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Way off: The effect of minimum distance regulation on the deployment and cost of wind power

Jan Stede[*a], Marc Blauert[a] and Nils May[a]

With the expansion of onshore wind power, countries increasingly consider the introduction of minimum distance regulations between wind turbines to nearby residential areas, to increase public acceptance. In 2014, the German federal state of Bavaria introduced a minimum distance regulation that requires new wind turbines to be ten times their total height away from settlements (10-H regulation). This translates into a distance of 1,900 metres on average, which far exceeds national provisions on minimum distances. Using a difference-in-differences approach, we find that the introduction of the 10-H regulation led to a decline of the newly added wind power capacity in Bavaria of between 62 percent and 90 percent. Moreover, the legislation affected technological parameters of new wind turbines, with severe unintended consequences for the deployment and cost of wind power. The regulation triggered a reduction of the height of new turbines, which lowered energy yields and increased levelized costs of electricity (LCOE) by about 0.2 ct/kWh. Furthermore, lower energy yields also require a higher absolute number of turbines in the long term to achieve the expansion targets for onshore wind energy, counteracting the goal of increasing acceptance of wind power.

Keywords: Onshore wind power; minimum distance regulation; separation distance; panel data; difference-in-differences; causal inference
JEL codes: C21, Q42, R14, R15

Declaration of competing interest: None

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1 Introduction

Energy transitions worldwide rely on the rapid deployment of renewable energy technologies to reduce greenhouse gas emissions (IPCC 2018; Williams et al. 2012). For this transition, onshore wind power is considered one of the key technologies (Chu and Majumdar 2012). In recent years, levelized costs of electricity (LCOE) for onshore wind have decreased significantly due to technological learning and improved financing conditions (Egli et al. 2018; IRENA 2019). On a global scale, onshore wind is projected to be the lowest-cost power generation option on average by 2025 (IEA 2020). Against this background, the regulatory framework for the construction of new onshore wind turbines is of high relevance for the decarbonisation of energy production worldwide.

This paper focuses on minimum distances to nearby residential areas, which is one of the key aspects within the regulatory framework for new wind turbines. While minimum distances are necessary to avoid negative externalities for residents, they can also become a limiting factor for the expansion of wind power if applied extensively. Mandatory minimum distance regulations have been applied as an explicit policy instrument on national or regional level in countries such as Germany, Hungary, and Poland (JRC 2018; Sokołowski 2017; Papież et al. 2019; Salomon et al. 2020). Our paper analyses the effects of the introduction of a strict minimum distance regulation on the deployment and cost of generating wind power in the German Federal State of Bavaria. While we focus on the effects in a state with particularly stringent minimum distance regulation, the results we obtain can be generalised to other countries with similar regulations such as Poland.

In Germany, the share of electricity generated by onshore wind has increased from less than 2 percent in 2000 to about 17.5 percent of electricity consumption in 2019 (BMWi 2020). Furthermore, the latest version of the German Renewable Energy Sources Act (EEG) specifies an increasing expansion path for onshore wind to reach 71 gigawatt (GW) of installed capacity by 2030 (EEG 2020) to meet national emission targets. Since 2018, however, the national expansion rates for onshore wind energy have declined sharply and have remained on a low level since then. One of the main reasons for this development is that permits for wind projects are being challenged in court by local residents (Fraunhofer IEE 2019). In response, the public debate in Germany, as in other countries, has shifted towards considering the introduction of stricter minimum distances between wind turbines and settlements to increase acceptance.

The German Federal State of Bavaria has been the first to introduce a stringent minimum distance regulation for wind power plants in 2014. It stipulates that new wind turbines must be ten times their total height away from settlements (10-H regulation). On the national level, the German Federal Immission Control Act defines maximum tolerable noise emissions to settlements, which imply implicit minimum distances to wind turbines (TA Lärm 1998). In practice, those legal requirements are translated into state-specific distance recommendations that range from 400 to 1,100 meters from settlements (FA Wind 2021). Considering average turbine heights, the Bavarian 10-H regulation therefore by far exceeds these limits, implying minimum distances for newly built wind turbines of around 1,900 meters on average.

While the impact of such far-reaching minimum distance regulations has been estimated for Germany in terms of reductions in land availability in spatial modelling studies (Masurowski et al. 2016; Umweltbundesamt 2019), an ex-post investigation of the effect on wind power expansion and

the costs of generating electricity from newly built wind turbines has not yet been carried out. We address this research gap by applying statistical inference to a novel dataset of wind turbine permits in Germany between 2010 and 2018. Specifically, we apply a difference-in-differences approach to assess the impact of the 10-H regulation on the capacity associated with new permits for wind power projects, as well as on technological parameters of newly built wind turbines.

We show that the Bavarian minimum distance regulation has reduced newly issued wind power permits by 62 (lower bound) to 90 percent (upper bound) compared to the development in the rest of Germany, where no strict minimum distance rule applied. We back this finding with a battery of robustness checks. Additionally, we also establish novel evidence that the intervention unintentionally influenced the trend of technological parameters for new wind turbines. On average, new turbines in Bavaria are 6.6 meters smaller as compared to the counterfactual trend. This change in turbine parameters translates into lower wind yields of about 5.4 percent. We estimate that the lower energy yields are only partially compensated by the cost reduction associated with smaller turbines and that therefore the introduction of the 10-H regulation also leads to an increase in the LCOE of about 0.19 ct/kWh, thus increasing the cost of producing electricity from wind energy. Finally, we estimate how the lower energy yield from smaller turbines also affects the absolute number of turbines needed in the long term to meet renewables expansion targets.

Our paper is structured as follows. Section 2 provides background information on the 10-H minimum distance regulation in Bavaria and on previous assessments of how different distances impact land availability for wind power development. It also reviews the academic literature on public acceptance of wind energy in relation to minimum distance regulations. Section 3 presents our methodology. Section 4 introduces our dataset. In section 5, we report results on the effects of the regulation on the expansion of wind power, as well as the associated costs. Section 6 discusses policy implications and concludes.

2 Background on 10-H regulation and public acceptance of wind power

2.1 Minimum distances and land available for wind power

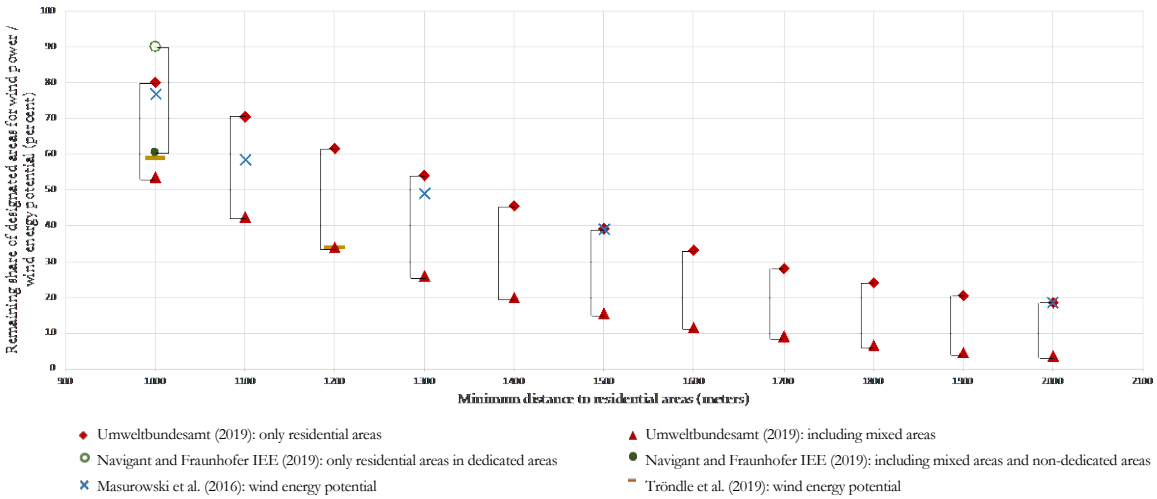
The federal state of Bavaria introduced its minimum distance regulation (10-H regulation) to restrict deployment of new wind turbines in proximity to settlements. The regulation applies to new permits for wind turbines and came into effect in November 2014 (see appendix A.1 for details on the timing of the introduction and its legal treatment). After this date, new permits were only granted for installations that have a distance of ten times the total height of the wind turbine to residential areas. The regulation does not differentiate according to visibility or noise emissions (i.e. a turbine on top of a hill is restricted in the same way as a turbine in a valley). The height of a turbine is measured as the sum of the hub height and the rotor blade length. In practice, this translates into a uniform minimum distance of on average 1,900 meters (see average height of turbine in Table 1).

There are exceptions to the 10-H minimum distance regulation in Bavaria. First, local administrations at the municipal level may issue permits without enforcing the regulation when these permits had

been filed prior to February 2014. Alternatively, these authorities may introduce exemptions for turbines to also be built at lower distances. Consequently, to be able to identify the effect of the Bavarian 10-H regulation on new installations, it is necessary to differentiate between installations that received their permits under application of the new regulation and those that were still issued under the old regulation (see section 4).

Previous spatial modelling work shows that strict minimum distances have strong effects on the land available for wind power. Taking into account the pre-existing restrictions, introducing a uniform minimum distance of 1,000 meters would reduce the land area available for wind power in Germany by 10 to 47 percent (see Figure 1). This reduction increases to 81 to 96 percent for a distance of 2,000 meters. Furthermore, the impact of minimum distances on available land varies considerably with the definition of the type of residential areas to which the minimum separation distance applies (Umweltbundesamt 2019). Minimum distances towards individual housing reduce available land considerably more than distances only to larger settlements. For example, a stricter definition of a minimum distance of 1,000 meters can have similar effects as a less strict definition of 1,300 meters (Figure 1).

