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

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Public acceptance of onshore wind power becomes a more pressing issue as the number of wind turbines increases around the world. Several regions have introduced mandatory minimum distances of wind turbines to nearby residential areas in order to increase acceptance. Germany's largest federal state, Bavaria, introduced such minimum distances of ten times the height of newly installed wind turbines in 2014. However, such regulation reduces the land available for onshore wind turbines. Here, we provide a novel monthly district-level dataset of construction permits for wind turbines constructed in Germany between 2010 and 2018. We use this dataset to evaluate the causal effect of the introducing the Bavarian minimum distance regulation on the issuance of construction permits for wind turbines. We find that permits decreased by up to 90 per cent.

Keywords: Onshore wind, separation distance, energy transition, acceptance, panel data, difference-in-differences, causal inference, event study
JEL codes: C21, Q42, R14, R15

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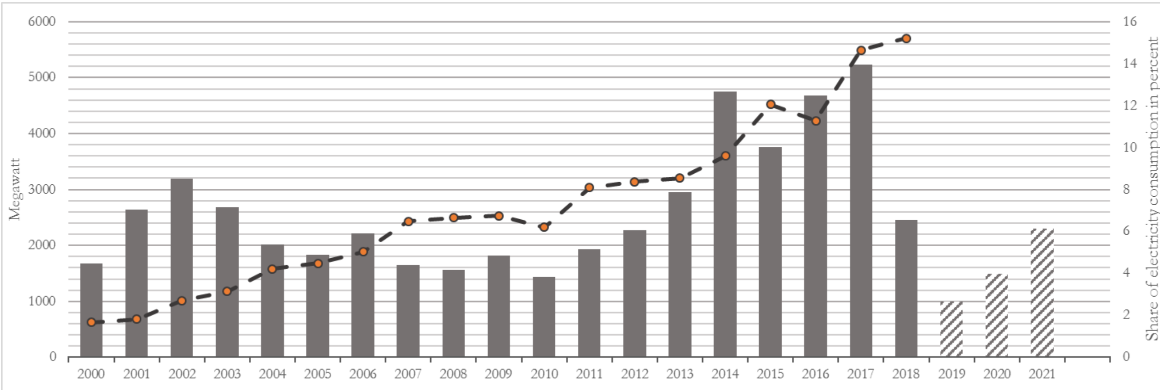
Introduction

Energy transitions worldwide rely on large amounts of electricity from renewable energy sources to reduce emissions.[1,2] Renewable energies are needed to replace conventional power plants, as well as to power the decarbonisation in other sectors like transport and industry. Consequently, the International Energy Agency expects global electricity demand to grow by more than 2.6 per cent annually until 2040.[3]

Wind power is a cornerstone of energy transitions in many countries. Onshore wind power generates electricity at relatively low cost due to learning of technology and financing[4], as falling auction bids indicate.[5] In Germany, the share of electricity demand covered by onshore wind has increased steadily in the last two decades (Figure 1). Since the introduction of the German renewables support scheme in 2000, it has risen from less than two per cent to more than fifteen per cent in 2018.[6] While new installations peaked between 2014 and 2017, newly added capacity has plummeted since and is projected to remain low. One of the reasons for this decline is a high number of wind projects that cannot be built since the construction permit is being contested in court.[7]

Figure 1: Wind power in Germany



The figure plots the annual onshore wind power additions in Germany (bars, left axis), as well as the respective share of onshore wind power of electricity consumption (dotted line, right axis), based on data from Betreiber-Datenbasis and the German Federal Ministry for Economic Affairs and Energy.

There is some evidence that opposition against the deployment of wind power has increased in countries where social acceptance has traditionally been very high.[8] In general, onshore wind power requires land and has negative externalities on local residents.[9] Opposition by residents against new projects may prolong permission processes or prevent installations altogether. Consequently, securing local acceptance of wind turbines is crucial for the deployment of wind power.[10]

Mandatory separation distances between wind turbines and residential areas reduce the land area available for new deployment. However, proponents argue that these policies facilitate future growth by increasing acceptance of wind power.[11] In recent years, minimum distance regulation has become more popular: Poland, Scotland (in the shape of "recommended separation distances") and the German federal state of Bavaria introduced separation distances in 2016 and 2014, respectively. Moreover, the German *Climate Action Programme 2030* includes the intention to introduce such regulation nationally.

While the effects of minimum distance regulation on available land have been assessed before, the actual net effect on new projects is unclear. Research on this question is hampered by a lack of suitable data. The separation distances in Bavaria, for example, directly affect construction permits for wind power plants. New installations of wind turbines (on which data is readily available), on the other hand, are only affected indirectly. Thus far, there is no comprehensive dataset on building permits for German wind power plants.

We address this gap by evaluating the effect of the minimum distance regulation in Bavaria on the issuance of permits for wind power projects. We do so by creating a new dataset that comprises information on all permits for wind turbines that are eventually installed. We combine three distinct datasets and apply statistical inference to identify location, permit date and capacity for all wind turbines installed in Germany between 2010 and 2018. The results are presented in three steps: First, we introduce our new dataset and information on the federal minimum distance regulation. Second, we identify the causal effect of the regulation on new permits by comparing developments in the federal state of Bavaria to the rest of Germany. Third, we show how our results relate to federal separation distances, and discuss in how far minimum distance regulation achieves the goal of increasing socio-political acceptance of onshore wind expansion.

