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Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development

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Optimal wind farm locations require a strong and reliable wind resource and access to transmission lines. As onshore and offshore wind energy grows, preferred locations become saturated with numerous wind farms. An upwind wind farm generates 'wake effects' (decreases in downwind wind speeds) that undermine a downwind wind farm's power generation and revenues. Here we use a diverse set of analysis tools from the atmospheric science, economic and legal communities to assess costs and consequences of these wake effects, focusing on a West Texas case study. We show that although wake effects vary with atmospheric conditions, they are discernible in monthly power production. In stably stratified atmospheric conditions, wakes can extend 50+ km downwind, resulting in economic losses of several million dollars over six years for our case study. However, our investigation of the legal literature shows no legal guidance for protecting existing wind farms from such significant impacts.

Wind energy has grown rapidly in the United States, from less than 1% of US electricity generation in 2007 to more than 6% in 2016, mirroring global trends[1]. State and federal policies driven by public support[2] influence this growth, but siting of individual wind farms originates from a decentralized process. Wind developers identify locations with strong wind resources, buildable areas and proximity to transmission lines and roads[3]. Developers then negotiate with landowners to lease wind rights, establish power purchase agreements with electricity buyers and construct turbines and supporting infrastructure. Owners of decades-old wind farms may suddenly find themselves downwind from a newly constructed wind farm. As this new wind farm extracts momentum from the atmosphere, it may generate 'wake effects' (decreases in downwind wind speeds), undermining the existing wind farm's generation and revenues[4,5]. Grid integration studies rarely consider wakes that extend beyond 1 km (ref. [6]), but wind farm wakes 45 km long have been observed[7]. The United States had 994 individual wind farms in 2016. Of these, 884 (or 88.8%) are located within 40 km of another wind farm and thus could be impacted by these wake effects.

Most investigations of wakes focus on physical reductions of downwind wind speeds[8,9] or temperature effects[10–13], whereas some studies investigate possible impacts on regional-scale weather phenomena[14,15] or speculate on global limitations to wind energy[16]. Assessments of wake impacts on power production are rare, limited to unique datasets made publicly available for research purposes[5,17–19].

To assess impacts of wind farm wakes, we employ two types of scientific investigation. First, we develop an econometric model of monthly wind generation using publicly available data, and apply it to a wind farm in West Texas, selected because of its proximity to an upwind neighbour. Using a third nearby wind farm as a control for month-to-month variation in the wind resource, we estimate that the construction of the upwind wind farm reduced generation at the downwind farm by 5% on average because of wake effects. Next, we design and execute numerical weather prediction simulations with and without the presence of the upwind wind farm, using a wind farm parameterization[20–23] validated with wind turbine power production data[19,24]. These physics-based simulations illuminate the spatio-temporal variability of the wind farm wake, fundamentally supporting the econometric analysis that the upwind wind farm reduces generation at the downwind wind farm. Finally, we consider the legal implications. No centralized regulation exists at either the national or state level. Legal constructs guiding wind development are haphazard, varying from state to state or locality to locality. Moreover, they are not based on empirical study of the physical or economic effects of wakes. Any required spacing between wind turbines, or 'setbacks', generally follows standard zoning code principles or aesthetics instead of being crafted for protection of wind resources or maximizing public benefit from the wind[25]. Given ongoing increases in global wind development, we highlight the need to understand physical, economic and legal interactions between wind farms to ensure sustainable development and stewardship of wind resources.