Figure 1: Effect of minimum distance regulation on energy potential and land availability in Germany



The figure displays the remaining share of land available for wind power as a function of different minimum distances, based on simulation studies. On the vertical axis, we depict the remaining share of the land dedicated to the construction of wind turbines in regional plans in Germany (Umweltbundesamt 2019; Navigant and Fraunhofer IEE 2019), and the remaining wind energy potential compared to a minimum distance baseline of 800 meters (Masurowski et al. 2016; Tröndle et al. 2019).

2.2 Public acceptance of wind power

In light of the expansion plans for onshore wind energy in many countries, maintaining and supporting local acceptance of wind power deployment is an important policy goal. However, the academic literature on public acceptance of wind energy does not support the hypothesis of a significant uptake of public acceptance due to increased minimum distances: On the one hand, wind turbines have been shown to exert negative externalities locally, for example on well-being of local residents (Krekel and Zerrahn 2017). Moreover, large accumulations of wind turbines nearby residential areas affect acceptance negatively (Ladenburg and Dahlgaard 2012; Ladenburg et al. 2013; Ott and Keil 2017). However, the often-touted not-in-my-backyard theory has been abandoned by

the academic literature for a lack of explanatory power (Wolsink 2012; Zerrahn 2017). There is evidence that negative effects of wind turbines on well-being are transitory and disappear a few years after the installation (Krekel and Zerrahn 2017). In addition, there is no evidence that an increasing proximity to wind turbines exacerbates the negative external effects of wind turbines (Krekel and Zerrahn 2017; Langer et al. 2016, 2018; Rand and Hoen 2017; Hoen et al. 2019; Hübner et al. 2019). This indicates that increasing minimum distances will likely have no effect on the social acceptance of wind power.

One explanation for this paradox is that residents in many countries are already protected from noise, shadowing and visual impairment of wind turbines. In Germany, federal law and most importantly the Federal Immission Control Act (TA Lärm) mandates that project developers need to prove on a case-by-case basis that the effect of noise and other disturbances is limited (Wegner 2017). This might also explain why the identified willingness-to-pay for larger minimum distances is low and lies well below the additional costs of reducing the available land area under a minimum distance regulation (Drechsler et al. 2017).

3 Methodology

We aim to answer two basic research questions with our methodology. First, using an empirical causal model design, we aim to identify how the introduction of the 10-H minimum distance regulation in Bavaria affected the deployment of wind turbines as compared to the trend in the rest of Germany, where no strict distance regulation applied. We estimate the effect in terms of newly added capacity and technological turbine parameters (section 3.1). Second, we move to a cost perspective and estimate how the change in technological parameters affected the LCOE for power generation from onshore wind in Bavaria (section 3.2).

3.1 Empirical model

We use a difference-in-differences model design to identify the causal effect of the Bavarian minimum distance regulation on wind power capacity expansion and the technological parameters of newly built wind turbines. The baseline specification is given by

$$q_{i,t}^{Wind} = \delta D_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t} \quad (1)$$

where the dependent variable q is the capacity (or other technical parameter[1]) associated with wind turbine permits granted in district i in month t in MW. μ_i is a district-level fixed effect that controls for differences in the number of permits between districts that are constant over time. τ_t is a vector of monthly fixed effects that control for the impact of national-level shocks on the number of permits. Such shocks may include lower costs for building wind turbines over time or changes to the German renewables remuneration regime that affect Bavaria and the rest of Germany equally. δ is the coefficient of interest, measuring the effect of the 10-H regulation on the capacity associated with permits (or on the technical parameters hub height, rotor blade length, and rated power) in the

[1] In addition to the capacity, we quantify the effect of the 10-H regulation on the technical parameters hub height, rotor blade length, and rated power.

average Bavarian district. δ thus quantifies the causal effect of the 10-H regulation on wind turbine capacity, as well as on the technical parameter of newly built wind turbines, compared to the counterfactual scenario where no such stringent minimum distance regulation exists.

3.2 Implications for the levelized costs of electricity

The 10-H regulation does not set an absolute distance to nearby settlements, but this distance increases with the height of the wind turbine. This means project developers have an incentive to reduce the size of newly built turbines to be able to build turbines in areas that would be inaccessible to larger turbines. However, smaller turbines generate lower wind yields. The 10-H regulation may therefore have an implication for the per-unit (ct/kWh) life cycle costs of generating electricity, i.e., the levelized costs of electricity (LCOE).

We test how the 10-H regulation affects the cost of generating electricity from wind power with a three-step procedure. First, we use the causal model (1) described in the previous section to assess whether the introduction of the 10-H regulation affected the technical parameters hub height, rotor blade length, and rated power of new installations in Bavaria. Second, we calculate the implication of the change in these parameters for energy yields of wind turbines (section 3.2.1). Third, to quantify the impact of the 10-H regulation on the cost of producing electricity from wind energy, we compute the LCOE by combining the effect on the wind yield with common cost parameters for wind turbines (section 3.2.2).

3.2.1 Energy yield

The technological parameters hub height and rotor blade length affect the energy yield of a wind turbine through two different channels. First, winds blow stronger at higher elevations, leaving shorter towers exposed to lower wind speeds. This difference in wind speeds can be approximated by a logarithmic height profile (Hau 2013).[2] Secondly, shorter rotor blades have less swept area and therefore capture less wind also reducing the electricity generation. Following Narbel et al. (2014), equation (2) shows the energy yield P_{Pot}.

$$P_{Pot} = \frac{1}{2}\varphi_{air}\pi C_p(v) r^2 v^3 \qquad (2)$$

The air density φ_{air} is independent of the technical parameters of the wind turbine (Deutsches Institut für Bautechnik 2012). The same applies to the mechanical efficiency $C_p(v)$, which is also assumed to be independent of the turbine technology. Thus, the change in rotor blade length r and change in wind speeds at hub height v describe the change in energy yield.

[2] The wind speed v_{h1} at the hub height h_1 of the shorter tower is, therefore, given by equation (3). It depends on the wind speed v_{h2} at the hub height h_2 without 10-H regulation and the roughness length z_0, which, for rural sites, is assumed to be 0.1 (Silva et al. 2007).

$$v_{h1} = v_{h2}\frac{\ln\frac{h_1}{z_0}}{\ln\frac{h_2}{z_0}}$$

3.2.2 Implications for the levelized costs of electricity

To quantify the impact of the 10-H regulation on the cost of producing electricity from wind energy, we turn to LCOE as a per-unit measure of the economic trade-off associated with building smaller turbines. Smaller wind turbines generate less electricity, but also save costly building material during the construction phase. By calculating the LCOE, we quantify which of the two effects dominates the per-unit cost of producing electricity.

In order to quantify the net effect of the 10-H legislation on LCOE, we estimate the difference in LCOE between the observed choice of turbine parameters under the 10-H regulation and the expected choices in a counterfactual scenario. We use equation (4) to estimate LCOE in the observed and counterfactual scenarios (Fraunhofer ISE 2018; McKenna et al. 2014).

$$LCOE_{ct/kWh} = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_t}{(1+i)^t}} \qquad (4)$$

Here, I_0 is the sum of the initial investment, A_t is the annual sum of fixed and variable costs, M_t is the amount of energy generated in a year, i is the real interest rate, and n is the expected economic lifetime of a project. Following Fraunhofer ISE (2018), the real interest rate i is assumed to be 2.55 percent and the expected economic lifetime n of a new turbine is assumed to be 25 years.

Energy generated M_t is affected by the change in energy yield estimated with equation (2). For the counterfactual scenario (expected trend without 10-H regulation), we assume 2,000 full load hours (McKenna et al. 2014) and 3.5 MW of rated power (Deutsche WindGuard 2021) represent a realistic specification for a new wind turbine in Bavaria.

Both the initial investment and the operational costs are affected by turbine parameters. The investment costs I_0 consist of main investment costs and incidental investment costs. While the main investment costs are expected to decrease due to a lower use of materials for smaller towers and rotors, the incidental investment costs are expected to remain constant. For calculating the difference in the main investment costs, we rely on data from Deutsche WindGuard (2015), which gives an average estimate of 330 €/m^2 for the main investment costs as a function of swept rotor area of a turbine. Incidental investment costs of 387 €/kW are assumed in both scenarios (Deutsche WindGuard 2015).

For the operating costs A_t, only the variable costs are expected to differ between the two scenarios. Following Fraunhofer ISE (2018), the fixed operational costs for the yield-independent maintenance of a turbine are assumed to equal 30 €/kW. The variable costs, which integrate the difference in operational time, are assumed to be 0.5 ct/kWh.

4 Data

4.1 Creating a novel wind permit dataset

For our empirical model, we create a novel district-level dataset (corresponding to NUTS 3 level) containing monthly permits (in megawatt) and technological parameters of wind turbines installed in Germany between 2010 and 2018. The novel dataset builds on three different sources of data.

The first source is the private *Betreiber-Datenbasis (2019)*. It contains information on the installation date of wind turbines in Germany, their location, and technical parameters (rated power, hub height, and rotor blade length). For the period between 2010 and 2018, it consists of 10,993 turbines, with an average capacity of 2.7 megawatts (MW). Since the aggregate figures on yearly wind expansion match almost perfectly with the data provided for the German Wind Power Association and the German Engineering Association (Deutsche Windguard 2019), the data quality is considered to be high.

