivers of lower-level planning decisions themselves. How do top-down guidelines (e.g., expansion goals) versus bottom-up decisions (e.g., by local and regional councils) manifest in the zoning of designated areas? Does state-level, regional or local responsibility lead to more or less zoning of designated areas? Or, in general, which factors drive the zoning of designated areas by policymakers and planning authorities? Based on an extensive collection of local land-use plans further research may answer these questions.

Appendices

Appendix A: Summary statistics

See Tables 6, 7

Table 6 Panel data summary statistics

Variable	Counties	Overall				Between			Within			N	n	T
		Mean	Std. Dev	Min	Max	Std. Dev	Min	Max	Std. Dev	Min	Max			
Added capacity (MW)	All	6.1	18	0	593	11.4	0	105	14	−90.7	494	6,817	401	17
	Rural	8.13	20.6	0	593	12.7	0	105	16.3	−88.6	496	4,998	294	17
Expansion goal (0/1)	All	.602	.489	0	1	.275	0	1	.405	−.339	1.48	6,817	401	17
	Rural	.6	.49	0	1	.269	.118	1	.41	−.341	1.48	4,998	294	17
Forest ban (0/1)	All	.261	.439	0	1	.361	0	1	.252	−.327	1.03	6,817	401	17
	Rural	.268	.443	0	1	.372	0	1	.242	−.321	1.03	4,998	294	17
Setback distance (in km)	All	.731	.349	.5	2	.122	.5	.882	.327	.348	2	6,817	401	17
	Rural	.728	.342	.5	2	.123	.5	.882	.32	.345	2	4,998	294	17
Exclusive Planning (0/1)	All	.195	.396	0	1	.332	0	1	.216	−.747	1.14	6,817	401	17
	Rural	.238	.426	0	1	.351	0	1	.241	−.703	1.18	4,998	294	17
Total designated area (km^2)	All	3.3	9.1	0	73.8	7.92	0	54.5	4.51	−51.2	56.6	6,817	401	17
	Rural	4.43	10.4	0	73.8	8.98	0	54.5	5.26	−50.1	57.8	4,998	294	17
Avg. size of ind. designated areas (km^2)	All	.254	.541	0	5.93	.422	0	2.43	.34	−2.18	4.06	6,817	401	17
	Rural	.318	.592	0	5.93	.46	0	2.43	.375	−2.11	3.82	4,998	294	17
Avg. shape of ind. designated areas (A/P^2)	All	.0258	.0217	0	.0774	.0213	0	.0743	.00405	−.0165	.0569	6,817	401	17
	Rural	.0313	.0197	0	.0743	.0192	0	.0743	.00466	−.011	.0624	4,998	294	17
Avg. capacity density (MW/km^2)	All	2.88	7.2	0	173	4.77	0	42	5.4	−39.1	159	6,817	401	17
	Rural	3.4	6.97	0	173	4.5	0	37.4	5.33	−34	160	4,998	294	17
Stock of installed capacity (MW)	All	45.6	100	0	1,605	81	0	467	59.5	−404	1,207	6,817	401	17
	Rural	60.5	113	0	1,605	89.8	0	467	69.3	−390	1,222	4,998	294	17
Density of installed capacity (MW/km^2)	All	5.52	14.4	0	309	11.6	0	150	8.53	−133	198	6,817	401	17
	Rural	5.24	8.54	0	127	6.48	0	35	5.58	−28.1	97	4,998	294	17
Population density (1000/km^2)	All	.522	.675	.036	4.71	.675	.0396	4.27	.0252	.147	.965	6,817	401	17
	Rural	.207	.177	.036	1.25	.177	.0396	1.22	.00621	.161	.25	4,998	294	17

Table 6 (continued)

Variable	Counties	Overall				Between			Within			N	n	T
		Mean	Std. Dev	Min	Max	Std. Dev	Min	Max	Std. Dev	Min	Max			
GDP per capita (T€)	All	29.2	13.3	11.2	180	12.6	13.1	104	4.48	−3.46	105	6,817	401	17
	Rural	24.8	7.92	11.2	105	7.03	13.1	91.2	3.66	5.72	42.7	4,998	294	17
Total Remuneration (Mio. €/MW)	All	1.26	.383	.425	2.89	.296	.583	2.49	.243	.813	1.7	6,817	401	17
	Rural	1.31	.38	.602	2.89	.288	.831	2.49	.249	.86	1.75	4,998	294	17
Green Party votes (%)	All	7.96	3.4	2.1	28.7	3.26	2.68	25.2	.978	4.37	13.5	6,817	401	17
	Rural	7.21	2.81	2.1	20.8	2.66	2.68	18.5	.93	3.62	12.8	4,998	294	17
County area (km^2)	All	891	721	35.5	5,495	722	35.5	5,495	0	891	891	6,817	401	17
	Rural	1,161	656	222	5,495	657	222	5,495	0	1,161	1,161	4,998	294	17
Technical potential land (100 km^2)	All	7.33	6.29	.0938	45.2	6.3	.0938	45.2	0	7.33	7.33	6,817	401	17
	Rural	9.73	5.67	1.46	45.2	5.68	1.46	45.2	0	9.73	9.73	4,998	294	17
Wind power potential (W/m^2)	All	185	54.4	82.7	526	54.5	82.7	526	0	185	185	6,817	401	17
	Rural	194	54.7	115	526	54.8	115	526	0	194	194	4,998	294	17
Aesthetic landscape quality (0–100)	All	56.3	9.62	27.4	78	9.63	27.4	78	0	56.3	56.3	6,817	401	17
	Rural	58.6	8.05	38.2	78	8.07	38.2	78	0	58.6	58.6	4,998	294	17

Table 7 Correlation matrix

	Added capacity (MW)	Expansion goal (0/1)	Forest ban (0/1)	Setback distance (in km)	Exclusive Planning (0/1)	Total designated area (km^2)	Avg. size of ind. designated areas (km^2)	Avg. shape of ind. designated areas (A/P^2)	Avg. capacity density (MW/km^2)	Stock of installed capacity (MW)	Density of installed capacity (MW/km^2)	Population density ($1000/km^2$)	GDP per capita (T€)	Total Remuneration (Mio. €/MW)	Green Party votes (%)	County area (km^2)	Technical potential land ($100 km^2$)	Wind power potential (W/m^2)	Aesthetic landscape quality (0–100)
Added capacity (MW)	1.000																		
Expansion goal (0/1)	0.097***	1.000																	
Forest ban (0/1)	0.149***	0.451***	1.000																
	(0.000)	(0.000)																	
Setback distance (in km)	0.014	0.467***	0.302***	1.000															
	(0.245)	(0.000)	(0.000)																
Exclusive Planning (0/1)	0.265***	0.138***	0.323***	0.026*	1.000														
	(0.000)	(0.000)	(0.000)	(0.032)															
Total designated area (km^2)	0.439***	0.079***	0.131***	0.059***	0.531***	1.000													
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)														
Avg. size of ind. designated areas (km^2)	0.306***	0.046***	0.109***	0.049***	0.568***	0.753***	1.000												
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)													
Avg. shape of ind. designated areas (A/P^2)	0.163***	−0.052***	0.106***	−0.046***	0.338***	0.297***	0.361***	1.000											
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)												