Experimental design

Texas has the largest deployment of wind turbines in the United States, with 12,077 turbines comprising 131 wind projects, providing capacity of over 21 GW[26]. Our chosen complex of wind farms (Fig. 1) includes two farms closely located: the downwind Roscoe wind farm (operational March 2008) and the upwind wind farm Loraine (partially operational November 2009). A nearby control wind farm, Champion, became operational concurrent with the downwind farm (Roscoe). Some upwind (Loraine) turbines are located less than 300 m from downwind (Roscoe) turbines. Turbine types and total capacity at all three farms are described in Table 1. All three sites are fairly similar in other respects—they are on the order of hundreds of megawatts in capacity, have similar turbine sizes, produce tens of thousands of megawatt hours monthly (with high variability) and have capacity factors around 30%. We selected

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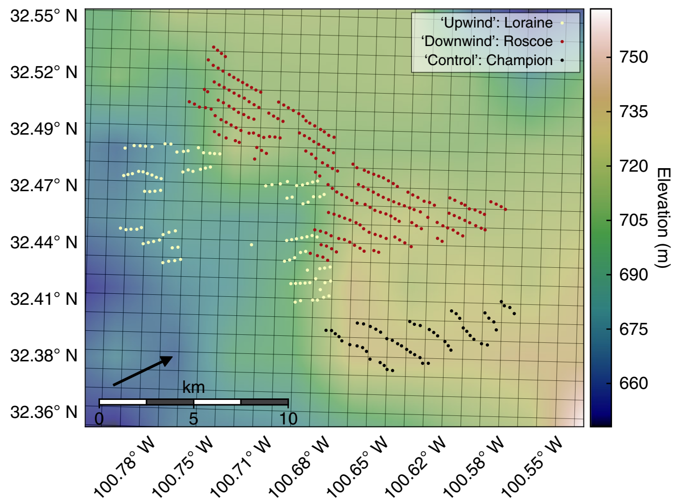

Fig. 1 | A map of the wind farms' turbine positions plotted over an elevation map of the surrounding terrain. The colour bar represents elevation in metres above sea level. 'Upwind' Loraine (yellow dots) is generally southwest of 'downwind' Roscoe (red dots), with Champion (black dots) as the 'control'. The grid appearing in the background represents the finest mesoscale simulation grid, at 1-km horizontal resolution. The black arrow denotes alignment between the centroids of the upwind (Loraine) and downwind (Roscoe) farms.

Table 1 | Characteristics of wind farms, Texas case, 2008–2015

Name	Roscoe	Loraine	Champion
Role	Downwind	Upwind	Control
Capacity (MW)	209	100	75
(Phase II)		50	
Turbine size (MW)	1.0	1.5	2.3
Operational month and year	March 2008	November 2009	March 2008
(Phase II)		July 2011	
Latitude	32.4690	32.4375	32.3983
Longitude	−100.6664	−100.7444	−100.6481
Monthly MWh (mean)	46,226	34,204	30,891
Monthly MWh (s.d.)	14,643	11,226	8,334
Monthly CF (mean)	0.30735	0.31346	0.34090
Monthly CF (s.d.)	0.09891	0.07229	0.09323

Loraine was developed in two phases (67 turbines in the first, 33 in the second). Operational month and year is based on discernible generation in EIA-923 reports that is consistent with the number of wind turbines, and may differ from that reported in EIA-860. CF, capacity factor.

this complex of wind farms because of: the proximity of the upwind and downwind farms, along the lines of the dominant wind direction (Supplementary Figs. 1 and 2); the timing of construction of the upwind, downwind and control farms; and the availability of meteorological data in the vicinity to validate the atmospheric science simulations (see Supplementary Notes 1, 2 and 4). Although we refer to Loraine as the upwind farm, to Roscoe as the downwind farm and to Champion as the control farm, these labels reflect the situation with westerly and southwesterly winds. Winds occasionally come from other directions, producing wake effects (for example, Roscoe waking Loraine) that are not directly addressed here because of their relative infrequency. Finally, this location is appropriate for a case study as it reflects the legal situation in most of the nation as the state and the relevant counties have no legislation currently regarding wake effects.