Second, from the *Anlagenregister*, a public register of renewable energy installations, we retrieve information on construction permit dates for wind turbines found in the *Betreiber-Datenbasis*. The *Anlagenregister* is an official publicly accessible database, where all German renewable energy installations between August 2014 and 2019 had to be registered. We merge *Anlagenregister* and *Betreiber-Datenbasis* based on an exact match of the variables' month-year of the construction of the wind turbine, their nominal power, as well as their zip code. This results in a dataset with installation data and technical parameters for all wind turbines, and permit dates for a subset of these installations.[3]

Third, not all permits granted after November 2014 were subject to the 10-H regulation, since the law introduced some exceptions (section 2). We identify those permits that did comply with the new regulation by using a range of official documents published by the Bavarian Federal Ministry of Economic Affairs as a response to various parliamentary questions by members of the Bavarian parliament. This allows us to estimate the share of permits after November 2014 granted without an application of the minimum distance regulation.

Based on these three data sources, in section 5 we calculate causal effects of the 10-H regulation using data from 2010 to 2016. The reason for not using a longer time series is that Germany shifted its renewables support regime from a feed-in tariff to an auctions design as of January 1st, 2017. We thus differentiate the causal effect of the minimum distance regulation in Bavaria from this major regulatory change that affected all of Germany. In order to exclude anticipatory effects (i.e., increases in the deployment of permits to benefit from the fixed feed-in tariff), we use data until the second quarter of 2016.

[3] For the variable month-year of the construction, we allow for a time lag of up to two months between *Betreiber-Datenbasis* and *Anlagenregister*. The reason is that the *Betreiber-Datenbasis* contains the date when the construction of a wind turbine is completed, whereas the *Anlagenregister* contains the commissioning date (i.e. when the installation starts producing electricity). Using this approach, we merge around 60 percent of the *Anlagenregister*'s wind turbines with information on the permit date to the *Betreiber-Datenbasis*.

4.2 Construction periods of wind turbines

Despite its official nature, the *Anlagenregister* does not contain all wind turbines constructed in Germany. In both 2013 and 2014, shortly before the Bavarian 10-H regulation was implemented, around 40 percent of all installations built in Germany were not registered in the *Anlagenregister*. Consequently, the wind permit database we create is based on the *Betreiber-Datenbasis* (which has complete data on all installations), complemented by information on permit dates from the *Anlagenregister*. After merging the two databases, we have precise information on the date of construction for all installations, but the date that the permits were granted is not available for all installations. For those turbines for which the permit date is not known, we approximate it by subtracting typical construction periods from the known construction dates. We do this in several steps.

First, we define the construction time as the commissioning date minus the permit date for all plants in the *Anlagenregister*. This gives us a distribution of construction periods for German wind power plants. The average construction period is twelve months (see Figure A-1 in appendix A.2). Second, we approximate the missing permit dates in the Betreiber-Datenbasis by subtracting from the (known) construction date a random draw of the distribution of construction times.[4] Since almost 99 percent of all wind turbines built after 2010 in Germany have a construction date below four years (cf. Figure A-1), we restrict the distributions from which we draw to 48 months in order to exclude extreme (possibly erroneous) observations. Lastly, we aggregate the turbine-specific information on the district level for every month.

The assumption underlying the approximation procedure is that the construction times for the plants for which we do have information on the permit date and the ones where we only have the construction date are similar. We provide evidence for this assumption by showing that the turbines in these two groups are very much alike in terms of height and power: These variables differ between both groups by around two percent (power) and by less than one percent (height) in a typical year (see appendix A.2).

4.3 Descriptive Statistics

Table 1 shows that only 7.7 percent of all building permits in the years 2010-2016 were granted to Bavarian wind turbines, although almost one-fourth of all German districts are located in Bavaria. Moreover, the average height of wind turbines of 190 meters in Bavaria implies that the 10-H regulation translates into a minimum distance of 1,900 meters on average.

[4] Specifically, we draw from two separate yearly distributions, one containing all Bavarian wind turbines, and a second one containing all other German wind turbines. Draws are from yearly distributions of the construction periods, reflecting that the duration of the construction might change over time. However, the construction times for the years 2010-2014 are pooled into a joint distribution, because the number of observations with information on the construction period is low in the individual years.

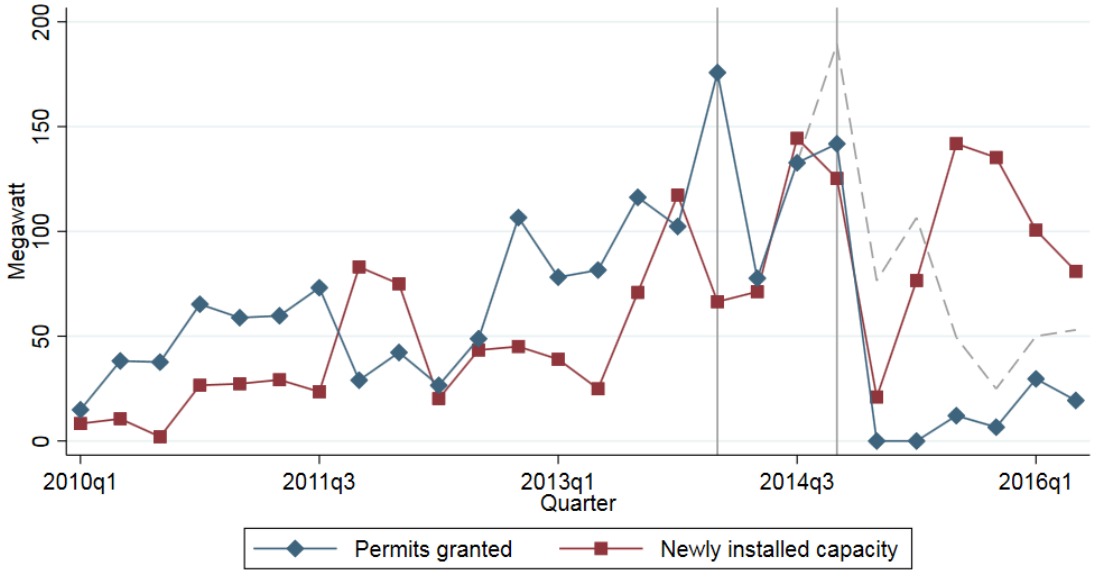
Table 1: Descriptive statistics of wind turbines in Bavaria and Germany

	Bavaria	Germany
Number of districts	96	401
Mean district area [km²]	734.8	891.7
Number of wind turbines	760	10,019
Total added wind capacity [MW]	1,986	25,125
Mean power of wind turbines [MW]	2.61	2.70
Mean height of wind turbines [meter]	190	171
Mean hub height [meter]	136	120
Mean rotor blade length [meter]	54	51
Mean number of permits per district [MW/month]	0.25	0.81
Mean construction period [months]	14.9	11.6

The statistics refer to wind turbines from our permit database that received their construction permits between 2010 and 2016. The districts refer to Germany's territorial status as of September 30th, 2019.

Figure 2 illustrates the advantage of our new permit dataset. It shows how an analysis based on newly installed wind turbines would be biased. Bavarian construction permits, which are directly affected by the 10-H regulation, declined sharply after November 2014. New installations of wind turbines, on the other hand, actually *increased* after the introduction of the mandatory minimum distances due to the time lag between granting of a permit and construction. Consequently, an analysis of the minimum distance regulation based on installation data would underestimate the effect of the policy.

Figure 2: Permits for wind turbines and newly installed wind power capacity in Bavaria



The figure shows the quarterly new construction permits and installations of wind power in Bavaria, as well as the cut-off dates of the introduction of the minimum distance regulation. Permits include the total number of permits (dashed line), or the permits under an application of the Bavarian minimum distance regulation only (blue solid line). The left vertical line marks the cut-off date to file for new permits that are not subject to the 10-H regulation in February 2014. The right vertical line indicates the introduction of the policy in November 2014. q1 denotes the first quarter for a given year.

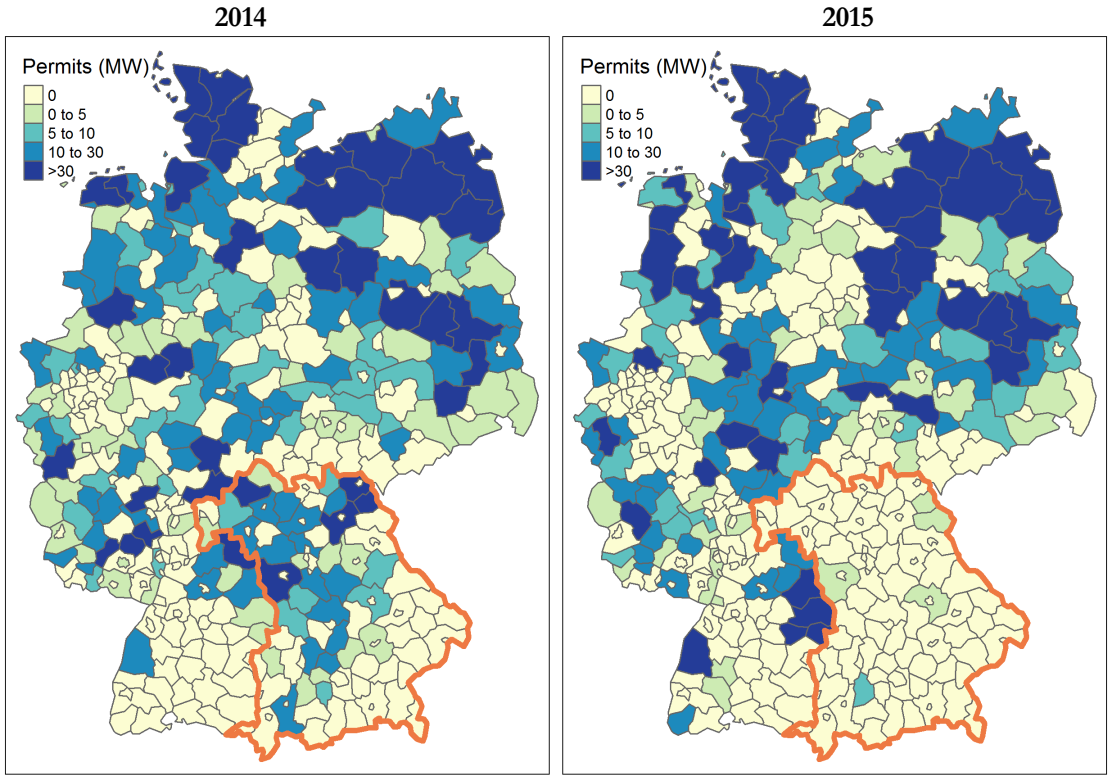
5 Results

In this section, we present results on the effects of the introduction of the 10-H regulation for the capacity expansion of wind power (section 5.1), as well as for the LCOE and long-term expansion targets (section 5.2).