Table 7 (continued)

	Added capacity (MW)	Expansion goal (0/1)	Forest ban (0/1)	Setback distance (in km)	Exclusive Planning (0/1)	Total designated area (km^2)	Avg. size of ind. designated areas (km^2)	Avg. shape of ind. designated areas (A/P^2)	Avg. capacity density (MW/km^2)	Stock of installed capacity (MW)	Density of installed capacity (MW/km^2)	Population density (1000/km^2)	GDP per capita (T€)	Total Remuneration (Mio. €/MW)	Green Party votes (%)	County area (km^2)	Technical potential land (100 km^2)	Wind power potential (W/m^2)	Aesthetic landscape quality (0–100)
Avg. capacity density (MW/km^2)	0.117***	0.187***	0.223***	0.074***	0.400***	0.169***	0.210***	0.257***	1.000										
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)											
Stock of installed capacity (MW)	0.583***	0.206***	0.283***	0.103***	0.415***	0.576***	0.415***	0.220***	0.302***	1.000									
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)										
Density of installed capacity (MW/km^2)	0.264***	0.171***	0.231***	0.093***	0.168***	0.199***	0.160***	0.099***	0.168***	0.479***	1.000								
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)									
Population density (1000/km^2)	−0.184***	0.029*	−0.054***	0.005	−0.206***	−0.204***	−0.230***	−0.441***	−0.142***	−0.245***	−0.057***	1.000							
	(0.000)	(0.015)	(0.000)	(0.705)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)								
GDP per capita (T€)	-0.134***	0.129***	-0.112***	0.108***	-0.145***	-0.173***	−0.218***	−0.327***	−0.094***	−0.152***	−0.002	0.520***	1.000						
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.891)	(0.000)							
Total Remuneration (Mio. €/MW)	0.263***	0.514***	0.398***	0.310***	0.234***	0.218***	0.103***	0.112***	0.256***	0.408***	0.391***	−0.220***	−0.077***	1.000					
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)						
Green Party votes (%)	-0.166***	0.098***	-0.050***	0.007	-0.192***	-0.195***	-0.229***	-0.256***	-0.058***	-0.231***	-0.076***	0.477***	0.492***	-0.102***	1.000				
	(0.000)	(0.000)	(0.000)	(0.549)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)					
County area (km^2)	0.373***	-0.047***	0.119***	-0.009	0.432***	0.473***	0.409***	0.427***	0.212***	0.519***	0.062***	-0.536***	-0.417***	0.223***	-0.392***	1.000			
	(0.000)	(0.000)	(0.000)	(0.468)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)				

Table 7 (continued)

	Added capacity (MW)	Expansion goal (0/1)	Forest ban (0/1)	Setback distance (in km)	Exclusive Planning (0/1)	Total designated area (km^2)	Avg. size of ind. designated areas (km^2)	Avg. shape of ind. designated areas (A/P^2)	Avg. capacity density (MW/km^2)	Stock of installed capacity (MW)	Density of installed capacity (MW/km^2)	Population density (1000/km^2)	GDP per capita (T€)	Total Remuneration (Mio. €/MW)	Green Party votes (%)	County area (km^2)	Technical potential land (100 km^2)	Wind power potential (W/m^2)	Aesthetic landscape quality (0–100)
Technical potential land (100 km^2)	0.369***	-0.051***	0.110***	-0.009	0.425***	0.473***	0.417***	0.441***	0.212***	0.514***	0.057***	-0.572***	-0.430***	0.219***	-0.410***	0.996***	1.000		
	(0.000)	(0.000)	(0.000)	(0.438)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)			
Wind power potential (W/m^2)	0.277***	0.183***	0.354***	0.050***	0.163***	0.228***	0.088***	0.168***	0.123***	0.294***	0.294***	-0.291***	-0.276***	0.746***	-0.181***	0.280***	0.275***	1.000	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)		
Aesthetic landscape quality (0–100)	−0.064***	−0.052***	−0.203***	−0.041***	−0.156***	−0.135***	−0.109***	0.150***	−0.013	−0.133***	−0.141***	−0.539***	−0.247***	0.139***	−0.061***	0.123***	0.153***	0.242***	1.000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.268)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	

p-values in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Appendix B: Extended model specifications

See Tables 8, 9

Table 8 State-level policies

Log capacity additions (ln(MW))	State Policies (1) A-Bond	+ Interactions (2) A-Bond
L2.Expansion goal (0/1)	0.268**	0.222
	(0.127)	(0.141)
1 L.Forest ban (0/1)	−0.018	0.277*
	(0.182)	(0.167)
L.Forest area (100 km^2)		−1.534**
		(0.610)
1 L.Forest ban (0/1) × L.Forest area (100 km^2)		−0.024
		(0.094)
L5.Setback distance (in km)	−0.249	−0.094
	(0.167)	(0.281)
L5.Population density ($1000/km^2$)	1.033	2.064
	(0.745)	(2.639)
L5.Setback distance (in km) × L5.Population density ($1000/km^2$)		0.028
		(0.148)
L.Log Stock of installed capacity (ln(MW))	0.412**	0.201
	(0.182)	(0.204)
L2.Density of installed capacity (MW/km^2)	−0.016***	−0.024***
	(0.005)	(0.007)
L4.Total Remuneration (Mio. €/MW)	3.236***	4.359***
	(0.918)	(1.105)
L.Green Party votes (%)	0.071	−0.074
	(0.104)	(0.132)
L.GDP per capita (T€)	−0.007	−0.009
	(0.007)	(0.007)
Year dummies	Yes	Yes
Observations	4812	4812
Counties	401	401
R−squared		
AR(1)	0.000	0.000
AR(2)	0.295	0.478
Hansen's J-statistic	0.493	0.395
MMSC-AIC	−9.585	−11.351