Ideally, data from individual wind turbines would be available, but access to detailed production data is generally considered 'business confidential'. Nonetheless, we hypothesize that these wake effects may be discernible in public monthly generation data, and so all analysis is based on publicly available data and simulation tools. The use of coarse, publicly available data limits the statistical power of the analysis to provide precise estimates. Nevertheless, we find statistically significant evidence of the existence of wake effects using these datasets. The econometric analysis relies on four publicly available datasets. EIA-923[27] from the Energy Information Administration reports monthly net generation in megawatt hours for individual wind farms in the United States since 2001. Next, EIA-860[28] reports annual unit characteristics for all power plants, including capacity in megawatts, operating month and year and latitude/longitude since 2001. The US Geological Survey WindFarm tool[29] provides individual wind turbine characteristics and locations based on the Federal Aviation Administration databases and satellite imagery. The National Center for Environmental Information's Climate Data Online[30] provides historical hourly surface wind direction (degrees) and speed (miles per hour) from their network of Automated Surface Observing System sites across the country. The atmospheric science analysis uses the publicly available Weather Research and Forecasting (WRF) simulation tool[31,32] with the open-source Wind Farm Parameterization[19,20,22] and a turbine model based on the GE 1.5-MW turbine[33] in conjunction with the turbine locations from the US Geological Survey WindFarm tool. The West Texas Mesonet[34] provides validation data for quantifying the accuracy of the WRF simulations (see Supplementary Note 4 and Supplementary Figs. 10–13).

Economic findings

By considering the alignment of monthly winds with the spatial orientation of the farms, wake effects are discernible in the monthly generation data for the downwind farm (Table 2), estimated over the time period of March 2008 to December 2015. The coefficient on the interaction term between upwind capacity and wind direction index (MW × direction) is negative and statistically significant, providing evidence of the existence of wake effects from the upwind farm on the downwind farm's capacity factor when the wind direction aligns with their spatial orientation (winds from the southwest). The median value of the wind direction index is 0.554, which implies a marginal effect from an additional megawatt of upwind capacity of -0.00013 ± 0.00021, or a total capacity factor reduction of 0.0196 ± 0.0323 at the downwind site. The 90th percentile of wind direction is 0.610, with a marginal effect of $-0.0004 \pm 0.00026\,\mathrm{MW}^{-1}$ and a larger total reduction in downwind capacity factor of 0.0604 ± 0.0388. For the 94 months in our sample, statistically significant wake effects are found in the 33 months with winds more frequently out of the southwest, while in the remaining months, we cannot reject the null hypothesis that wake effects are zero. Across specifications (see Supplementary Note 3), the econometric model consistently predicts that capacity factors downwind would have been higher in the absence of wake effects caused by the upwind farm during months with frequent southwesterly winds.

To visualize these results, we compare the difference between predicted and actual capacity factors at the downwind farm (Fig. 2a and Supplementary Fig. 3). The solid line is the predicted capacity factor net of actual at the downwind farm and inclusive of the wake effects of the upwind farm. The dashed line is the predicted capacity factor net of actual when wake effects are excluded. The two lines track each other until November 2009 when upwind

Table 2 | Estimated wake effects at the downwind site (Roscoe) due to the upwind site (Loraine)

	CF at control site	MW at upwind site	Direction	MW × direction
CF at Roscoe	0.958***	0.00249***	0.585**	−0.00490***
	(0.0419)	(0.000963)	(0.233)	(0.00169)

The dependent variable is monthly capacity factor (CF) at the waked downwind site (Roscoe). The coefficients of interest are megawatts at the upwind site (Loraine) and MW × direction. Controls include CF at the control site (Champion), direction and year fixed effects. $N = 94$ and $R^2 = 0.879$. Robust standard errors clustered by season-year in parentheses. ***$P < 0.01$, ** $P < 0.05$.

(Loraine) Phase I was completed. Following that point (and exacerbated by the completion of upwind (Loraine) Phase II in summer 2011), the lines diverge. The predicted capacity factor net of actual without wake effects (dashed) is generally more positive than the predicted capacity factor net of actual with wakes (solid), with larger gaps in months when winds were more consistently southwesterly. Note that in some months, the dashed line is less than the solid line, implying increased generation at the downwind farm (Roscoe) due to the upwind farm's (Loraine's) wind turbines, but as per the above, wake effects in those months are not statistically significant. Similarly, Fig. 2b compares the actual capacity factor and the predicted capacity factor with and without wake effects for the downwind farm (Roscoe). Predicted capacity factors with wake effects resemble the actual capacity factors closely. In contrast, the predicted capacity factor absent wake effects frequently exceeds observed capacity factors.