5.1 Effect on new installations

The capacity associated with wind power permits (in MW) issued in Bavaria dropped drastically after the introduction of the 10-H minimum distance regulation. In most Bavarian districts, no permits for wind power plants were issued under the new regulation in 2015 (see Figure 3). Minor deviations can also be identified for individual districts in other states, but a uniform decline as in Bavaria cannot be observed.

Figure 3: Wind permits before and after the introduction of minimum distances in Bavaria

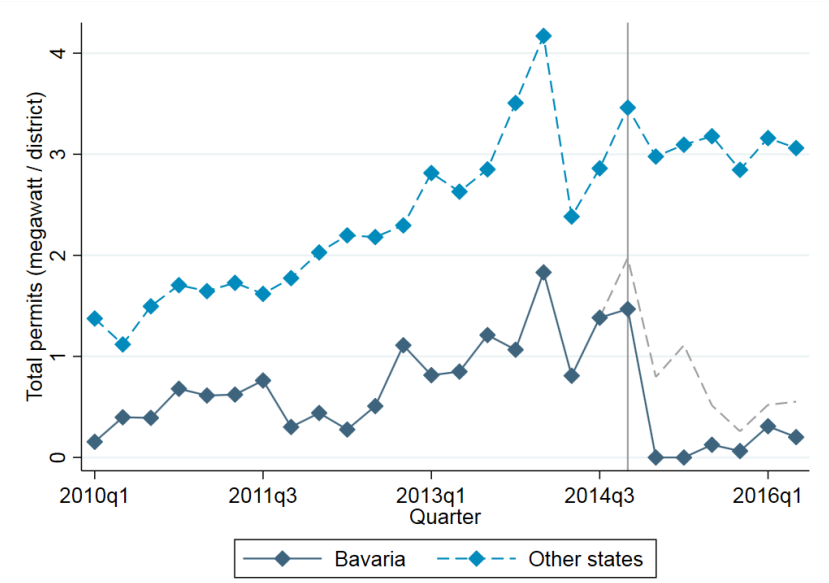


The figure shows the total permits for wind turbines (in megawatt) issued in the twelve months before the introduction of minimum distances in Bavaria (left panel), as well as the twelve months after (right panel). Permits in Bavaria (marked by the orange line) include the permits subject to the Bavarian minimum distance regulation only.

Furthermore, Figure 4 shows that the capacity of new permits issued in Bavaria and the rest of Germany followed a common trend before the introduction of the 10-H regulation in November 2014. This provides visual evidence for the identifying assumption, namely that Bavarian permits would have evolved similarly to the rest of Germany, if the 10-H regulation had not been introduced.

We further substantiate this identifying assumption by implementing an event study design below.[5] However, after the introduction of the 10-H regulation in November 2014, the trends of the two lines in Figure 4 clearly disconnect. Capacity from permits is declining sharply in Bavaria, while it remains stable in the rest of Germany. The divergence is most pronounced when looking only at those permits that are subject to the minimum distance regulation (solid line in Figure 4).

Figure 4: Wind power permits in Bavaria and the rest of Germany



The graph shows the average number of permits for wind turbines (in megawatt) issued quarterly per district. Permits in Bavaria include the total number of permits (dashed line), or the permits under an application of the Bavarian minimum distance regulation only (solid line). q1 denotes the first quarter for a given year.

In line with the visual evidence, the regression results using the difference-in-differences model show that the Bavarian regulation significantly reduced the capacity associated with permits. The results are presented in Table 2. All coefficients are highly statistically significant. Columns 3 and 6 correspond to the baseline specification (1) presented in section 3.1. The results are stable across specifications with different time fixed effects. The model with monthly fixed effects is our preferred specification (columns 3 and 6), since these take up more detailed variation than quarter or annual fixed effects.

[5] The lower capacity per district in Bavaria before treatment, visible in the difference between the two lines in Figure 4, is not surprising, but still warrants explanation. The difference arises from two general conditions that are independent of the introduction of the 10-H regulation. The first condition is that the average wind speeds in Bavaria are lower than in the northern and central parts of Germany (Deutscher Wetterdienst 2004; Drücke et al. 2021). Due to the location disadvantage less capacity is deployed in the southern regions (see Figure 3). The second condition is the smaller average district area in Bavaria compared to the average district area in the rest of Germany (see Table 1).

Table 2: Effect of minimum distances on wind power construction permits in Bavaria

Dependent Variable:	All permits			Permits under minimum distance regulation		
Specification:	(1)	(2)	(3)	(4)	(5)	(6)
Treatment: Minimum distance regulation	-0.316*** (0.0809)	-0.326*** (0.0825)	-0.343*** (0.0855)	-0.468*** (0.0812)	-0.477*** (0.0827)	-0.499*** (0.0855)
Change [%]	-57	-59	-62	-84	-86	-90
Observations	31,278	31,278	31,278	31,278	31,278	31,278
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

Values shown are the coefficients of fixed effects regressions of monthly construction permits in megawatt at the district level from 2010 to Q2 2016. The percentage decrease of wind turbine permits in Bavaria relative to the counterfactual building permits is also tabulated. Standard errors clustered at the state level are in parentheses. All coefficients remain statistically significant when ordinary wild bootstrap standard errors are used (see Table). Significance: * p<0.1, ** p<0.05, *** p<0.01.

We estimate the model with two different dependent variables to obtain a lower and an upper bound of the effect. In our upper bound estimation (columns 4-6 of Table 2), we assume that after the introduction of the mandatory minimum distances, wind turbines constructed under an exception from the 10-H regulation would not have been built had the strict minimum distance regulation been applied. Alternatively, a lower bound of the effect of the regulation can be calculated by assuming that all wind turbines that benefitted from such an exception would have survived the strict minimum distance regulation. Under this alternative assumption, the estimated effect is lower, but remains statistically and economically highly significant (columns 1-3 of Table 2).

For the estimated treatment effects in Table 2, we also calculate the Bavaria-wide relative capacity decline associated with the 10-H regulation. We do this by using the point estimates from the respective specification. These are to be interpreted as the average monthly capacity difference per district between the observed and the counterfactual scenario. The counterfactual scenario reflects the expected development in Bavaria based on the development in the rest of Germany if the 10-H regulation had not been introduced.

We present the results from the lower bound estimations in columns 1-3 of Table 2. They rely on the assumption that all permits issued under exemptions from the Bavarian 10-H regulation would have been issued even if the regulation had been applied. Under this assumption, the new regulation reduced capacity from permits on average by 0.34 megawatt (MW) per month (12 months) and district (96 districts). This corresponds to an aggregate effect on capacity in Bavaria of 395 MW per year. This figure, in turn, corresponds to a 62 percent reduction in capacity from new permits compared to the counterfactual scenario (column 3 of Table 2).

The optimistic assumption used for the estimates in columns 1-3 of Table 2 likely underestimates the true effect of the Bavarian minimum distance regulation. The required distances, strongly restricted the number of projects able to receive permits, making it unlikely that all of these projects would be in line with the new regulation. Consequently, in columns 4-6 of Table 2, we re-estimate

our models under the assumption that projects granted a permit without applying the 10-H regulation would *not* have received a permit had it been enforced. In other words, we estimate an upper bound of the regulation's effect by including only Bavarian wind turbines that did receive the permit under the new regulation after November 2014 in our estimation. Here, capacity from permits dropped by almost 0.5 MW per district per month (or 90 percent compared to the counterfactual scenario) in our preferred specification (column 6 of Table 2). Over the course of a year, this means that (summing over all districts) 571 MW of wind power capacity were not installed in Bavaria. Our results are robust to the estimation of standard errors with an ordinary wild bootstrap procedure instead of the clustering at the state level (cf. Table).