Permits for wind power

As a first step, we create a new dataset containing information on all wind turbines installed between 2010 and 2018 in Germany (see Methods for a detailed description). The *Betreiber-Datenbasis*, a private database, contains information on the date of construction for all wind turbines installed in Germany in the period 2010-2018. From the *Anlagenregister*, a public register of renewable energy installations, we retrieve information on construction permit dates for some of these wind turbines. We merge these existing permit dates with the information from the *Betreiber-Datenbasis*. This results in a dataset with installation data and technical parameters for all wind turbines, and permit dates for a subset of these installations. Based on known construction dates, we then derive permit dates for remaining installations by drawing from the distribution of construction times. Lastly, we aggregate the turbine-specific information on the district level for every month.

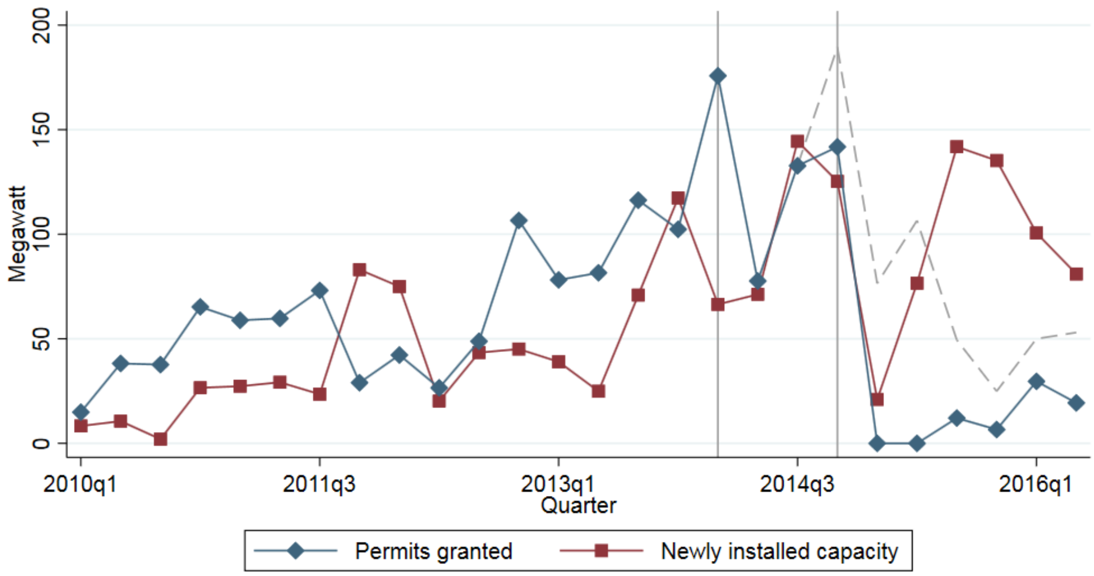
We therefore provide a unique dataset on permitted capacity in every district in Germany for turbines installed between 2010 and 2018. These data can be used to assess the effect of different policies on construction permits for wind turbines in Germany. In this paper, we evaluate the causal effect of the Bavarian separation distance on the issuance of wind permits.

Minimum distance regulation in Bavaria

The Bavarian minimum distance regulation ("10 H" regulation) applies to new building permits for wind turbines. The regulation became effective in November 2014 (see Supplementary Note 1). Subsequently, new permits were only granted for installations that have a ten-fold distance to residential areas (see Supplementary Note 1 for details regarding the German system of preferential land use for wind power). In practice, this translates into a distance of almost 2,000 meters (see Supplementary Table 1 and Supplementary Discussion). However, exemptions to the tenfold separation distance exist. First, permits can be issued without enforcing the regulation when they had been filed prior to 4 February 2014. Alternatively, local administrations 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. We retrieve this information from official responses by the Bavarian Federal Ministry of Economic Affairs to parliamentary inquiries and merge it with our permit dataset.

Figure 2 illustrates the advantage of our new permit dataset by showing how an analysis based on newly installed wind turbines would be biased. Bavarian construction permits, which are directly affected by the separation distances, declined sharply after November 2014. On the other hand, following a short decline, new installations of wind turbines actually *increased* after the introduction of mandatory separation distances. Consequently, an analysis of the minimum distance regulation based on installation data would underestimate the effect of the policy.