These differences in wind power generation due to wakes have significant economic and environmental impacts. For each month with statistically significant wake effects, multiplying the difference in predicted capacity factors with and without wakes by the downwind farm's total capacity (209 MW), by 24 h, and by the number of days in each month, and summing from November 2009–December 2015, we estimate a total generation loss of 184,415 ± 120,930 MWh downwind due to wake effects from the upwind farm. Zonal wholesale prices for the real-time market are available[35] in 15-min intervals from 2011–2015. Combining monthly average zonal prices, weighted by total Electric Reliability Council of Texas hourly generation, with monthly generation losses gives a total lost revenue of approximately US$3.7 ± 2.4 million from 2011–2015, or roughly US$730,000 ± 485,000 in lost sales annually. Incorporating the foregone production tax credit[36] pre-tax value of US$35 MWh^{-1} increases the lost revenue for Roscoe to US$2 ± 1.29 million annually. Finally, each megawatt hour of wind generation in Texas offsets roughly 0.6 tons of CO_2 during this time period[37–39]. Multiplying this emission savings rate by the lost generation above implies a forgone CO_2 savings of 110,649 ± 72,558 tons from the downwind farm from November 2009 to December 2015, which has a value of over US$4.1 ± 2.7 million at a US$37 per ton[39] social cost of carbon. Three other sets of wind farms in other states also exhibit wake effects (Supplementary Tables 2, 4 and 6 and Supplementary Figs. 4–6).

Atmospheric science findings

The econometric wake effects emerge from physical wakes. By simulating wind flow at the downwind farm (Roscoe) with and without the presence of the upwind farm (Loraine), we illuminate the wake effect and its spatio-temporal variability. These physics-based simulations fundamentally support the econometric analysis that the upwind wind farm reduces generation at the downwind wind farm. We focus on January 2013, as the econometric model (Fig. 2) suggests that January 2013 was one of the stronger, but not the strongest, wake effect months.