Event study

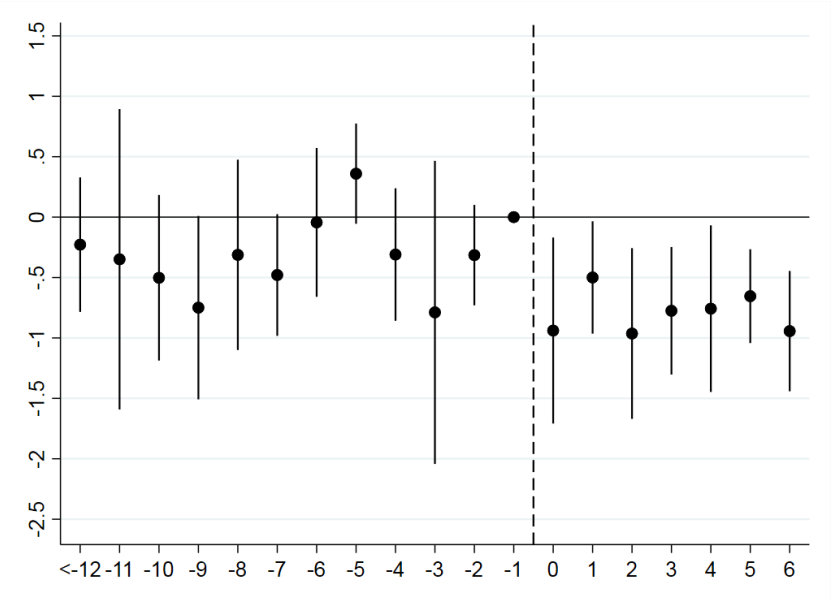
The main identifying assumption underlying the difference-in-differences model is that the number of permits granted in Bavaria and the rest of Germany follow a common trend. A visual inspection of Figure 4 supports this hypothesis. To provide additional support, we implement an event study approach given by

$$q_{i,t}^{Wind} = \sum_{j=-m}^{s} \delta_j D_{i,t+j} + \mu_i + \tau_t + \varepsilon_{i,t} \qquad (3)$$

where m "leads" and s "lags" of the treatment effect are included instead of the single treatment effect in (1).

Figure 5 provides strong evidence for the validity of the main identifying assumption, namely that Bavarian permits would have evolved similarly to the rest of Germany, had the minimum distance regulation not been introduced. The graph shows that there was no statistical difference between the trend of wind permits in Bavaria and the rest of Germany in any of the 12 months before the 10-H became effective. After the introduction of the 10-H regulation, on the other hand, all interactions of the treatment with time lags to the reform are statistically significant.

Figure 5: Event study approach



The figure plots coefficient estimates and 99% confidence intervals from an interaction of the reform with indicators on the time difference to the reform (in months). For Bavaria, only permits granted under an application of the minimum distance regulation are included in the regression. The dashed line marks the introduction of the reform in November 2014.

A battery of additional robustness checks to support the empirical results and the identification assumption is discussed in Appendix A.3.

5.2 Cost of wind power and renewables expansion targets

In addition to the impact on new capacity, a minimum distance regulation may also have a less salient but economically relevant impact on the technological parameters of new turbines. Specifically, the Bavarian 10-H regulation may lower the heights of new wind turbines since the minimum distance is relative to the total height of an installation. Project developers might deviate from the cost-minimizing best available technology and build smaller turbines to make land usable that would otherwise not be accessible for development. In this section, we show that, compared to the trend in the rest of Germany, such a decrease in technological parameters has occurred under the 10-H regulation. We also show that this effect has unintended implications for the levelized costs of electricity (LCOE) and the long-term expansion targets for onshore wind in Bavaria.

First, we run a regression for the effect of the Bavarian minimum distance regulation on the technological parameters – total height, hub height, rotor blade length, and rated power – of newly built turbines, using the same model employed in the previous section to identify causal effect of the Bavarian minimum distance regulation on wind power expansion (section 5.2.1). Second, we feed the results of the regression into the theoretical model of the energy yield of wind turbines discussed in section 3.2.1. This allows us to quantify the change in energy yield due to the 10-H regulation (section 5.2.2). Third, we quantify the difference in the LCOE between the observed and the counterfactual scenario based on the change in energy yield and change in costs for turbine projects (section 5.2.3). Fourth, we put the reduction in energy yield into context by quantifying the number of additional wind turbines needed in Bavaria to contribute a fair share to the 2030 renewable energy expansion targets for onshore wind in Germany (section 5.2.4).

5.2.1 Effect on technological parameters

We test for an effect of the Bavarian minimum distance regulation on the technological parameters of wind turbines using the same causal model as in the previous section, i.e. model (1). Table 3 presents the regression results of the effect of the regulation on the total height, hub height, rotor blade length, and rated power of new installations.[6] Common trend graphs displaying the development of the four technological parameters in Bavaria and in the rest of Germany are shown in appendix A.4.

Table 3: Effect of minimum distance regulation on the technological parameters of wind turbines in Bavaria

Dependent Variable:	Total height	Hub height	Rotor blade length	Rated power
Treatment: Minimum distance regulation	-6.587*** (1.149)	-5.411*** (0.836)	-1.173** (0.415)	-0.0609* (0.0300)
Observations	4,029	4,029	4,031	4,031
Month fixed effects	x	x	x	x

Values shown are the coefficients of fixed effects regressions at the district level from 2010 to Q2 2016, using the preferred specification with month fixed effects. Rated power is in MW, all other variables are in meters. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 3 shows that the 10-H rule not only reduced the expansion of wind power in Bavaria, but it also affected the technical parameters of those wind turbines that were still being built. The introduction of the 10-H rule led to a reduction of the total height of Bavarian wind turbines by around 6.6 meters compared to the counterfactual trend. This reduction in total height can be disaggregated into a 5.4 meters reduction in hub height and 1.2 meters shorter rotor blades. In contrast to the effects on the height of turbines, there is no strong evidence for a change in the rated power. The effect for rated power is statistically significant only at the ten percent level and insignificant when using year or quarter fixed effects.

With regard to hub height, it should be noted that hub heights in Bavaria are generally higher than in most other federal states (see appendix A.4) due to the lower wind speeds. This could lead to the assumption that a peak for hub heights was already reached in Bavaria before the introduction of the 10-H regulation. However, recent analysis shows that hub heights in other southern German states have still increased in the last years, and will continue to increase according to current technological forecasts (Deutsche WindGuard 2020).

5.2.2 Reduction in energy yield

Energy yield declined as a result of the changes in technical parameters induced by the Bavarian minimum distance regulation. The observed hub height of the average Bavarian wind turbine after the introduction of the 10-H regulation was 138,8 meters and the rotor blade length 58,3 meters.

[6] Table 3 shows the results of the preferred specification with month fixed effects. The other specifications with year and quarter fixed effects are qualitatively similar. Results are available from the authors on request.

Using this information and the regression results for hub height and rotor blade length from Table 3 in equation (2) shows that the relatively smaller turbine parameters induced by the 10-H regulation decreased the energy yield of Bavarian wind turbines by 5.4 percent. This total can be broken down to the two parameters of shorter rotor blades and lower hub height. The reduction in rotor blade length is the main driver of the effect lowering energy yield by about 3.9 percent. The lower hub height reduces energy yield by an additional 1.5 percent.

5.2.3 Levelized cost of electricity

Inserting the assumptions for the two scenarios into equation (4) results in estimated LCOE of about 6.11 ct/kW in the observed scenario (with 10-H) and 5.92 ct/kW in the counterfactual scenario (expected trend without 10-H).[7] This difference of about 0.19 ct/kW corresponds to a relative increase in LCOE of about 3.2 percent induced by the 10-H regulation.

Our results shows that the lower investment and operating costs associated with smaller turbines can only partially offset the financial impact of a lower energy yield induced by the introduction of the 10-H legislation. This means that the change in turbine technologies triggered by the regulation had an economically relevant negative effect on the costs of generating electricity from wind power.

Beyond the rise in LCOE, the change in turbine parameters may have further negative implications for the cost of integrating wind power into the electricity grid. Since the rated power of wind turbines was likely not affected by the regulation but energy yield was reduced, full load hours of new wind turbines were reduced relative to the counterfactual scenario. Lower full-load hours of wind turbines imply a higher volatility of electricity feed-in. Thus, a more flexible and extensive power system is needed to balance output this increased volatility, e.g. by installing more batteries, extending grids, or incentivising demand response (Hirth et al. 2015; Zerrahn et al. 2018). Hence, the 10-H regulation may not only affect the per-unit costs of an individual wind project, but also the electricity system costs by increasing the integration costs of wind energy.

5.2.4 Implications for expansion targets

Another implication of lower wind yields is that they also require the installation of a larger absolute number of wind turbines in order to meet deployment targets for onshore wind energy. Although the number of installations in Bavaria has sharply decreased in the short-term (see section 5.1), even more wind turbines would be needed in the long-term to generate the same amount of renewable electricity that could also be produced with fewer but larger turbines. This would counteract the hoped-for positive effects on acceptance of the minimum distance regulation, as large agglomerations of turbines, rather than their individual height, have been identified as a factor reducing the acceptance of wind power (see section 2.2).

To put this additional implication into context, we first quantify a fair share that Bavaria might contribute to the current renewable energy expansion targets for onshore wind in Germany. The latest version of the German Renewable Energy Sources Act (EEG) specifies 71 gigawatt (GW) as

[7] Based on the parameters described in section 3.2.2, I_0 amounts to 1,394 €/kW in the observed scenario and 1,434 €/kW in the counterfactual scenario. In line with the regression results, we keep the nominal power unchanged in the observed scenario and reduce the full load hours to 1,892, which corresponds to the estimated decrease in energy yield of 5.4 percent resulting from the reduced turbine size.

the expansion target for 2030 (EEG 2020). Due to the imbalance in onshore wind expansion between the northern and southern districts (cf. Figure 3) resulting from the better wind conditions in the north, the recent EEG introduced tender volumes reserved for the southern districts only. Of the total tender capacity of 31.3 GW until 2030, southern volumes amount to about 5.07 GW (i.e. 16 percent, EEG 2020). Almost all Bavarian districts are classified as southern districts in the EEG. Together, they account for about 54 percent of the land area of all southern districts specified (see Figure A-4 in appendix A.5). Assuming that the 5.07 GW southern volumes are to be deployed evenly across the land area, we arrive at an estimate of 2.74 GW as a fair share that Bavaria might reasonably contribute to the expansion of onshore wind until 2030.[8]

Given the decrease in wind turbine size induced by the 10-H regulation, 39 additional turbines or six percent of the overall number of turbines would need to be built in Bavaria to meet the 2.74 GW capacity expansion target based on the estimated fair share. Without the 10-H regulation, 684 turbines would need to be built, assuming 2,000 full load hours per turbine and an increase in average rated power of 4 MW per turbine over the next decade. If the assumed full load hours are adjusted downwards by the 5.4 percent drop in energy yield, the number of additional turbines required rises to 723.