Figure 2: Development of permits and newly installed wind power capacity in Bavaria

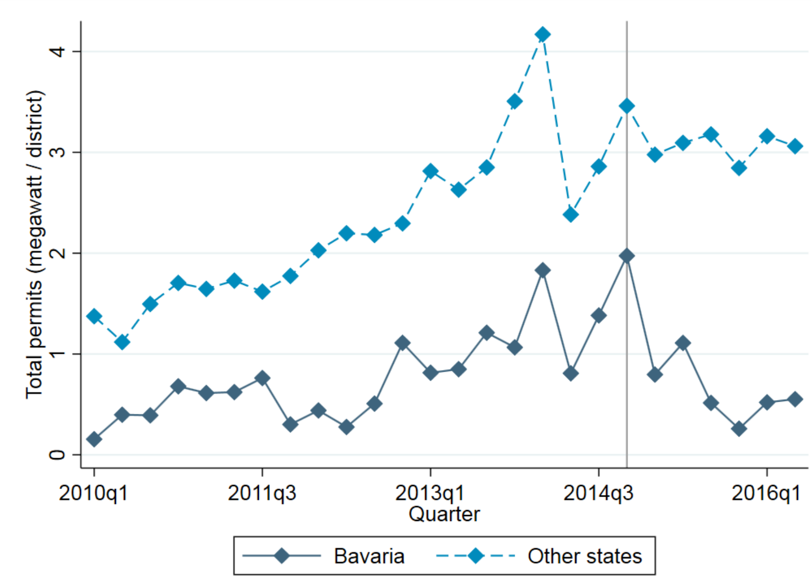


The figure shows the quarterly new construction permits and installations of wind power in Bavaria, as well as the cut-off dates of the introduction of the minimum distance regulation. Permits include either the total number of permits (dashed line), or the permits under an application of the Bavarian minimum distance regulation only (solid line). The left vertical line marks the cut-off date to file for new permits that are not subject to strict separation distances 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.

Effect on wind power expansion

As Figure 3 illustrates, the number of construction permits issued in Bavaria and the rest of Germany between 2010 and mid-2014 followed a common trend. The lower level of permits per district in Bavaria results from the smaller district areas relative to districts in the rest of Germany (see Supplementary Table 1 and Supplementary Discussion). Moreover, average wind speeds are in Bavaria than in Northern and parts of Central Germany.[12] However, while the issuance of permits remained stable in Germany after November 2014, their number dropped strongly in Bavaria in the same period. This divergence is even more pronounced when focusing on the permits that were actually granted under the new minimum distances (solid line in Figure 3).

Figure 3: Wind power permits in Bavaria and the rest of Germany



The graph shows the total number of permits for wind turbines (in megawatt) issued quarterly in an average district. Permits in Bavaria include either 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.

We use a difference-in-differences model to identify the causal effect of the Bavarian separation distances on permits for new wind turbines (see Methods). We find that the Bavarian regulation drastically reduced the number of construction permits. The regression results are presented in Table 1. All coefficients are highly statistically significant. Columns 3 and 6 correspond to the baseline specification (1) discussed in the Methods section. 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 and annual effects.

In columns 1-3 of Table 1, we estimate conservative models of the minimum distance effect. Here, we assume that all permits granted under exceptions from the Bavarian 10 H regulation would also have been granted had the strict separation distances been applied. Under this strong assumption, the new mandatory separation distances reduced permits by around 0.34 megawatt (MW) per month per district, i.e. around 396 MW per year in Bavaria. This amounts to a reduction of the number of permits issued in Bavaria by 62 per cent because of the introduction of strict minimum distances (column 3 of Table 1).

The strong assumption that permits granted under an exemption from the minimum distance regulation would have also been issued had the regulation been applied underestimates the true effect of the Bavarian minimum distances. The separation 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 rules.

Consequently, in columns 3-6 of Table 1 we re-estimate our models under the more realistic assumption that projects granted a permit without applying the 10 H rule would *not* have received a permit had the 10 H rules been enforced. In other words, we use only Bavarian wind turbines that did receive the permit under the new regulation after November 2014 in our estimation. Here, permits in Bavaria dropped by almost 0.5 MW per district per month, or 90 per cent (column 6 of Table 1). Over the course of a year, this means that 571 MW of wind power capacity were not installed in Bavaria.

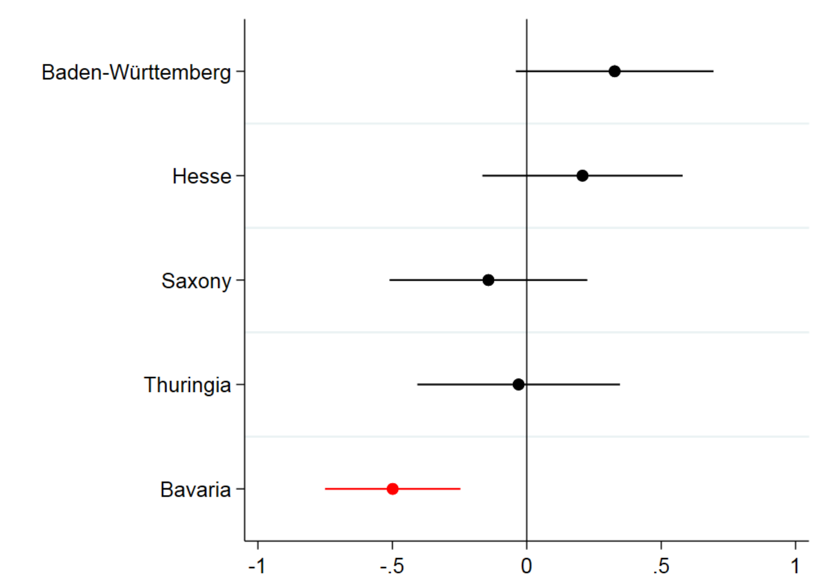
Table 1: Effect of minimum distances on wind construction permits in Bavaria

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
R^2 (within-plant)	0.007	0.008	0.010	0.007	0.008	0.010
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. The percentage decrease of wind turbine permits in Bavaria relative to the counterfactual building permits is also tabulated. All specifications include district fixed effects. Standard errors clustered at the state level are in parentheses. All coefficients remain statistically significant when ordinary wild bootstrap standard errors are used (see Supplementary Discussion). Significance: * $p<0.1$, ** $p<0.05$, *** $p<0.01$.