Standard errors in parentheses. $*p < 0.10$, $**p < 0.05$, $***p < 0.01$

Table 9 Regional policies and zoning details

Log capacity additions (ln(MW))	+ Regional Interactions		+ Zoning Details		
	(1)	(2)	(3)	(4)	(5)
	A	B	A	B	C
L.Log Stock of installed capacity (ln(MW))	0.657***	0.651***	0.442**	0.466***	0.312
	(0.182)	(0.182)	(0.176)	(0.160)	(0.203)
L2.Density of installed capacity (MW/km^2)	−0.018***	−0.016***	−0.017***	−0.016***	−0.017***
	(0.006)	(0.006)	(0.005)	(0.006)	(0.005)
1 L.Exclusive Planning (0/1)	−0.634	−0.412	0.115	−0.331	−0.159
	(0.472)	(0.423)	(0.376)	(0.376)	(0.448)
L.Total designated area (km^2)	−0.026	−0.024	0.060	0.114	0.372
	(0.018)	(0.027)	(0.060)	(0.073)	(0.273)
1 L.Exclusive Planning (0/1) × L.Total designated area (km^2)	0.126**	0.089**			
	(0.057)	(0.044)			
L.Avg. capacity density (MW/km^2)	−0.014	−0.012	−0.004	−0.007	−0.010
	(0.015)	(0.013)	(0.014)	(0.014)	(0.016)
1 L.Exclusive Planning (0/1) × L.Avg. capacity density (MW/km^2)	0.014	0.022			
	(0.027)	(0.029)			
L.Total designated area (km^2) × L.Avg. capacity density (MW/km^2)		−0.000			
		(0.013)			
1 L.Exclusive Planning (0/1) × L.Total designated area (km^2) × L.Avg. capacity density (MW/km^2)		−0.002			
		(0.013)			
L.Avg. size of ind. designated areas (km^2)			−0.563*		1.043
			(0.291)		(1.810)
L.Total designated area (km^2) × L.Avg. size of ind. designated areas (km^2)			0.013		−0.112
			(0.015)		(0.104)
L.Avg. shape of ind. designated areas (A/P^2)				−36.929	−19.143
				(24.137)	(32.661)

Table 9 (continued)

Log capacity additions (ln(MW))	+ Regional Interactions		+ Zoning Details		
	(1)	(2)	(3)	(4)	(5)
	A	B	A	B	C
L.Total designated area (km^2) × L.Avg. shape of ind. designated areas (A/P^2)				−1.291	−6.203
				(1.358)	(5.629)
L.Avg. size of ind. designated areas (km^2) × L.Avg. shape of ind. designated areas (A/P^2)					−37.958
					(48.102)
L.Total designated area (km^2) × L.Avg. size of ind. designated areas (km^2) × L.Avg. shape of ind. designated areas (A/P^2)					2.603
					(2.494)
L5.Population density ($1000/km^2$)	−1.008	1.165	0.624	0.621	0.479
	(3.212)	(3.372)	(0.764)	(0.754)	(0.780)
L4.Total remuneration (Mio. €/MW)	1.246	2.245**	2.469***	2.108***	1.894**
	(1.087)	(1.101)	(0.744)	(0.807)	(0.869)
L.Green party votes (%)	0.170	0.139	0.131	0.079	0.084
	(0.117)	(0.124)	(0.107)	(0.109)	(0.109)
Year dummies	Yes	Yes	Yes	Yes	Yes
Observations	4812	4812	4812	4812	4812
Counties	401	401	401	401	401
AR(1)	0.000	0.000	0.000	0.000	0.000
AR(2)	0.384	0.383	0.336	0.267	0.251
Hansen's J-statistic	0.363	0.358	0.191	0.317	0.464
MMSC-AIC	−9.988	−11.779	−7.186	−9.350	−15.170

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

Appendix C: Robustness checks

See Tables 10, 11

Table 10 Subsample of rural counties

Log capacity additions (ln(MW))	Main Policies	State Policies		Regional Policies	
	(1)	(2)	(3)	(4)	(5)
			+ Interactions		+ Interactions
L2.Expansion goal (0/1)	0.268	0.332*	0.398**		
	(0.189)	(0.185)	(0.198)		
1 L.Forest ban (0/1)			0.190		
			(0.300)		
L.Forest area (100 km^2)			−1.312*		
			(0.786)		
1 L.Forest ban (0/1) × L.Forest area (100 km^2)			−0.000		
			(0.115)		
L5.Setback distance (in km)	−0.625***	−0.578**	0.040		
	(0.218)	(0.241)	(0.528)		
L5.Population density ($1000/km^2$)	7.647	4.224	5.929	10.841	4.046
	(11.177)	(10.489)	(11.334)	(19.025)	(18.028)
L5.Setback distance (in km) × L5.Population density ($1000/km^2$)			−0.692		
			(0.821)		
1 L.Exclusive Planning (0/1)	0.250			0.143	−0.387
	(0.383)			(0.403)	(0.516)
L.Total designated area (km^2)	0.025			0.026	−0.021
	(0.024)			(0.029)	(0.019)
1 L.Exclusive Planning (0/1) × L.Total designated area (km^2)					0.100**
					(0.049)
L.Avg. capacity density (MW/km^2)	0.020			0.014	−0.031
	(0.030)			(0.036)	(0.046)

Table 10 (continued)

Log capacity additions (ln(MW))	Main Policies	State Policies		Regional Policies	
	(1)	(2)	(3)	(4)	(5)
			+ Interactions		+ Interactions
1 L.Exclusive Planning (0/1) × L.Avg. capacity density (MW/km^2)					0.054
					(0.053)
L.Log Stock of installed capacity (ln(MW))	0.269	0.233	−0.261	0.228	0.655
	(0.351)	(0.401)	(0.366)	(0.416)	(0.408)
L2.Density of installed capacity (MW/km^2)	−0.039**	−0.031*	−0.040**	−0.040*	−0.038**
	(0.019)	(0.019)	(0.017)	(0.022)	(0.017)
L4.Total Remuneration (Mio. €/MW)	4.699***	4.799***	5.458***	3.831**	2.716*
	(1.391)	(1.350)	(1.428)	(1.499)	(1.555)
L.Green Party votes (%)	0.217	0.308**	0.010	0.238	0.353
	(0.162)	(0.156)	(0.218)	(0.244)	(0.226)
L.GDP per capita (T€)	−0.021	−0.021	−0.019	−0.022	−0.019
	(0.017)	(0.017)	(0.015)	(0.018)	(0.018)
Year dummies	Yes	Yes	Yes	Yes	Yes
Observations	3528	3528	3528	3528	3528
Counties	294	294	294	294	294
AR(1)	0.000	0.000	0.000	0.000	0.000
AR(2)	0.440	0.393	0.607	0.501	0.403
Hansen's J-statistic	0.420	0.151	0.503	0.213	0.299
MMSC-AIC	−11.675	−4.738	−12.692	−5.987	−9.085