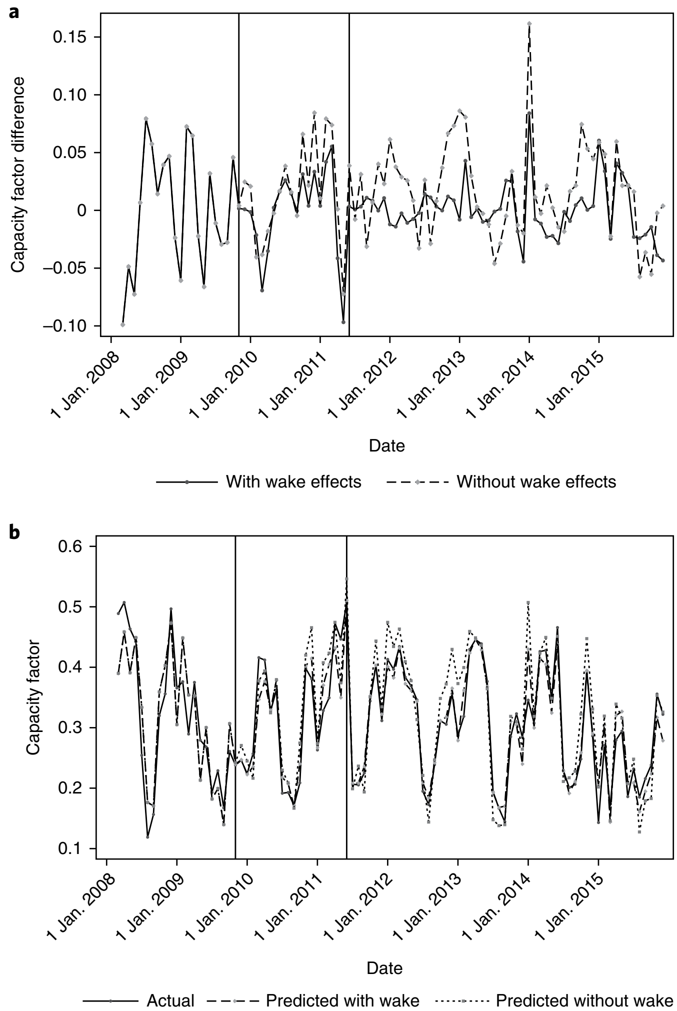

Fig. 2 | Comparing predicted capacity factors with the actual capacity factors at the downwind farm using econometric analysis. a, Predicted capacity factor minus actual at Roscoe. The solid line indicates predicted capacity factor net of actual capacity factor downwind, inclusive of wake effects. The dashed line indicates predicted capacity factor net of actual capacity factor downwind, exclusive of wake effects. **b**, Actual and predicted capacity factors at Roscoe. The time period analysed is from March 2008 to December 2015. The vertical lines indicate when Phase I (2009) and Phase II (2011) were completed at the upwind farm. The solid line indicates observed capacity factor downwind, the dashed line indicates predicted capacity factor downwind inclusive of wake effects, and the dotted line is predicted capacity factor downwind exclusive of wake effects.

Wake impacts emerge in the time series of power production (Fig. 3). The orange region shows the difference in power production downwind (Roscoe) without and with the upwind farm in the simulations (for example, 24 January). The green region marks the power production at the downwind farm with the upwind farm included in the simulation. The purple area shows the upwind farm's power production when only the upwind farm is included in the simulations. Although more total power production occurs with the upwind farm's presence (the purple plus green area), power production at the downwind farm suffers. Simulated January 2013 power production downwind was 92,703 MWh without the upwind farm, and only 85,265 MWh with the upwind farm, an impact of 7,438 MWh, or an 8% decrease. These simulations should not exactly match the predictions from the econometric model; physical

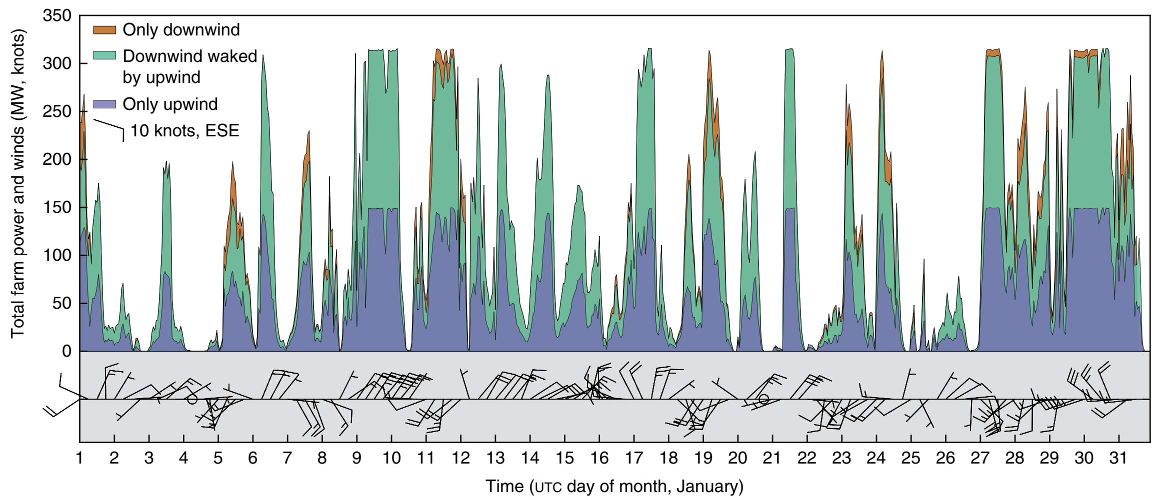

Fig. 3 | Time series of WRF-simulated power production for the Texas complex of wind farms for January 2013. The purple areas show the WRF-simulated power production only for the upwind wind farm, whereas the green areas show the WRF-simulated power production of the downwind wind farm when both the upwind and downwind farms are involved. The brown area shows the WRF-simulated power production of the downwind wind farm in the simulations with the upwind farm excluded. The wind barbs (knots) show the simulated wind speed and wind direction at turbine hub height (80 m) as a function of time. One full flag represents 10 knots, with a minimum of 5 knots and a maximum of 30 knots on this time series.