Next, we run placebo regressions for all the four neighbouring states of Bavaria to demonstrate that our strong results can be attributed to the introduction of the separation distances. These regressions serve to rule out a general shock to wind expansion that also affected those southern German states, which have similarly mediocre wind speeds as Bavaria. Figure 4 visualises the regression results. The regression coefficients are statistically insignificant for all of the neighbouring states. This means that no general economic or policy shock that similarly 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. Supplementary Table 1).

Figure 4: Placebo regressions for neighbouring states of Bavaria



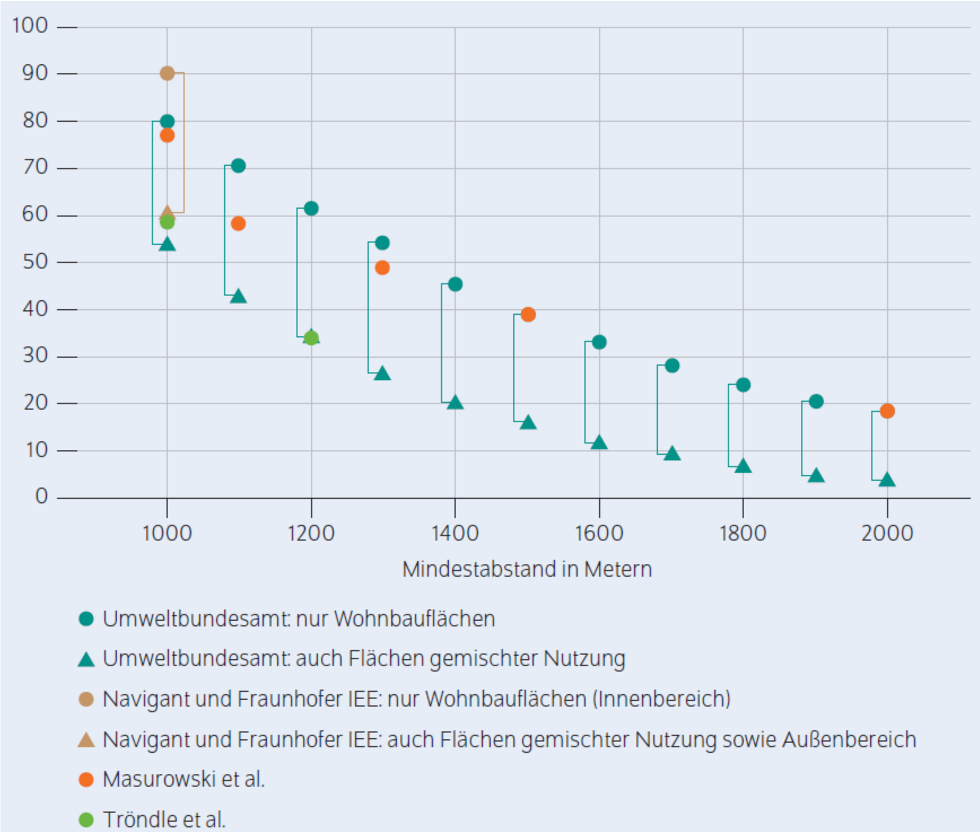
The figure compares the coefficients of placebo regressions for the neighbouring states of Bavaria to the baseline specification (Table 1, column 6), with standard errors at the 99% significance level.

Our results are robust to a whole range of further robustness checks (for details see Methods and Supplementary Discussion). For example, we take into account potential anticipation effect of ±6 months and ±12 months, which confirms the findings of the baseline specification (see Supplementary Tables 3 and 4). An event study approach substantiates the common trend assumption pre-treatment, i.e. that the number of new permits in Bavaria and the rest of Germany co-moved before November 2014 (Supplementary Figure 2). We also rule out that the approximation of permit dates from their construction dates for some of the wind turbines confounds our estimates by reproducing our results using only installations where we have information on both dates. The estimated effects of the minimum distance regulations are even stronger in this specification (see Supplementary Table 6).

Effects on available land

Our main finding of strong negative effects on new permits is in line with model-based estimates of the effect of minimum distances on the land available for wind power. Taking into account the pre-existing regulation, introducing a minimum distance of 1000 meters reduces the land area by 10 to 47 per cent in Germany (see Figure 5). This reduction increases to 81 to 96 per cent for a distance of 2000 meters. Moreover, the impact of minimum distances on available land varies considerably with the definition of the type of residential areas for which the separation distance holds.[13] Minimum distances towards individual housing reduce available land considerably more than distances only to larger settlements. For example, a strict definition of a minimum distance of 1000 meters can have effects similar to a less strict definition of 1300 meters (Figure 5). Hence, when analysing the effects of minimum distance regulation, it is crucial to specify the reference to which the distance applies.