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 11 Conditional fixed-effects poisson regression

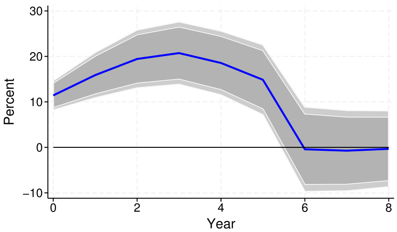
	All Counties		Rural Counties	
	(1)	(2)	(3)	(4)
	MW	MW/km^2	MW	MW/km^2
L2.Expansion goal (0/1)	0.145	0.253*	0.178	0.371***
	(0.135)	(0.146)	(0.138)	(0.143)
L.Forest ban (0/1)	−0.270*	−0.373**	−0.282*	−0.397**
	(0.154)	(0.169)	(0.156)	(0.158)
L5.Setback distance (in km)	−0.281*	−0.482**	−0.243	−0.301*
	(0.155)	(0.188)	(0.166)	(0.169)
L.Exclusive Planning (0/1)	0.078	0.234*	0.065	0.300**
	(0.130)	(0.120)	(0.134)	(0.121)
L.Total designated area (km^2)	0.028***		0.028***	
	(0.006)		(0.007)	
L.Share of Total designated area (%)		0.281***		0.311***
		(0.078)		(0.079)
L.Avg. capacity density (MW/km^2)	−0.053***	−0.048***	−0.053***	−0.058***
	(0.018)	(0.016)	(0.018)	(0.016)
L4.Total Remuneration (Mio. €/MW)	4.157***	3.532***	4.343***	4.126***
	(1.187)	(1.203)	(1.207)	(1.138)
L.Stock of capacity (MW)	0.000		0.001	
	(0.000)		(0.000)	
L2.Density of installed capacity (MW/km^2)	−0.022***		−0.027***	
	(0.007)		(0.006)	
L.Stock of installed capacity (MW/km^2)		−0.002***		−0.001**
		(0.001)		(0.000)
L5.Population density (1000/km^2)	1.760	9.648*	−1.150	−5.174
	(6.401)	(5.429)	(12.972)	(13.974)
L.Green Party votes (%)	0.105	0.101	0.117	0.162*
	(0.076)	(0.079)	(0.084)	(0.087)
L.GDP per capita (T€)	−0.009	−0.051*	−0.004	−0.020
	(0.030)	(0.029)	(0.033)	(0.029)
Year dummies	Yes	Yes	Yes	Yes
Observations	3408	3408	3000	3000
Counties	284	284	250	250
Log-Likelihood	−16703.6	−18984.2	−15880.7	−14187.5
Wald test	335.467	293.921	397.83	340.938

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

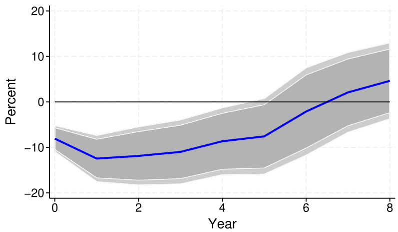
The FE-Poisson estimator (in STATA implemented via *xtpoisson, fe*) drops all observations of a county if the dependent variable is zero across all years. Among rural counties there are 34 counties that saw no wind power deployment within our period of investigation

Appendix D: Time delay of policy impacts

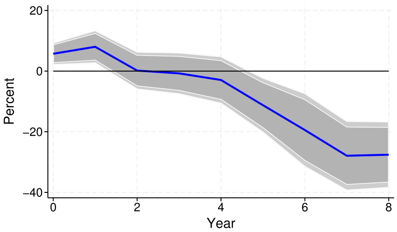
See Figure 10.



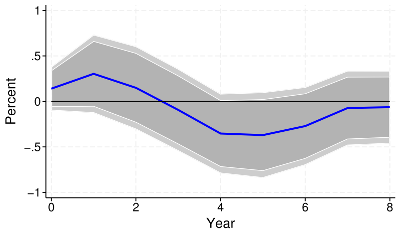
(a) Expansion goal



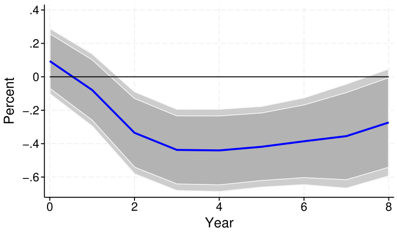
(b) Forest ban



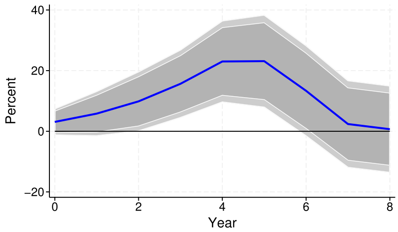
(c) Setback distance



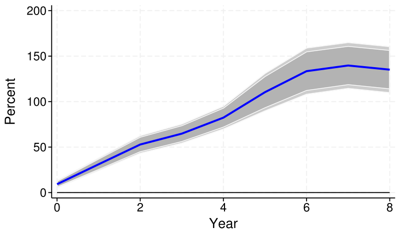
(d) Total designated area



(e) Avg. capacity density



(f) Exclusive planning



(g) Total remuneration

Notes: Plots show the estimated coefficients of policy variables using the FE model with the dependent variable being the change in existing wind power capacities in $t-1$ versus in $t+h$ for all values of $h = 0, 1, ..., 8$. Regressor variables are the same as in the main specification. See eq. (8). You can read the plot as depicting the change in the stock of wind power capacities before a policy treatment came into effect, i.e. one unit increase in the corresponding policy variable, versus h years after the policy treatment came into effect. The dark gray and light gray area depict the 90% and 95% confidence interval. The regression equation reads as follows: $ln(Y_{i,h}) - ln(Y_{i,t-1}) = ln(Y_{i,t-1})\lambda + X^P_{i,t}\beta^P + X^C_{i,t}\beta^C + \alpha_i + \xi_t + \epsilon_{it}$.

Fig. 10 Impact response analysis

Appendix E: Marginal effects

Specification: "state interactions", Table 8 column 2

See Table 12, Figure 11.