effects (for example, waking within a grid cell, different turbines) cause some differences between the simulations and reality.

Wind farm wakes exhibit significant spatial and temporal variability. Most strong wakes occur during night-time stable conditions. Maps of power deficit (Fig. 4a) and wind speed deficit (Fig. 4b) for 2:00 UTC 24 January (21:00 LST 23 January) are calculated by differencing simulations with and without the upwind farm. The largest power deficits occur within the downwind farm in specific locations, such as simulation grid cells with large numbers of downwind farm turbines immediately downwind (to the northeast) from cells with multiple upwind farm turbines. The deficits decay further downwind. For this specific hour, the downwind farm produced 45 MW less power (270 MW) with the upwind farm than it did without the upwind farm (315 MW). The upwind farm's turbines southwest of the downwind farm remove momentum from the atmosphere, creating a wind speed deficit of nearly 2 m s^{-1} in the closest downwind area (Fig. 4b), reducing power available to the downwind farm's turbines. Nocturnal stable stratification and low levels of ambient turbulence prevent the wake from eroding as it moves downwind. Even 50 km downwind, simulated wind speed deficits of 0.5 m s^{-1} occur.

The atmospheric simulations emphasize the critical role of wind speed and direction. The strongest power deficits occur when winds are south-southwesterly to westerly (Roscoe downwind from Loraine) with hub-height wind speeds between 8 and 12 m s^{-1} in the region of the wind turbine power curve where power varies with the cube of wind speed (Fig. 5a). We aggregate the simulated hourly power deficits at the downwind farm, organized by the wind speed and wind direction at the centre of the downwind farm (Fig. 5b). At higher wind speeds, downwind turbines also experience reduced wind speeds, but for this wind turbine, the same amount of power is produced at 14 m s^{-1} as at 16 m s^{-1}. Small power deficits, less than 18 MW over the farm, occur during a range of wind speeds and wind directions primarily due to the interwoven locations of turbines (Fig. 1): a few upwind farm turbines are in cells upwind of downwind farm turbines even in northeasterly conditions. The strongest wakes occur at night during stable conditions with negative heat flux (Fig. 5c).

Legal results

Through economic analysis and atmospheric science simulations, we demonstrate that wakes have discernible impacts. Furthermore, our research found that nowhere in the United States have legislators enacted laws specifically recognizing or protecting against the damages caused by wind waking. At the federal level, a few bills have been introduced to fund research that would address wake effects[40,41], but Congress has not passed any nationwide legislation to fund or regulate terrestrial wind siting on private land in the United States (see Supplementary Note 5).

Our search of statutes in all 50 states uncovered a diverse patchwork of laws with no uniformity from state to state, or even from locality to locality within a state. States, and more commonly the various counties and smaller subdivisions of the states, are the foci for any regulation of construction, operation and decommissioning of wind projects. Setbacks, if any, follow standard zoning code principles or aesthetic concerns instead of being crafted for efficiency or protection of wind resources. When projects cross municipal or county boundaries, they must comply with multiple, diverse requirements that do not reflect the physical reality that wakes cross county and state borders[25]. For example, the wind speed wake from Loraine affects three separate counties (Fig. 4b). Our legal research indicates that the state of Texas and none of these counties (Supplementary Note 6) have enacted laws to address the financial damage caused by wakes, which could include lost power, as quantified herein, or could refer to increased loads, causing wear and tear on the turbine and premature retirement of the capital investment.