Figure 5: Effect of minimum distance regulation on energy potential and land available for wind turbines in Germany



The figure [to be translated in English] displays the remaining share of land dedicated to the construction of wind turbines in regional plans in Germany[13,14], as well as the remaining energy potential[15,16], as a function of different minimum distances.

The Bavarian 10 H regulation applies to distances towards medium-sized residential areas, such that the regulation falls roughly into the middle of the GIS-based assessments of the land effects depicted in Figure 5. In our preferred specification, we estimate an effect of the Bavarian separation distances of minus 90 per cent, which is well in line with the range of land reductions that would be expected (see Figure 5). This suggests that reduction of available land can translate directly into reductions of construction permits in a similar order of magnitude. This casts doubt on the hypothesis that separation distances may support the expansion of wind power by increasing public acceptance.

Policies to support public acceptance of wind power

In light of the massive extension plans for onshore wind power in many countries, maintaining and supporting local acceptance of wind power deployment is an important policy goal. However, the academic literature on public acceptance does not support the hypothesis of a significant uptake of public acceptance due to increased separation distances. On the one hand, wind turbines have been shown to exert negative externalities locally, for example on well-being of local residents.[9] Large accumulations of wind turbines affect acceptance negatively.[17–19] On the other hand, the often-touted not-in-my-backyard (NIMBY) theory has been abandoned by the academic literature for a lack of explanatory power.[20,21] In addition, there is no evidence that an increasing proximity to wind turbines exacerbates the negative external effects of wind turbines.[9,22–25] Negative effects are transitory:

negative effects on life satisfaction do not differ under 4000 m proximity and disappear five years after installation.[9]

One explanation for this paradox is that in many countries residents are already protected from noise, shadowing and visual impairment of wind turbines. In Germany, federal law mandates that project developers need to prove on a case-by-case basis that the effect of noise and other disturbances is limited.[26] Consequently, increasing the (implicit) legal separation distances may not improve acceptance significantly. 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 minimum distance regulation.[27]

Procedural and distributional fairness are important determinants for public acceptance of renewables. Regarding onshore wind power, one obstacle is that the economic benefits mostly accrue where manufacturers, project developers and related companies are based, rather than where the turbines are located.[28] One solution is to address this issue by financially compensating local residents or communities. Denmark and the German state of Mecklenburg Western Pomerania have implemented investment opportunities for residents, whose homes are located very close to the turbines. The German federal state of Brandenburg, on the other hand, has recently introduced annual payments to local municipalities. 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 increase acceptance more strongly.[29,30]

Conclusion

Minimum distance regulation for wind turbines have been introduced and discussed for many regions and countries around the world, but the effects have not been assessed comprehensively. Since no comprehensive dataset of wind power permits for Germany existed, existing research on separation distances was limited to descriptive analyses. We address this issue by providing a newly compiled dataset, comprising all permits granted to wind power installations that were installed between 2010 and 2018. We use these data to provide causal evidence that minimum distance regulation in the federal state of Bavaria reduced the deployment of wind power by up to 90 per cent in the years 2015 and 2016. This indicates that the reduction in available land areas, identified in previous studies, can translate into reductions in new installations of similar orders of magnitude.

For policymakers, this research shows that separation distances not only reduce land available for wind power deployment, but may translate into drastic reductions of new installations. Possible local exemptions from the regulation were not able to reverse this reduction in the case of Bavaria. There is also no evidence that tighter separation distances have a significant effect on public acceptance of wind turbines. Direct payments to local municipalities, on the other hand, address the externalities of wind turbines more directly. Such a financial compensation improves public acceptance by allowing the communities that are directly affected to participate in the value added of wind power generation.

For researchers, this paper has three implications. First, our new dataset on all permits issues 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 can look at the introduction of mandatory separation distances in other countries such as Scotland (2010) and Poland (2016), 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.

Methods

In this section, we discuss the process of compiling the dataset, the identification strategy of estimating the effect of the minimum distance policy on construction permits for wind turbines, as well as robustness checks.

Creation of new wind permit dataset. We create a unique district-level dataset containing monthly permits (in megawatt) of wind turbines constructed in Germany between 2010 and 2018. The permit dataset builds on a combination of three different data sources. First, the backbone of our analyses is the *Betreiber-Datenbasis*, in which German wind power plants have been collected since 1988. The *Betreiber-Datenbasis* contains information on the installation date of wind turbines and their location, as well as technical parameters like capacity, height and rotor blade lengths. It consists of 10,993 plants constructed between 2010 and 2018, with an average power of 2.7 megawatt (MW). The data quality is very good: Aggregate figures on yearly wind expansion match almost perfectly with official data published by the German Ministry of Economic Affairs and Energy.

The *Betreiber-Datenbasis*, however, does not contain information on the permit dates of the single plants. We retrieve this information from the publicly accessible *Anlagenregister*, the official database where all renewable energy installations had to be registered between August 2014 and 2019. However, despite its official nature, the *Anlagenregister* does not contain all wind turbines constructed in Germany. In both 2013 and 2014, shortly before the Bavarian separation distances (the 10 H regulation) were implemented, around 40 per cent 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*, complemented by information on permit dates from the *Anlagenregister*.