Table 12 Average marginal effects (AME) of State Policies

Log capacity additions (*ln(MW)*)	(1)
1 L.Forest ban (0/1)	0.212
	(0.239)
L5.Setback distance (in km)	−0.079
	(0.223)
Observations	4812
Counties	401
AR(1)	0.000
AR(2)	0.478
Hansen's J-statistic	0.395
MMSC-AIC	−11.351

Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

Average marginal effects are evaluated at the means of all regressor variables

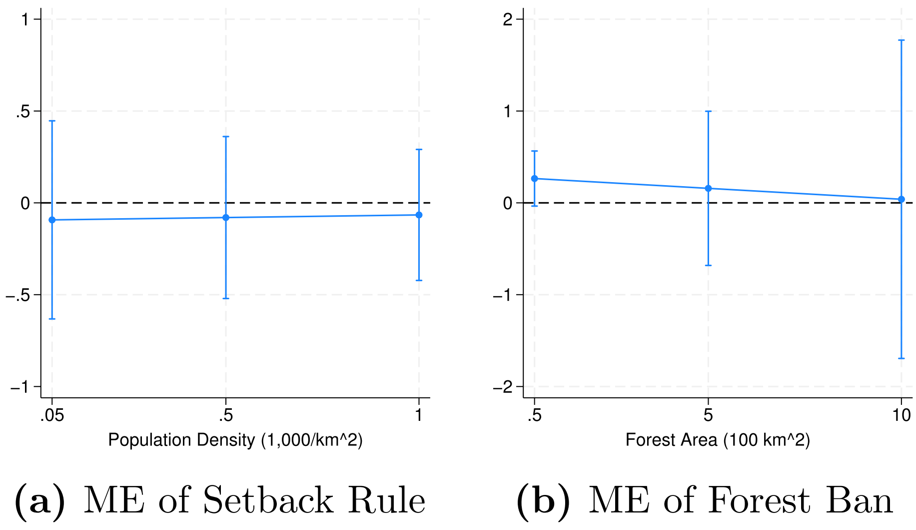


Fig. 11 Marginal effects conditional on geographical characteristics

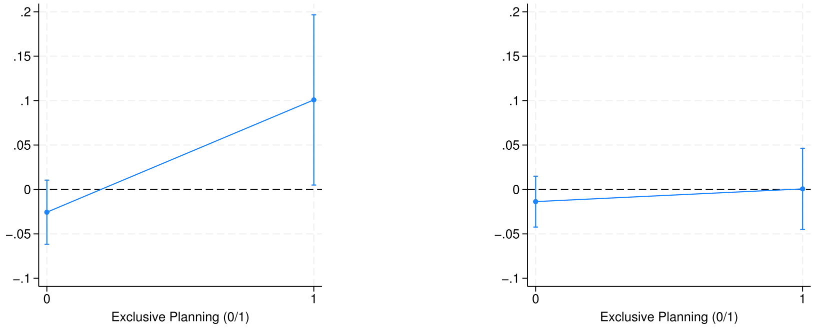
Specification: "regional interactions (A)", Table 9 column 1

See Table 13, Figures 12, 13

Table 13 Marginal effects (ME) of total designated area conditional on type of planning

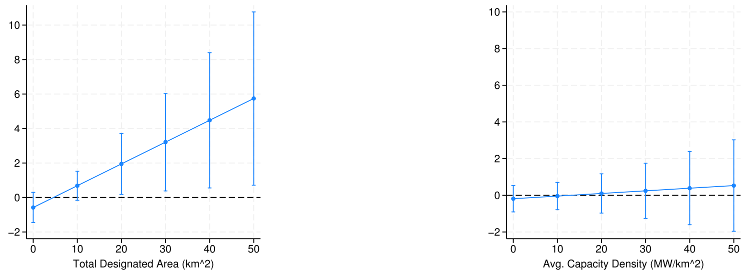
Log capacity additions (ln(MW))	Type of planning	
	(1)	(2)
	exclusive	non-exclusive
L.Total designated area (km^2)	−0.026	0.101**
	(0.018)	(0.049)

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$



(a) ME of Total Designated Area **(b)** ME of Avg. Capacity Density

Fig. 12 Marginal effects conditional on exclusive planning



(a) conditional on Total Designated Area **(b)** conditional on Avg. Capacity Density

Fig. 13 Marginal effect of exclusive planning

Specification: "regional interactions (B)", Table 9 column 2

See Table 14, Figure 14.

Table 14 Marginal effects (ME) of total designated area under exclusive planning

Log capacity additions (ln(MW))	(1) at 0 MW/km^2	(2) at 30 MW/km^2
L.Total designated area (km^2)	0.066*	0.005
	(0.037)	(0.067)

Standard errors in parentheses. $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

(a) ME of Total Designated Area under exclusive planning

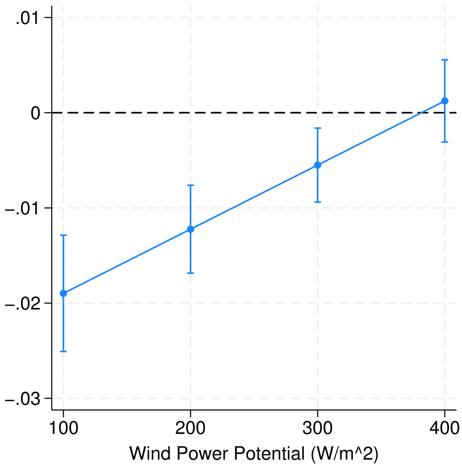
(b) ME of Total Designated Area under non-exclusive planning

Fig. 14 Marginal effects conditional on avg. capacity density and exclusive planning

Main specification: RE model, Table 3 column 3

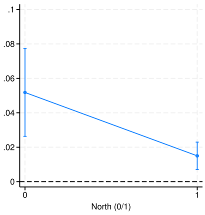
See Figure 15.

Fig. 15 Conditional marginal effects of wind power potential (based on RE estimates)

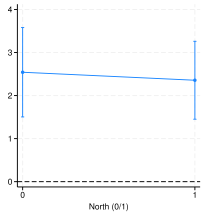


Marginal effects for Northern and Southern German Counties

See figure 16



(a) ME of Total designated area



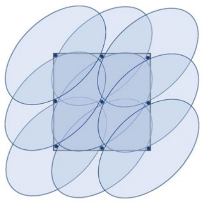
(b) ME of Total remuneration

Notes: The depicted marginal effects come from the RE model (cf. column 3 in Table 3) that was extended by a dummy variable *north* indicating Northern counties by *north*=1. The variable *north* is interacted with *total designated area* respectively *total remuneration*. All counties from Bavaria, Baden-Wuerttemberg, Rhineland-Palatinate, and Saarland are coded as Southern counties (*north*=0). State fixed effects are not included.