Currently, the only state attempting to regulate wind wakes is Minnesota (Supplementary Note 7). State statutes and the related administrative regulations do not specifically mention the word 'wake'. However, the statute mandates that the Minnesota Public Utility Commission (PUC) establish 'property line setbacks'[42] (section 216F.08(c)), and that projects subject to PUC permits be 'designed and sited in a manner that ensures efficient use of the wind resources, long term energy production, and reliability'[43]. This language has been used by the Minnesota PUC to establish standard setbacks and to include 'wake loss studies' in some permit applications.

Over a hundred years ago, the 'rule of capture' allowed an adjacent landowner to tunnel underground to capture a neighbour's oil resources, resulting in millions of dollars of waste before states intervened to regulate the production of oil via well-spacing, pooling and other conservation measures. Similarly, some states

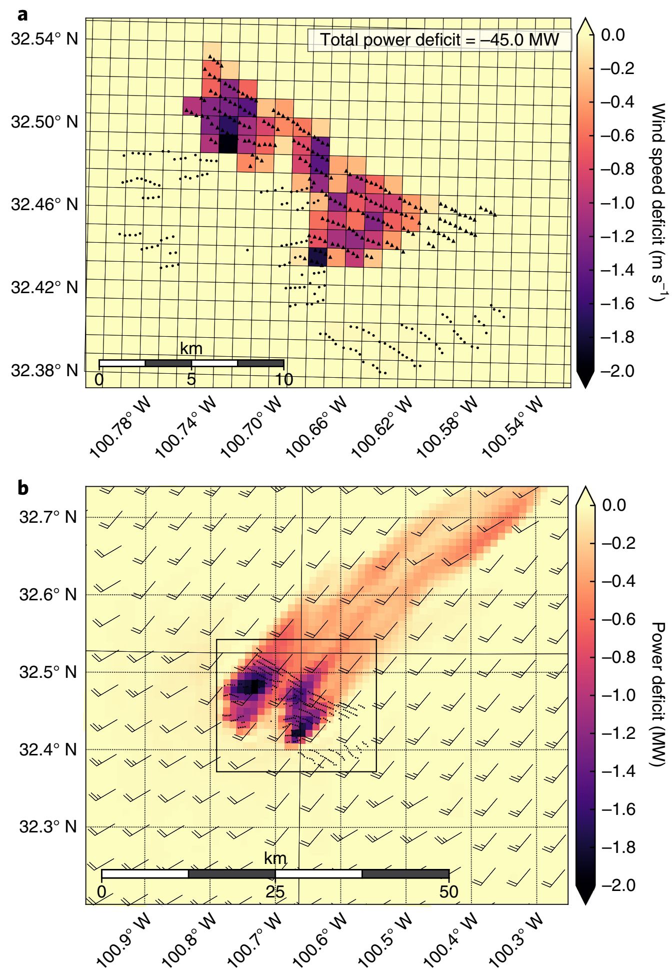

Fig. 4 | WRF-calculated wind farm wakes. **a**,**b**, Power (**a**) and wind speed (**b**) deficits at the downwind farm (Roscoe), calculated by WRF, for 2:00 UTC on 24 January 2013 (21:00 LST on 23 January 2013). The grid cells in **a** denote the 1-km × 1-km grid cells of the WRF simulations and a ~25 × 16 km domain is shown. The domain in **b** is larger, ~70 km × 50 km, and the grid cells denote 0.1° changes in latitude and longitude, with wind barbs showing the 80-m wind speed and direction for that cell. The 1-km grid cells can be seen in the pixels of the wind speed deficits, which show the upwind farm's (Loraine's) wind farm wake at an 80-m altitude extending more than 50 km downwind and clearly impacting the winds at the downwind farm (Roscoe).

recognize a 'prior appropriation' or right of the first user to regulate water resources. US property law has not similarly caught up with a regime to avoid waste by protecting wind developments from a neighbour's wake.