We merge *Anlagenregister* and *Betreiber-Datenbasis* based on an exact match of the variables month-year of the construction of the wind turbine, its power, as well as the zip code. 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 per cent of the *Anlagenregister*'s wind turbines with information on the permit date to the *Betreiber-Datenbasis*.

Third, not all permits granted after November 2014 were subject to the 10 H rule, since the law introduced some exceptions (see Supplementary Note 1). We identify those permits that did comply with the new regulation by using a range of official documents published by the government of the state of Bavaria 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.

Approximation of construction times. After merging the two databases *Betreiber-Datenbasis* and *Anlagenregister*, there are some plants where we do have precise information on the date of construction, but not on the date of the permits. For these installations, we approximate the permit date by subtracting typical construction periods from the 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 with an average of twelve months (see Supplementary Figure 1). 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. 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 each of those individual years. Since almost 99 per cent of all wind turbines built between 2011 and 2017 in Germany have a construction date below four years, we restrict the distributions from which we draw to 48 months in order to exclude extreme (possibly erroneous) observations. Lastly, we aggregate the installation data for every German county by 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 per cent (power) and by less than one per cent (height) in a typical year (see Supplementary Table 2 and Supplementary Discussion). Moreover, our regression results also hold when we restrict the sample to only those observations where we do have information on both the date of construction and the permit date (see Supplementary Table 6 and Supplementary Discussion).

Estimation of the effect of minimum distance regulation. We use a difference-in-differences model to estimate the effect of the 10 H regulation on wind power expansion in Bavaria. The baseline specification is given by

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

where the dependent variable q is the number of wind turbine permits granted in district i in month t (in MW). μ_i is a district-level fixed effect that controls for those differences in the number of permits between districts that are constant over time. τ_t is a vector of month fixed effects, controlling for the impact of national shocks to the number of permits. Such shocks may include lower costs for building wind turbines over time, as well as changes to the German renewables remuneration regime that affect Bavaria and the rest of Germany similarly. δ is the coefficient of interest, measuring the effect of the 10 H regulation on the number of permits in the average Bavarian district.

For the estimated δ coefficients presented in Table 1, we also estimate the relative decrease of construction permits in Bavaria. We do this by comparing the point estimate of δ to the number of permits that would be expected had the minimum distance policy not been in place. In other words, the treatment effect is compared to the counterfactual permits that we would expect in the average Bavarian district, had the 10 H rule not been implemented.

Identification. 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 3 in the main text supports this hypothesis. Moreover, we implement an event study approach given by

$$q_{i,t}^{Wind} = \sum_{j=-m}^{s} \delta_j D_{i,t+j} + \mu_i + \tau_t + \varepsilon_{i,t} \qquad (2)$$

where m "leads" and s "lags" of the treatment effect are included instead of the single treatment effect in (1). The approach confirms that the development of construction permits in Bavaria and the rest of Germany was parallel prior to the introduction of the 10 H regime (see Supplementary Figure 2 and Supplementary Discussion). This gives confidence that the identifying assumption is correct, namely that Bavarian permits would have evolved similarly to the rest of Germany, had the minimum distance regulation not been introduced.

Number of permits in Bavaria. In the baseline specification, we assume that after the introduction of mandatory separation distances, wind turbines built under an exception from the 10 H regime would not have been built had the strict minimum distance rules been applied. Alternatively, a lower bound of the effect of the 10 H regime can be calculated by assuming that all wind turbines that benefitted from such an exception would have survived the strict minimum distance rules. Under this alternative assumption, the estimated effect is lower, but remains statistically and economically highly significant (see Table 1 in the main text).

Placebo regressions, anticipation effects and spillover. We carry out a whole range of robustness checks (for a detailed description see Supplementary Discussion). The fact that our main conclusions remain virtually unchanged adds confidence to the robustness of our results. First, we carry out placebo regressions with the neighbouring states of Bavaria (Baden-Württemberg, Hesse, Saxony and Thuringia). All estimated pseudo treatment effects are statistically insignificant. 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 (see discussion of Figure 1 in the main text).

Second, we demonstrate that our results are robust to possible anticipatory effects. If market participants reacted to the introduction of the 10 H regime by increasingly filing for building permits before the new rules became effective, such anticipatory behaviour would confound our estimates. In order to exclude this possibility, we re-estimate model (1), but exclude observations within a window of up to 12 months of the treatment. The estimated relative effect of the separation distances on permits in these specifications is almost identical to the main results in Table 1, and the point estimates remain highly statistically significant (see Supplementary Tables 3 and 4).

Third, we show that our findings are qualitatively robust to spillover effects. 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 10 H. However, it is conceivable that at least some of the wind projects that were not realised in Bavaria moved to other parts of Germany. This would confound our estimates. Supplementary Table 5 re-estimates some of the central specifications 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 10 H regulation remains virtually unchanged (see Supplementary Table 5 and Supplementary Discussion).