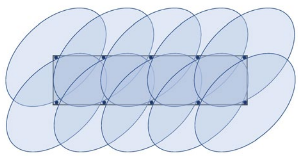
Fig. 16 Marginal effects conditional on geographic region

Appendix F: Micrositing

See Figures 17, 18



(a) Square



(b) Elongated rectangle

Notes: *Both areas – the square and the elongated rectangle – are of same size. Assuming the main wind direction is Southwest–Northeast (or vice versa) the designated area in Figure 17a can maximally host nine wind turbine sites, whereas the designated area in Figure 17b can maximally host ten wind turbine sites. The depicted example is based on commonly applied siting parameters. In the main wind direction turbines are placed apart with a distance of five times the rotor diameter, and in secondary wind direction three times their rotor diameter (Bons et al., 2019). While both areas have the same size, their shape value as measured by our regressor variable differs. Assuming d to be the side-length of the square, then size value for both areas is equal to* $d^2 = 2d * \frac{d}{2}$*. In contrast, the shape value for the square equals* $\frac{d^2}{(4d)^2} = \frac{1}{16}$ *which is lower than the value for the elongated rectangle with* $\frac{d^2}{(2*2d+2*\frac{d}{2})^2} = \frac{d^2}{(5d)^2} = \frac{1}{25}$.

Fig. 17 Example for micrositing in areas of different shape

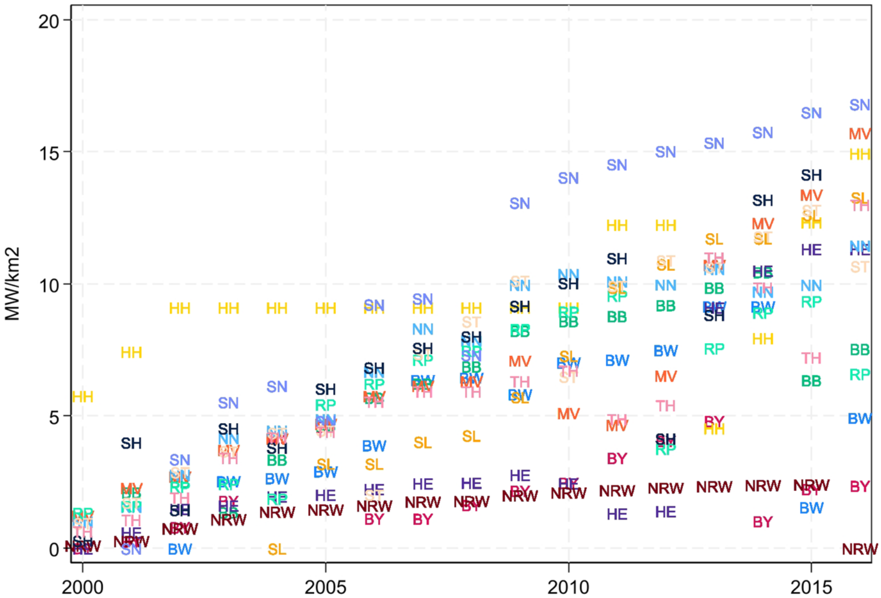
(a) Compact (b) Non-compact

Notes: *The (a) compact area has a capacity density of 24 MW/km^2 and the (b) non-compact area has a capacity density of 34 MW/km^2.*

Fig. 18 Real world example for micrositing in areas of different shape

Appendix G: Capacity density

See Figure 19.



Notes: Values of the average state-specific capacity density may jump between consecutive years, among others, as a result of court decisions which judge regional plans respectively the zoning of designated areas as legally invalid.

Fig. 19 Development of the average capacity density per state

Appendix H: Calculation of the county-specific and time-variant RES support level

See Table 15.

Table 15 Input values and calculation steps

	2000–2004	2005–2008	2009–2011	2012–2014	2015–2016
Turbine type	Enercon E-70	Enercon E-82		Enercon E-101	
Hub height	70 m	85 m		99 m	
Power capacity	2.30 MW	2.30 MW		5.05 MW	
Five–year Reference yield					
of turbine type, *RY* (*kWh*)	22,550,944	29,220,906		43,333,265	
Site quality, *SQ* (“Standortgüte”)	$SQ_{i,t} = \frac{5*e_{i,t}}{RY*100}$				
Legal basis	EEG 2000	EEG 2004	EEG 2009	EEG 2012	EEG 2014
Applicable remuneration levels					
Basic rate, *BR* (ct/kWh)	6.19	5.50	5.02	4.78	4.95
Initial rate, *IR* (ct/kWh)	9.10	8.70	9.20	8.93	8.90
Years with initial remuneration, *YIR*	$YIR_{i,t} = 5 + max\left(\frac{2*(150-SQ_{i,t})}{0.75*12}, 0\right)$				
Average yearly remuneration per *kWh*, *AYR*	$AYR_{i,t} = \frac{1}{20}(IR_t * (5 + YIR_{i,t}) + BR * (15 - YIR_{i,t}))$				
Total remuneration, *TR*	$TR_{i,t} = AYR_{i,t} * 20$				
Discounted total remuneration, *DTR*	$DTR_{i,t} = \sum_{s=1}^{20} \frac{YR_{i,s}*e_{i,s}}{(1+r)^{s-1}}$				
	with *YR* denoting Yearly Remuneration				

We assume a discount rate of $r = 7\%$ and yield losses of $l = 15\ \%$. Yearly gross power production by the respective wind turbine type in each county $E_{i,t}$ was calculated by means of the respective performance curve as stated by the manufacturers in combination with the site-specific wind power potential according to the (DWD Climate Data Center 2014). Our calculation follows Hau (2014). Yearly net power production results from substracting the assumed yield losses: $e_{i,t} = (1 - l)\ E_{i,t}$

Appendix I: State-level policies

See Table 16, 17, 18.