Thus, strict minimum distance regulations like the 10-H regulation may lead to the unintended consequence of eroding public acceptance by increasing the total number of wind turbines built. By reducing the wind yield attained by an individual wind mill, more turbines must be built in order to generate a given amount of renewable electricity and reach renewables expansion targets. Minimum distance regulation may thus exacerbate persisting conflicts with distance requirements, zoning regulations, and alternative land-uses, ultimately decreasing public acceptance (Ladenburg and Dahlgaard 2012; Ladenburg et al. 2013; Ott and Keil 2017).

6 Discussion and conclusion

Strict minimum distance regulations between wind turbines and residential areas have been introduced and discussed for many regions and countries around the world, but their effects on the rate of new wind power projects have to date remain unassessed. Since no comprehensive dataset of wind power permits for Germany existed, research on minimum distances so far was limited to spatial modelling. We extend the field of research on minimum distances by evaluating the effects on the expansion of wind power, as well as potential unintended consequences related to a change of technical parameters of newly built wind turbines. We use a newly compiled dataset, comprising all permits granted to wind power installations that were installed between 2010 and 2018 in Germany. We provide causal evidence that the 10-H minimum distance regulation in Bavaria reduced the deployment of wind power by 62 (lower bound) to 90 percent (upper bound) compared to the expected trend.

Our paper also presents novel evidence on the less salient, yet economically relevant effect of minimum distance regulation on the technological parameters of wind turbines. Project developers built smaller turbines with shorter rotor blades to make use of the scarce land area. This translates

[8] For the few Bavarian districts that are classified as northern in the EEG and therefore have to participate in the regular tenders, we do not add any capacity in order to obtain a more conservative and realistic estimate.

to turbines in Bavaria generating about 5.4 percent less electricity than in the counterfactual trend. Since this decrease in energy yield is only partially offset by a simultaneous decrease in investment and operating costs, levelized costs of electricity increase by about 3.2 percent (0.19 ct/kWh).

Rising per-unit costs indicate that investors needed to deviate from their profit-maximizing strategy, which is generally associated with cost minimization (May 2017). With the additional constraints on available sites that depend on the height of the wind turbines, investors could no longer choose the cost-minimizing technology parameters and had to revert to smaller turbines. This effect may even amplify in the future if the trend towards larger turbines continues. This is because the change in energy yield develops non-linearly with greater hub heights and longer rotor blades. Yet, the proportional height provision makes further growth in turbine height increasingly difficult since the number of viable sites would be reduced even further.

From the perspective of the long-term expansion targets for renewable energies, lower energy yields also require a higher absolute number of turbines to achieve these targets. This might even reverse the originally intended effect of supporting public acceptance of wind power: While there is no evidence that larger separation distances elevate acceptance, agglomerations of wind turbines have been shown to decrease acceptance. Consequently, in the long term, the regulation could even reduce the acceptance of onshore wind power.

For policymakers, this research shows that minimum distance regulations not only reduce land available for wind power deployment, but may create perverse incentives for smaller wind turbines, leading to higher per-unit costs of generating electricity and an increased number of turbines needed to meet renewable expansion targets. While there is no evidence that stricter minimum distances have a significant effect on public acceptance of wind turbines, alternatives to increasingly strict minimum distance regulation exist. Direct payments to local municipalities or investment opportunities for residents that live close to the turbines, for example, address the externalities of wind turbines more directly, improving public acceptance by allowing the communities that are directly affected to participate in the value added of wind power generation. Denmark, as well as the German federal states of Mecklenburg Western Pomerania and Brandenburg have implemented such financial compensations (Stede and May 2019). Choice experiments and surveys from Germany, Norway and Switzerland suggest that annual payments to local municipalities are preferred to investment opportunities for individual residents and can help to increase acceptance for new wind turbines (García et al. 2016; FA Wind 2019; Vuichard et al. 2019).

For researchers, this paper has three implications. First, our new dataset on all permits issued for onshore wind power in Germany allows researchers to analyse the effects of various policies that address permission processes rather than installations. This includes, for example, the introduction of environmental regulation, or the opposition by local anti-wind power groups. Second, researchers could look at the introduction of mandatory separation distances in other countries such as Poland, in order to evaluate whether the results of this paper extend to other jurisdictions. Third, as the number of installations grows, ensuring public acceptance of onshore wind power becomes increasingly important. Therefore, regulatory frameworks are needed that facilitate acceptance without hampering the expansion of wind power. Towards this end, analysing the effects of local investment participation on public acceptance and deployment of wind power is an interesting venue for future research.

Appendix

A.1. Timing and legal treatment of the minimum distance regulation

Timeline of introduction. The 10-H regulation came into effect on November 21st, 2014. New permits granted for wind turbines after this date had to adhere to the distance regulation in principle. However, when project developers had filed for permits before February 4th, 2014, a permit could still be granted without considering the 10-H regulation if the decision on the permit was taken until the end of 2015. This also implied that filings that happened in between these dates could be evaluated differently according to the decision date: In case that the filings were still evaluated before November 21st, the old regulation was applied. If decisions were taken by the relevant authority after the cut-off date, the 10-H regulation applied.

Legal treatment. The 10-H regulation is widely discussed and understood as a minimum distance regulation. Legally, the regulation took away the prioritization of wind power in the buildings code. In Germany, wind power is prioritized outside of residential areas and municipalities assign specific areas for wind power deployment. The regulation removed this prioritization. However, individual counties could decide to keep the preferential treatment of wind power in their local planning processes. Permits granted under such exemptions, together with the permits for filings before February 4th, 2014, are reflected in the specifications shown in columns (1-3) in Table 2. These estimations rely on the assumption that even in the absence of the exemptions or had the filings been made only later, all permits would also have been granted under the strict application of the 10-H regulation. Thus, these estimates are a lower bound of the effect of the Bavarian minimum distance regulation.

A.2. Approximation of permit date

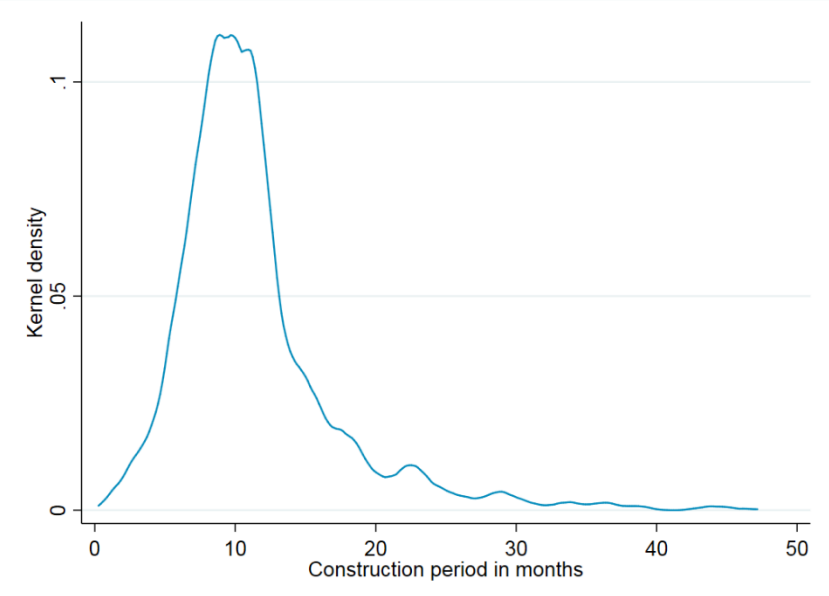
Table A-1 provides evidence that wind turbines with and without information on the date of the permit are very similar Within the periods from which we use the distributions to approximate the construction date (i.e. 2010-2014, 2015 and 2016), the two variables rated power and total height differ on average by 2.4 percent (rated power) and 0.8 percent (total height). Moreover, we show the overall distribution of the construction period in Figure A-1, illustrating that the average wind turbine takes one year to build. Figure A-1 also illustrates that the vast majority of wind power plants (more than 94 percent) are constructed within less than two years.

Table A-1: Comparison of wind turbines with and without information on the date of the building permit

	Turbines with information on the date of the permit			Turbines without information on the date of the permit		
	Rated power	Total height	N	Rated power	Total height	N
2010-2014	2.65	165	1,653	2.52	163	4,429
2010	2.12	138	209	2.23	150	649
2011	2.22	148	107	2.38	155	860
2012	2.81	170	109	2.55	162	1,009
2013	2.73	164	307	2.66	167	1,182
2014	2.77	172	921	2.68	175	729
2015	2.81	182	814	2.81	182	590
2016	3.03	183	1,902	2.96	185	631

The table displays average rated power (in megawatt) and average total height (in meters) by the year in which the building permits were granted.