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Supplementary Information

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

Jan Stede* and Nils May*

Table 1: Descriptive statistics

	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 number of permits per district [MW/month]	0.25	0.81
Mean construction period [months]	14.9	11.6

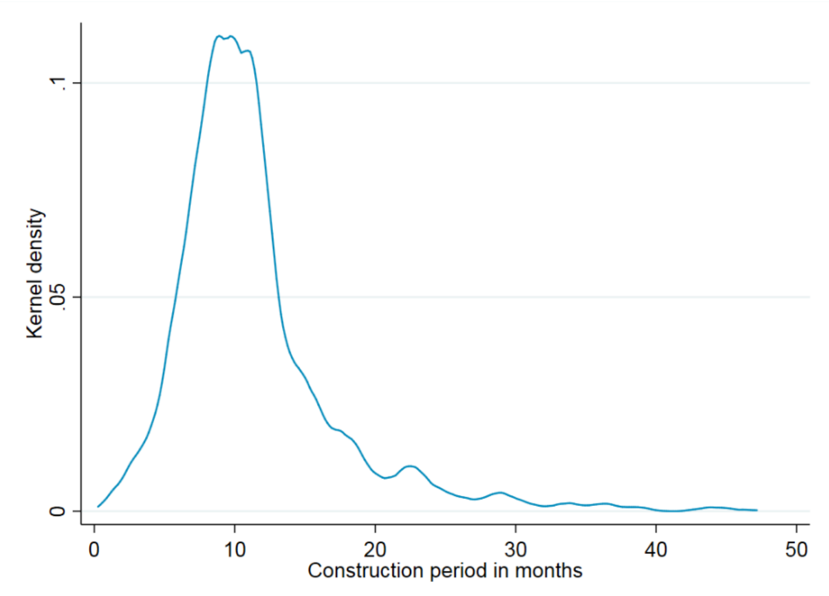
The statistics refer to wind turbines that received the construction permits between 2010 and 2016. The districts refer to Germany's territorial status as of 30.09.2019.

Table 2: 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		
	Power	Height	N	Power	Height	N
2010-2014	2.65	165	1,653	2.53	162	4,389
2010	2.12	138	209	2.25	150	611
2011	2.22	148	107	2.38	155	888
2012	2.81	170	109	2.55	162	983
2013	2.73	164	307	2.66	167	1,183
2014	2.77	172	921	2.69	175	724
2015	2.81	182	814	2.81	182	637
2016	3.03	183	1,902	2.98	185	591

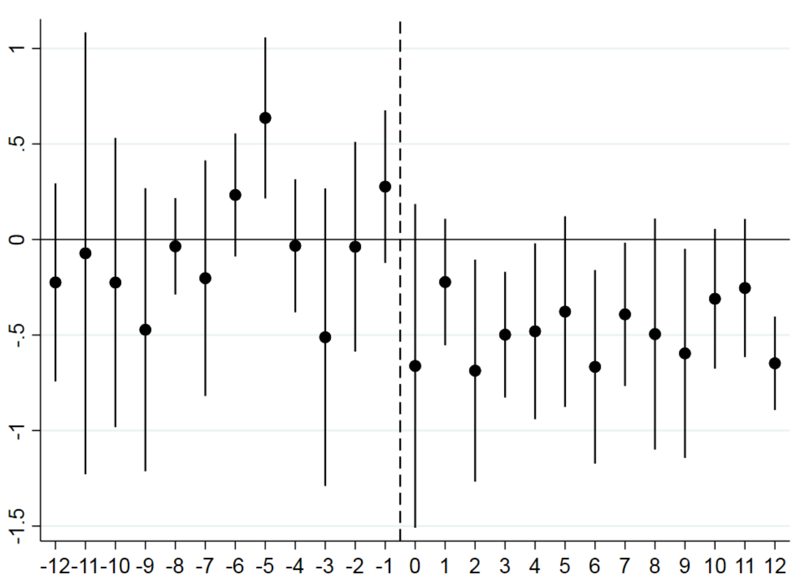
The table displays average power (in megawatt) and average height (in meters) by the year in which the building permits were granted.

Figure 1: Distribution of construction period 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.

Figure 2: Event study approach - effect of minimum distances on wind permits in Bavaria



The figure plots coefficient estimates and 95% confidence intervals from an interaction of the reform with indicators on the time difference to the reform (in months). The dashed line marks the introduction of the reform in November 2014.

Table 3: Effect of minimum distances on permits in Bavaria, 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)
Reduction [%]	-71	-71	-71	-90	-90	-90
Observations	26,466	26,466	26,466	26,466	26,466	26,466
R^2 (within-plant)	0.008	0.010	0.012	0.008	0.010	0.012
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, excluding observations within a window of six months before and after the introduction of the 10 H rule. The percentage decrease of building permits in Bavaria relative to the counterfactual is also tabulated. All specifications include district fixed effects. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 4: Effect of minimum distances on permits in Bavaria, 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)
Reduction [%]	-71	-71	-71	-88	-88	-88
Observations	21,654	21,654	21,654	21,654	21,654	21,654
R^2 (within-plant)	0.008	0.009	0.010	0.008	0.009	0.010
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, excluding observations within a window of 12 months before and after the introduction of the 10 H rule. The percentage decrease of building permits in Bavaria relative to the counterfactual is also tabulated. All specifications include district fixed effects. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 5: 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)
Reduction [%]	-50	-51	-52	-84	-85	-88
Observations	31,278	31,278	31,278	31,278	31,278	31,278
R^2 (within-plant)	0.006	0.007	0.009	0.006	0.007	0.009
Month fixed effects	x	x	x	x	x	x