Table 16 Forest Ban

State	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MV	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
NN	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NRW	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
RP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SN	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
ST	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
TH	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0

Table 17 Setback rule

State	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BB										1000	1000	1000	1000	1000	1000	1000	1000
BE																	
BW													700	700	700	700	700
BY													800	800	800	2000	2000
HB																	
HE											1000	1000	1000	1000	1000	1000	1000
HH																	
MV					1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
NN					1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
NW						1500	1500	1500	1500	1500	1500						
RP	500	500	500	500	500	500	1000	1000	1000	1000	1000	1000	1000	800	800	800	800
SH	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	800	800
SL																	
SN														1000	1000		
ST																	
TH						1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

Table 18 Expansion goal

State	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BB	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
BE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BW	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
BY	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
HB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HE	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
HH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
NN	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NW	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
RP	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
SH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SL	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
SN	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
ST	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
TH	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1

The coding of state-level policy variables is based on an all-encompassing research of state development plans and guidelines for planning and permitting authorities that were in place between 2000 and 2016

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Declarations

Conflict of interest The authors declare no competing interests.

References

Andrews DW, Lu B (2001) Consistent model and moment selection procedures for GMM estimation with application to dynamic panel data models. J Econom 101(1):123–164. https://doi.org/10.1016/S0304-4076(00)00077-4

Arellano M, Bond S (1991) Some tests of specification for panel data: monte carlo evidence and an application to employment equations. Rev Econ Stud 58(2):277. https://doi.org/10.2307/2297968

Baltagi BH (2021) Dynamic panel data models. In: Baltagi BH (ed) Econometric analysis of panel data. Springer International Publishing, Cham, pp 187–228. https://doi.org/10.1007/978-3-030-53953-5_8

Bons M, Döring M, Klessmann C, Knapp J, Tiedemann S, Pape C, Stappel M (2019) Analyse der kurz- und mittelfristigen Verfügbarkeit von Flächen für die Windenergienutzung an Land: Kurztitel: Flächenanalyse Windenergie an Land. Dessau-Roßlau. https://www.umweltbundesamt.de/publikationen/analyse-der-kurz-mittelfristigen-verfuegbarkeit-von

Bunzel K, Bovet J, Thrän D, Eichhorn M (2019) Hidden outlaws in the forest? A legal and spatial analysis of onshore wind energy in Germany. Energy Res Soc Sci 55:14–25. https://doi.org/10.1016/j.erss.2019.04.009

Cameron AC, Trivedi PK (2005) Microeconometrics: methods and applications. Cambridge University Press, Cambridge

Cowell R, Ellis G, Sherry-Brennan F, Strachan PA, Toke D (2017) Energy transitions, sub-national government and regime flexibility: How has devolution in the United Kingdom affected renewable energy development? Energy Res Soc Sci 23:169–181. https://doi.org/10.1016/j.erss.2016.10.006

Dalla Longa F, Kober T, Badger J, Volker P, Hoyer-Klick C, Hidalgo Gonzales I, Zucker A (2018) Wind potentials for EU and neighbouring countries: input datasets for the JRC-EU-TIMES Model. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC109698 10.2760/041705

Drechsler M, Ohl C, Meyerhoff J, Eichhorn M, Monsees J (2011) Combining spatial modeling and choice experiments for the optimal spatial allocation of wind turbines. Energy Policy 39(6):3845–3854. https://doi.org/10.1016/j.enpol.2011.04.015

DWD Climate Data Center (2014) 200m x 200m Rasterdaten der mittleren jährlichen Windgeschwindigkeiten in 10 m bis 100 m Höhe (in 10m Stufen) und Weibullparameter für Deutschland: Version V0.1. https://opendata.dwd.de/climate_environment/CDC/grids_germany/multi_annual/wind_parameters/resol_200x200/

Egli F, Steffen B, Schmidt TS (2018) A dynamic analysis of financing conditions for renewable energy technologies. Nat Energy 3(12):1084–1092. https://doi.org/10.1038/s41560-018-0277-y

Ek K, Persson L, Johansson M, Waldo Å (2013) Location of Swedish wind power–Random or not? A quantitative analysis of differences in installed wind power capacity across Swedish municipalities. Energy Policy 58:135–141. https://doi.org/10.1016/j.enpol.2013.02.044

Enevoldsen P, Jacobson MZ (2021) Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. Energy Sustain Dev 60:40–51. https://doi.org/10.1016/j.esd.2020.11.004

Fachagentur Windenergie an Land (2021) Calculations based on data from the Marktstammdatenregister. Answer to the authors' direct data request. Berlin

Federal and State Statistical Offices (2021). https://www.statistikportal.de/de/statistische-aemter

Gibbons S (2015) Gone with the wind: valuing the visual impacts of wind turbines through house prices. J Environ Econ Manag 72:177–196. https://doi.org/10.1016/j.jeem.2015.04.006