Figure A-1: Distribution of construction periods of wind turbines in Germany



The graph depicts the Kernel density of the construction period of German wind turbines in the years 2010-2017 according to the *Anlagenregister*. The construction period is defined as the number of months elapsed between the issuance of the building permit of a wind turbine and the completion of its construction.

A.3. Robustness checks for the regression results on the deployment of wind power

In this section, we provide a battery of robustness checks, demonstrating that the main results shown in Table 2 of section 5.1 hold. This includes bootstrapped standard errors, possible anticipatory effects, placebo regressions for the neighbouring states of Bavaria, a demonstration that our results would hold even in the case of strong spillover effects, and re-estimating the parameters of Table 2 based on a subset of those plants where we do have information on the construction date from the *Anlagenregister*.

Bootstrap standard errors

Our results are robust to the estimation of standard errors with an ordinary wild bootstrap procedure instead of the clustering at the state level. In general, since the treatment (the minimum distance regulation) is assigned at the federal state level, standard errors need to be clustered at the state level (Abadie et al. 2017). However, as Germany consists of 16 states, there are only few clusters, which means the standard errors may be wrong (Cameron and Miller 2015). One solution to this is cluster bootstrapping, such as the wild cluster bootstrap. In the case of a small number of treated clusters, however, the wild cluster bootstrap often over-rejects or under-rejects severely (MacKinnon and Webb 2017). Thus, we compute p values for the models estimated in Table 2 based on the ordinary wild bootstrap (MacKinnon and Webb 2018). The statistical level of significance remains at the one percent level for the preferred specification including all Bavarian wind turbines (column 3 of Table A-2). In the preferred specification with only Bavarian wind turbines that received permits under the 10-H regime, the level of significance of the ordinary wild bootstrap is even higher (0.1% level, column 3 of Table A-2).

Table A-2: Bootstrap standard errors

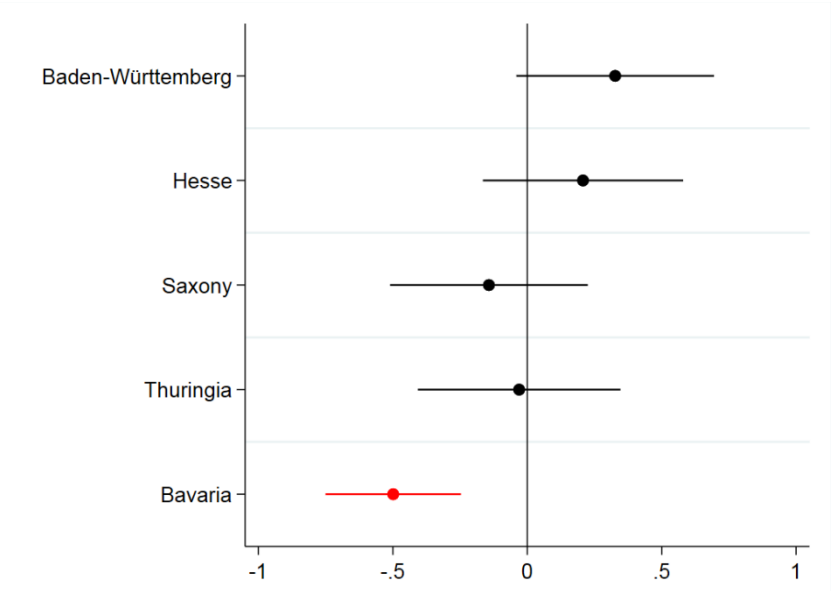
Dependent Variable:	All permits			Permits under minimum distance regulation		
Specification:	(1)	(2)	(3)	(4)	(5)	(6)
Treatment: Minimum distance regulation	-0.316	-0.326	-0.343	-0.468	-0.477	-0.499
p value – state cluster	0.0014	0.0013	0.0011	0.0000	0.0000	0.0000
p value – ordinary wild bootstrap	0.0080	0.0180	0.0030	0.0000	0.0010	0.0010
Observations	31,278	31,278	31,278	31,278	31,278	31,278
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

Values shown are the coefficients and p values of fixed effects regressions of monthly construction permits in megawatt at the district level from 2010 to Q2 2016. P values are clustered at the state level and computed with the ordinary wild bootstrap, respectively. The ordinary wild bootstrap uses 999 replications and Rademacher weights.

Testing for effects in neighbouring states

Identifying an effect in Bavaria that is caused by the minimum distance regulation is possible only if there were no parallel confounding effects on (parts of) the control group. One such confounder could be changes in renewable energy regulation, such as the change in the German support regime for onshore wind power in August 2014. This change might have disproportionally disadvantaged regions with mediocre wind conditions like Bavaria and its neighbouring states. To rule out this possibility, we conduct placebo regressions, assessing whether we find a similar "placebo" effect also in Bavaria's neighbour states. Figure 2 visualises the regression results. The regression coefficients are statistically insignificant for all of the neighbouring states. This demonstrates that the change in the number of permits in Bavaria was caused by the introduction of the minimum distance regulation and not by random changes over time that affect states with mediocre wind resources similarly. In other words, no general economic or policy shock that affected the other southern states can explain the observed effect in Bavaria. Moreover, the identified Bavarian coefficient is particularly large when considering that the state is divided into relatively many districts, such that individual districts are small (cf. Table 1).

Figure 2: Placebo regressions for neighbouring states of Bavaria



The figure compares the coefficients of placebo regressions for the neighbouring states of Bavaria to the baseline specification (Table 2, column 6), with standard errors at the 99% significance level.

Anticipatory effects

Investors into wind energy might have foreseen the introduction of the 10-H regulation and implemented some of their initiated projects already beforehand. In such a case, the baseline (i.e. installations in Bavaria before the introduction of the regulation) would be artificially high. Such a case also implies that the number of installations would drop to an artificially low level after the introduction. If wind energy investors reacted to the introduction of the minimum distance regulation by increasingly filing for building permits before the new regulation became effective, such anticipatory behaviour would confound our estimates.

In order to exclude this possibility, we re-estimate model (1) and its variants, taking into account potential anticipation effects by excluding observations within ±6 months and ±12 months of the introduction of the minimum distance regulation. Table A-3 and Table A-4 show that the estimated relative treatment effect of the separation distances on permits in these specifications is almost identical to the main results in Table 2, and the point estimates remain highly statistically significant. In our preferred specifications with only Bavarian wind turbines that received permits under the 10-H regulation (column 6 of Table A-3 and Table A-4), the relative effect size is virtually unchanged compared to Table 2. In the specification including all Bavarian wind turbines, the effect is even larger, rising to around 70 percent in the robustness checks (column 3 of Table A-3 and Table A-4). This shows that our results are robust to possible anticipation effects.

Table A-3: Effect of minimum distances on permits, excluding six months window

Dependent Variable:	All permits			Permits under minimum distance regulation		
Specification:	(1)	(2)	(3)	(4)	(5)	(6)
Treatment: Minimum distance regulation	-0.378*** (0.119)	-0.378*** (0.119)	-0.378*** (0.119)	-0.482*** (0.119)	-0.482*** (0.119)	-0.482*** (0.119)
Change [%]	-71	-71	-71	-90	-90	-90
Observations	26,466	26,466	26,466	26,466	26,466	26,466
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

Values shown are the coefficients of fixed effects regressions of monthly construction permits in megawatt at the district level from 2010 to Q2 2016, excluding observations within a window of six months before and after the introduction of the 10-H regulation. The percentage decrease of building permits in Bavaria relative to the counterfactual is also tabulated. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Table A-4: Effect of minimum distances on permits, excluding twelve months window

Dependent Variable:	All permits			Permits under minimum distance regulation		
Specification:	(1)	(2)	(3)	(4)	(5)	(6)
Treatment: Minimum distance regulation	-0.419*** (0.0958)	-0.419*** (0.0958)	-0.419*** (0.0959)	-0.515*** (0.0958)	-0.515*** (0.0958)	-0.515*** (0.0959)
Change [%]	-71	-71	-71	-88	-88	-88
Observations	21,654	21,654	21,654	21,654	21,654	21,654
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

Values shown are the coefficients of fixed effects regressions of monthly construction permits in megawatt at the district level from 2010 to Q2 2016, excluding observations within a window of 12 months before and after the introduction of the 10-H regulation. The percentage decrease of building permits in Bavaria relative to the counterfactual is also tabulated. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Spillover effects

It is conceivable that at least some of the wind projects that were not realised in Bavaria moved to other parts of Germany, since project developers chose to relocate their investment. Such potential spillover effects could confound our results, since we compare the developments in Bavaria to the rest of the country. Formally, our identification relies on the Stable Unit Treatment Value Assumption (SUTVA), which implies there are no spillovers to the rest of Germany because of the introduction of minimum distances in Bavaria. To test the implications of a violation of this assumption, we re-estimate our regression specifications from Table 2 under the assumption that all wind turbines that were not built in Bavaria were immediately constructed elsewhere in the country.

Even under this extreme assumption, the relative reduction of wind permits due to the minimum distance regulation remains virtually unchanged. In other words, our findings are qualitatively robust to spillover effects. We implement the estimation of this alternative sectorial by reducing the wind permits of all other German states by the amount of permits not issued in Bavaria because of the minimum distance regulation, and re-estimating the models of Table 2 based on these reduced permits. As can be seen from Table A-5, the point estimates of the treatment effect decrease in this scenario relative to the main specifications in Table 2. However, the relative reduction of construction permits in Bavaria remains virtually unchanged (-88 percent in the preferred specification). The reason is that the counterfactual development of Bavarian permits decreases when permits in the rest of Germany are assumed to be lower.