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. All specifications include district fixed effects. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 6: Regressions based on observations with full information on 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***	-0.588***	-0.647***	-0.701***	-0.715***	-0.781***
	(0.0894)	(0.0912)	(0.106)	(0.0894)	(0.0909)	(0.106)
Reduction [%]	-69	-71	-78	-84	-86	-94
Observations	31,278	31,278	31,278	31,278	31,278	31,278
R^2 (within-plant)	0.014	0.016	0.019	0.014	0.016	0.020
Year fixed effects	x			x		
Quarter fixed effects		x			x	
Month fixed effects			x			x

This table re-estimates the treatment effects of Table 1 in the paper using only wind turbine from the *Anlagenregister* that have information on the date of the building permit of the, discarding all observations where we approximate the permit date based on the construction 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. All specifications include district fixed effects. Standard errors clustered at the state level are in parentheses. Significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 7: Ordinary wild bootstrap

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. All specifications include district fixed effects. 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.

Supplementary Discussion

In the Supplementary Information section, we first report summary statistics in Supplementary Table 1. Although almost one-fourth of all German districts are located in Bavaria, only 7.7 per cent of all building permits in the years 2010-2016 were granted to Bavarian wind turbines. Moreover, the average height of wind turbines of 190 meters mean that the 10 H regulation translates into a separation distance of 1900 meters on average.

Next, we provide evidence that wind turbines with and without information on the date of the permit are very similar (Supplementary Table 2). Within the periods from which we use the distributions to approximate the construction date (i.e. 2010-2014, 2015 and 2016), the two variables power and height differ on average by 2.1 per cent (power) and 0.8 per cent (height). We show the overall distribution of the construction period in Supplementary Figure 1, illustrating that the average wind turbine takes one year to build. Moreover, the vast majority of wind power plants (more than 94 per cent) are constructed within less than two years.

Third, Supplementary Figure 2 provides support for the validity of the main identifying assumption of common trends. By taking an event study approach, the graph shows that there was no statistical difference between the trend of wind permits in Bavaria and the rest of Germany in all but one of the 12 months before the 10 H rule became effective. In the year after the introduction of the 10 H regime, on the other hand, most interactions of the treatment with time lags to the reform are statistically significant.

Fourth, we provide a battery of robustness checks in Supplementary Tables 3 to 7, demonstrating that the main results shown in Table 1 in the paper hold. Supplementary Tables 3 and 4 re-estimate the specifications shown in Table 1, excluding observations before and after the introduction of the 10 H rule within a window of six and twelve months, respectively. All coefficients are still highly statistically significant. In our preferred specifications with only Bavarian wind turbines that received permits under the 10 H regulation, i.e. columns 3-6, the relative effect size is virtually unchanged compared to Table 1. In the specifications including all Bavarian wind turbines, the effect is even larger, rising to around 70 per cent (cf. columns 1-3 of Tables 3 and 4). This shows that the results are robust to possible anticipation effects.

Supplementary Table 5 shows that our findings are qualitatively robust to spillover effects. We re-estimate the treatment effects under the assumption that *all* wind turbines that were not built in Bavaria were immediately constructed elsewhere in the country. The estimation is implemented by *reducing* the wind permits of all other German states by the amount of permits not issued in Bavaria and re-estimating the models of Table 1 in the paper based on these reduced permits. As can be seen from Supplementary Table 5, the point estimates of the treatment effect decrease in this scenario relative to the main specifications in Table 1. However, the relative reduction of construction permits in Bavaria remains virtually unchanged (between -85 and -88 per cent). The reason is that the counterfactual development of Bavarian permits decreases when permits in the rest of Germany are assumed to be lower.

Our results are also robust to the approximation procedure of the construction periods. To show this, we re-estimate the models shown in Table 1 in the main text based on the subset of those plants where we do have information on the construction date from the *Anlagenregister*. The results are qualitatively the same, but the effect of the 10 H regulation is even more pronounced: With this subset of installations, it rises to -78 per cent (all permits), and -94 per cent (10 H permits only, see columns 3 and 6 of Supplementary Table 6).

Finally, we show that the results are also robust when standard errors are estimated 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.[31] However, as Germany consists of 16 states, there are only few clusters, which means the standard errors may be wrong.[32] 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.[33] Thus, we compute p values for the models estimated in Table 1 in the main text based on the ordinary wild bootstrap.[34] The statistical level of significance is identical as in the case of clustering on the state level for the preferred specification with only Bavarian wind turbines that received permits under the 10 H regime (columns 3-6 of Supplementary Table 7). For the specifications including all Bavarian wind turbines, the statistical level of significance is at the five per cent level when the ordinary wild bootstrap is used.

Supplementary Note 1

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