Goetzke F, Rave T (2016) Exploring heterogeneous growth of wind energy across Germany. Utilities Policy 41:193–205. https://doi.org/10.1016/j.jup.2016.02.010
Hansen LP (1982) Large sample properties of generalized method of moments estimators. Econometrica 50(4):1029. https://doi.org/10.2307/1912775
Hau E (2014) Windkraftanlagen: Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, 5th edn. Springer, Berlin/Heidelberg, Berlin, Heidelberg
Haugen KMB (2011) International review of policies and recommendations for wind turbine setbacks from residences: setbacks, noise, shadow flicker, and other concerns. Minnesota department of commerce: energy facility permitting
Hermes J, Albert C, von Haaren C (2018) Assessing the aesthetic quality of landscapes in Germany. Ecosyst Serv 31:296–307. https://doi.org/10.1016/j.ecoser.2018.02.015
Hitaj C (2013) Wind power development in the United States. J Environ Econ Manag 65(3):394–410. https://doi.org/10.1016/j.jeem.2012.10.003
Hitaj C, Löschel A (2019) The impact of a feed-in tariff on wind power development in Germany. Resour Energy Econ 57:18–35. https://doi.org/10.1016/j.reseneeco.2018.12.001
Iglesias G, Del Río P, Dopico JÁ (2011) Policy analysis of authorisation procedures for wind energy deployment in Spain. Energy Policy 39(7):4067–4076. https://doi.org/10.1016/j.enpol.2011.03.033
Keenleyside C, Baldock D, Hjerp P, Swales V (2009) International perspectives on future land use. Land Use Policy 26:14–29. https://doi.org/10.1016/j.landusepol.2009.08.030
Kiviet JF (2020) Microeconometric dynamic panel data methods: model specification and selection issues. Econom Stat 13:16–45. https://doi.org/10.1016/j.ecosta.2019.08.003
Krekel C, Zerrahn A (2017) Does the presence of wind turbines have negative externalities for people in their surroundings? Evidence from well-being data. J Environ Econ Manag 82:221–238. https://doi.org/10.1016/j.jeem.2016.11.009
Kripfganz S (2019) Generalized method of moments estimation of linear dynamic panel data models. Proceedings of the 2019 London Stata Conference
Lauf T, Ek K, Gawel E, Lehmann P, Söderholm P (2020) The regional heterogeneity of wind power deployment: an empirical investigation of land-use policies in Germany and Sweden. J Environ Plann Manage 63(4):751–778. https://doi.org/10.1080/09640568.2019.1613221
Lerner M (2022) Local power: understanding the adoption and design of county wind energy regulation. Rev Policy Res 39(2):120–142. https://doi.org/10.1111/ropr.12447
Lundquist JK, DuVivier KK, Kaffine D, Tomaszewski JM (2019) Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development. Nat Energy 4(1):26–34. https://doi.org/10.1038/s41560-018-0281-2
Manske D, Grosch L, Schmiedt J, Mittelstädt N, Thrän D (2022) Geo-locations and system data of renewable energy installations in Germany. Data 7(9):128. https://doi.org/10.3390/data7090128
Masurowski F, Drechsler M, Frank K (2016) A spatially explicit assessment of the wind energy potential in response to an increased distance between wind turbines and settlements in Germany. Energy Policy 97:343–350. https://doi.org/10.1016/j.enpol.2016.07.021
McKenna R, Hollnaicher S, Ostman Leye Pvd, Fichtner W (2015) Cost-potentials for large onshore wind turbines in Europe. Energy 83:217–229. https://doi.org/10.1016/j.energy.2015.02.016
Meier JN, Bovet J, Geiger C, Lehmann P, Tafarte P (2019) Should the German climate package include a land area target for onshore wind energy? Wirtschaftsdienst. Zeitschrift für Wirtschaftspolitik 99(12):824–828. https://doi.org/10.1007/s10273-019-2537-2
Meyerhoff J, Ohl C, Hartje V (2010) Landscape externalities from onshore wind power. Energy Policy 38(1):82–92. https://doi.org/10.1016/j.enpol.2009.08.055
Millar JN, Oliner SD, Sichel DE (2016) Time-to-plan lags for commercial construction projects. Reg Sci Urban Econ 59:75–89. https://doi.org/10.1016/j.regsciurbeco.2016.05.002
Miller LM, Keith DW (2018) Observation-based solar and wind power capacity factors and power densities. Environ Res Lett 13(10):104008. https://doi.org/10.1088/1748-9326/aae102
National Research Council (2007) Environmental impacts of wind-energy projects. The National Academies Press, Washington, DC. https://doi.org/10.17226/11935
Nickell S (1981) Biases in dynamic models with fixed effects. Econometrica 49(6):1417. https://doi.org/10.2307/1911408
Oteri FA, Baranowski RE, Baring-Gould EI, Tegen SI (2018) 2017 State of Wind Development in the United States by Region. National Renewable Energy Laboratory (NREL/TP-5000-70738). https://www.osti.gov/biblio/1433800, https://doi.org/10.2172/1433800
Pahl-Weber E, Henckel D (eds) (2008) The planning system and planning terms in Germany: A glossary (vol 7). Hannover:Verl. der ARL. http://hdl.handle.net/10419/60979

Pettersson M, Ek K, Söderholm K, Söderholm P (2010) Wind power planning and permitting: comparative perspectives from the Nordic countries. Renew Sustain Energy Rev 14(9):3116–3123. https://doi.org/10.1016/j.rser.2010.07.008

Power S, Cowell R (2012) Wind power and spatial planning in the UK. In: Szarka J, Cowell R, Ellis G, Strachan PA, Warren C (eds) Learning from wind power. Palgrave Macmillan UK, London, pp 61–84. https://doi.org/10.1057/9781137265272_4

Reutter F, Drechsler M, Gawel E, Lehmann P (2023) Social costs of setback distances for onshore wind turbines: a model analysis applied to the German state of Saxony. Environ Resour Econ. https://doi.org/10.1007/s10640-023-00777-3

Roodman D (2009) How to do Xtabond2: an introduction to difference and system GMM in Stata. Stata J Promot Commun Stat Stata 9(1):86–136. https://doi.org/10.1177/1536867X0900900106

Ryberg DS, Caglayan DG, Schmitt S, Linßen J, Stolten D, Robinius M (2019) The future of European onshore wind energy potential: detailed distribution and simulation of advanced turbine designs. Energy 182:1222–1238. https://doi.org/10.1016/j.energy.2019.06.052

Salomon H, Drechsler M, Reutter F (2020) Minimum distances for wind turbines: a robustness analysis of policies for a sustainable wind power deployment. Energy Policy 140:111431. https://doi.org/10.1016/j.enpol.2020.111431

Shrimali G, Lynes M, Indvik J (2015) Wind energy deployment in the U.S.: an empirical analysis of the role of federal and state policies. Renew Sustain Energy Rev 43:796–806. https://doi.org/10.1016/j.rser.2014.11.080

Söderholm P, Ek K, Pettersson M (2007) Wind power development in Sweden: global policies and local obstacles. Renew Sustain Energy Rev 11(3):365–400. https://doi.org/10.1016/j.rser.2005.03.001

Staid A, Guikema SD (2013) Statistical analysis of installed wind capacity in the United States. Energy Policy 60:378–385. https://doi.org/10.1016/j.enpol.2013.05.076

Stede J, May N (2020) Way Off: the effect of minimum distance regulation on the deployment of wind power. Discussion Papers of DIW Berlin 1867 (DIW Berlin, German Institute for Economic Research)

Wallasch AK, Lüers S, Rehfeldt K (2015) Kostensituation der Windenergie an Land in Deutschland. Deutsche WindGuard GmbH

Wind FA (2015) Dauer und Kosten des Planungs- und Genehmigungsprozesses von Windenergieanlagen an Land. Berlin. [23.08.2021]. https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA-Wind_Analyse_Dauer_und_Kosten_Windenergieprojektierung_01-2015.pdf

Winikoff JB (2021). Farm Size, spatial externalities, and wind energy development. University of Wisconsin-Madison:. [21.2.2023]https://aae.wisc.edu/dparker/wp-content/uploads/sites/12/2021/02/wind_land_tex.pdf

Winikoff JB (2022) Learning by regulating: the evolution of wind energy zoning laws. J Law Econ 65(S1):S223–S262. https://doi.org/10.1086/718912

Zerrahn A (2017) Wind power and externalities. Ecol Econ 141:245–260. https://doi.org/10.1016/j.ecolecon.2017.02.016