Table A-5: Effect of minimum distances on permits, correcting for possible spillover effects

Dependent Variable:	All permits			Permits under minimum distance regulation		
Specification:	(1)	(2)	(3)	(4)	(5)	(6)
Treatment: Minimum distance regulation	-0.222** (0.0799)	-0.229** (0.0813)	-0.235** (0.0833)	-0.328*** (0.0805)	-0.332*** (0.0819)	-0.342*** (0.0834)
Change [%]	-50	-51	-52	-84	-85	-88
Observations	31,278	31,278	31,278	31,278	31,278	31,278
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

Values shown are the coefficients of fixed effects regressions of monthly construction permits in megawatt at the district level from 2010 to Q2 2016. The regressions correct for a hypothetical full spillover, under the extreme assumption that all wind turbines not built in Bavaria were directly built elsewhere in Germany. To implement this, permit data in non-Bavarian districts are reduced by the difference between predicted permits (according to the common trend assumption) and actual permits in Bavaria. The percentage decrease of building permits in Bavaria relative to the counterfactual is also tabulated. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Regressions without approximation of permit date

Our results are also robust to the approximation procedure of the construction periods. To show this, we re-estimate the models shown in Table 2 based on the subset of those plants where we do have information on the construction date from the *Anlagenregister*. The estimated effects of the minimum distance regulations are even stronger in this specification: With this subset of installations, it rises to -78 percent (all permits), and -94 percent (10-H permits only, see columns 3 and 6 of Table A-6). We therefore rule out that the approximation of permit dates from their construction dates for some of the wind turbines confounds our estimates.

Table A-6: Effect of minimum distances on permits, using only turbine data with full information on the construction permit date

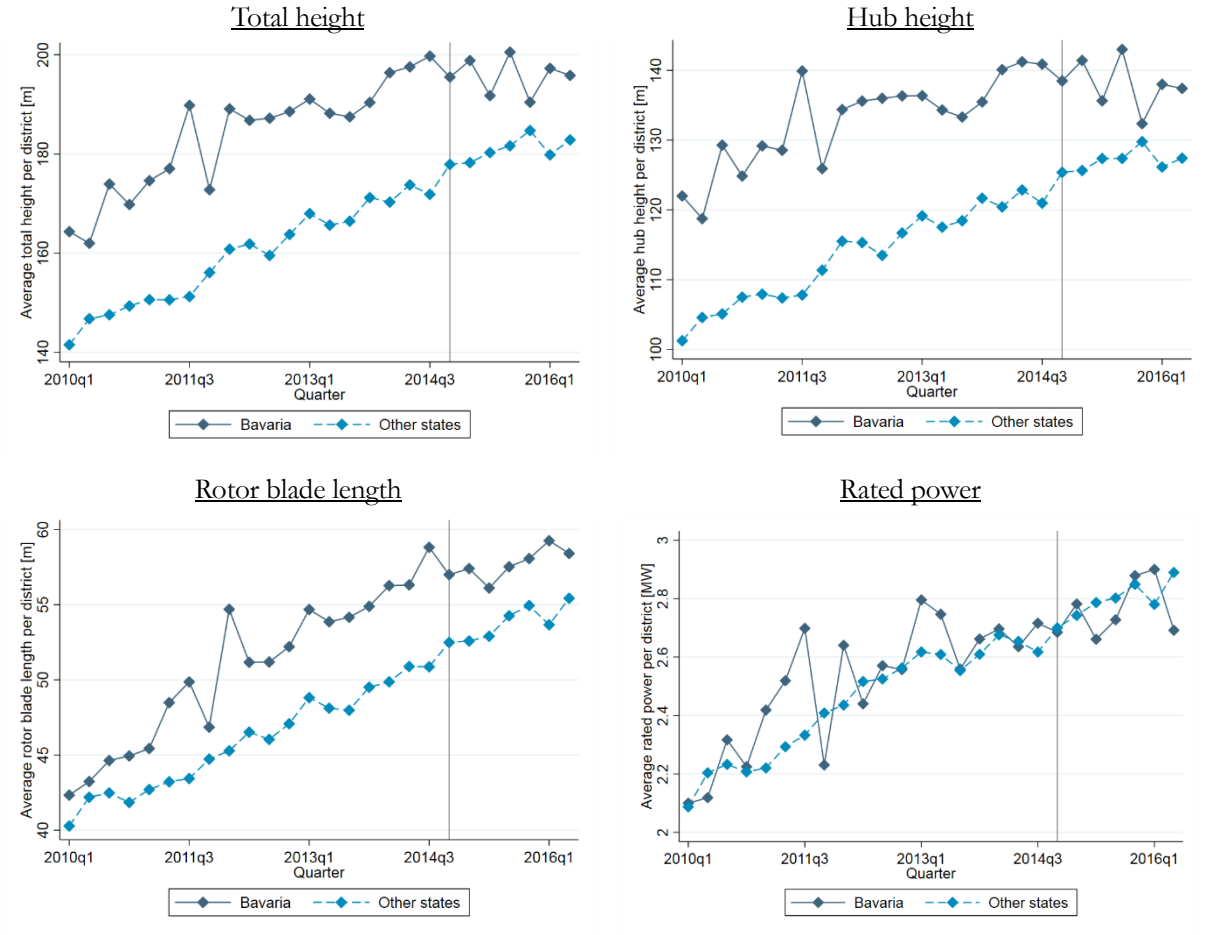
Dependent Variable:	All permits			Permits under minimum distance regulation		
Specification:	(1)	(2)	(3)	(4)	(5)	(6)
Treatment: Minimum distance regulation	-0.572*** (0.0894)	-0.588*** (0.0912)	-0.647*** (0.106)	-0.701*** (0.0894)	-0.715*** (0.0909)	-0.781*** (0.106)
Change [%]	-69	-71	-78	-84	-86	-94
Observations	31,278	31,278	31,278	31,278	31,278	31,278
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

For this table, we re-estimate the treatment effects of Table 2, using only wind turbine from the *Anlagenregister* that have information on the date of the building permit of the wind turbine. We thus discard all observations with an approximated permit date. Values shown are the coefficients of fixed effects regressions of monthly construction permits in megawatt at the district level. The percentage decrease of building permits in Bavaria relative to the counterfactual is also tabulated. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

A.4. Common trends technological parameters

Figure A-3 depicts the development of the technological parameters total height, hub height, rotor blade length at the district level. The graphs show that the trends in Bavaria and the rest of Germany are similar pre-treatment. The Bavarian time trend is noisy due to the low number of districts in Bavaria where wind turbines are built, translating into a low number of observations (cf. Figure 3).

Figure A-3: Development of the technological parameters in Bavaria and the rest of Germany

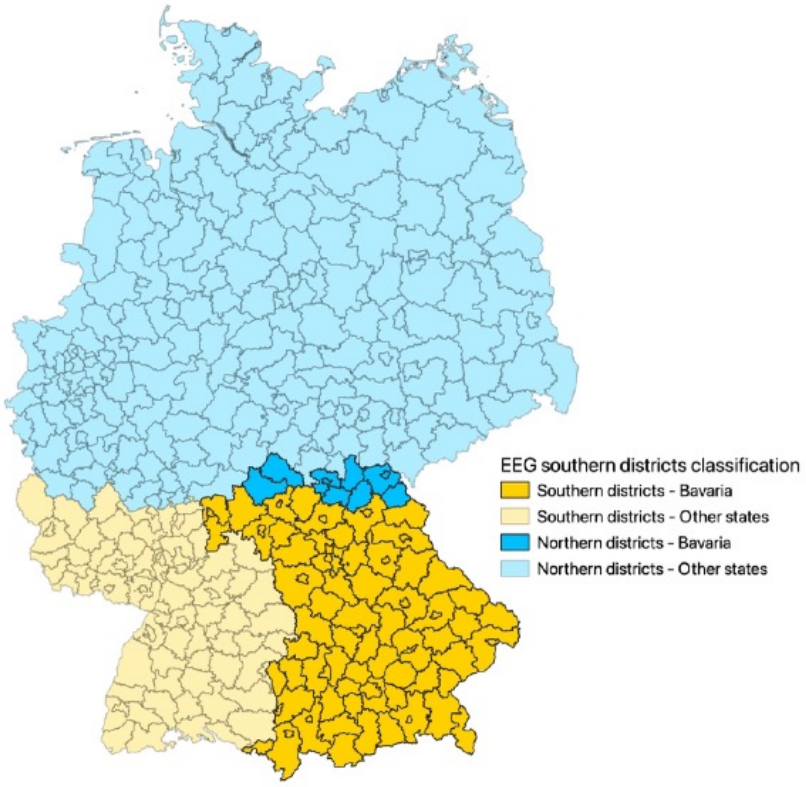


The graphs show the average technological parameters of wind turbines at the district level in Bavaria and Germany. Rated power is in MW, all other variables are in meters. q1 denotes the first quarter for a given year.

A.5. Classification of southern districts according to EEG

Figure A-4 depicts the division of the EEG districts in Germany into northern and southern districts for the purpose of targeted capacity allocation in onshore wind tenders to the southern regions beginning in 2022. The graph shows that almost all Bavarian districts are classified as southern districts (dark yellow) and that they account for about 54 percent of the land area of all southern districts (dark yellow and light yellow combined).

Figure A-4: Classification of southern districts according to EEG



The graph depicts the classification of southern districts according to the EEG for the purpose of targeted allocation to the southern districts in onshore wind tenders starting in 2022. Southern districts are marked in yellow, northern districts in blue. The Bavarian districts as respective subsets are marked as less transparent.

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