Discussion

Using two different scientific techniques, we demonstrate that wind farm wake effects are real, discernible and arise from clearly understood physical processes. The presence of an upwind wind farm can induce significant power losses at a downwind wind farm that are discernible even without access to proprietary power production data. In our Texas case study, the downwind wind farm suffered an estimated generation loss of roughly 5% from November 2009 to December 2015. Numerical weather prediction simulations can account for the elevated drag and increased turbulence of an upwind wind farm to assess the variability of these wake effects. We simulate downwind losses on the order of 7,500 MWh during 1 month. Wake effects are most notable during three conditions that occur with some regularity: when the wind direction places the upwind wind farm immediately upwind, when the atmosphere is stably stratified so that wakes persist further downwind, and when wind speeds are such that wind turbines exhibit high sensitivity to changes in wind speed. As nearly 90% of wind farms in the United States are located within 40 km of another wind farm—and often much closer—nearly every wind farm may become a downwind wind farm at some point and experience these wakes. US law is generally silent on the existence and consequences of these wakes. The failure to recognize the issue and predictably provide solutions for conflicts may raise the cost of wind energy and thereby slow development.

Sustainable development of wind resources is complicated by the fact that wind is invisible: the impact of waking has been difficult to measure. With continual increases in wind development, especially in constrained transmission corridors, the need to understand the physical, economic and legal interactions between wind turbines and their local environments is urgent to ensure sustainable development and stewardship of these resources. We focus on cases of wind farm interaction onshore in the United States: the nation has the second-largest capacity of wind energy in the world, with 82,143 MW deployed at the end of 2016, second only to China[44]. US deployments cluster in areas of high resource and near transmission lines, just as in prime offshore wind resource areas around the world, such as the North Sea. In our simulations, we observe wakes with distances of 50 km. Offshore wind farm wakes longer than 50 km have been observed with satellite measurements[45] and aircraft measurements[46]. These longer wakes offshore may allow wind farms from multiple countries to impact each other, pointing to the need for global recognition of wake effects, similar to the need for international efforts to manage other transboundary resources such as fresh water and fisheries.

It is beyond the scope of this study to suggest a single solution. The complexity of regulatory regimes, from state to local, and the competing interests of private landowners suggest that disputes between terrestrial, or land-based, wind farms will continue to be resolved through adversarial litigation. The costs of such disputes could be significantly reduced by federal or state legislation that establishes a definition of nuisance within a set space or time period[47], so that wake effects smaller than that nuisance level would be ignored. For example, to consider a parallel to solar energy law, the California Solar Shade Control Act defines a nuisance from vegetative shadows as 10% between the hours of 10:00 and 14:00. In contrast, offshore wind might better be developed following oil and gas strategies that 'pool' or 'unitize' areas. Federal waters provide an environment where uniform ownership and a single regulatory regime may provide opportunities for more efficient development and the recognition of competing interests without resorting to courts.

Methods

Site selection. To credibly estimate wake effects using publicly available data, a particular spatial and temporal arrangement of wind farms is necessary. Specifically, we need an existing 'downwind' site that we will investigate for evidence of wake effects. Next, we need a more recently built 'upwind' site located nearby to generate the wake effects. Finally, we need a nearby 'control' site that is un-waked by the upwind site, but close enough to the downwind site to serve as a plausible control for monthly fluctuations in generation caused by weather conditions. Furthermore, both the downwind and control sites need to have been in operation long enough prior to the upwind site to establish a credible pre-wake baseline capacity factor, and the upwind site has to have been built far enough in the past to have sufficient observation capacity factors in the post-wake period. On the basis of these criteria, we identify four potential sites: Texas (Table 1), Iowa (Supplementary Table 2), Illinois (Supplementary Table 4) and Kansas (Supplementary Table 6). We ultimately focus on the Texas case (see Supplementary Notes 1 and 2).

Econometric data. Using the datasets noted in the text, we construct several key variables. First, for each month in the sample, we calculate the monthly capacity factor CF_{mt} by dividing monthly net generation MWh_{mt} by the corresponding

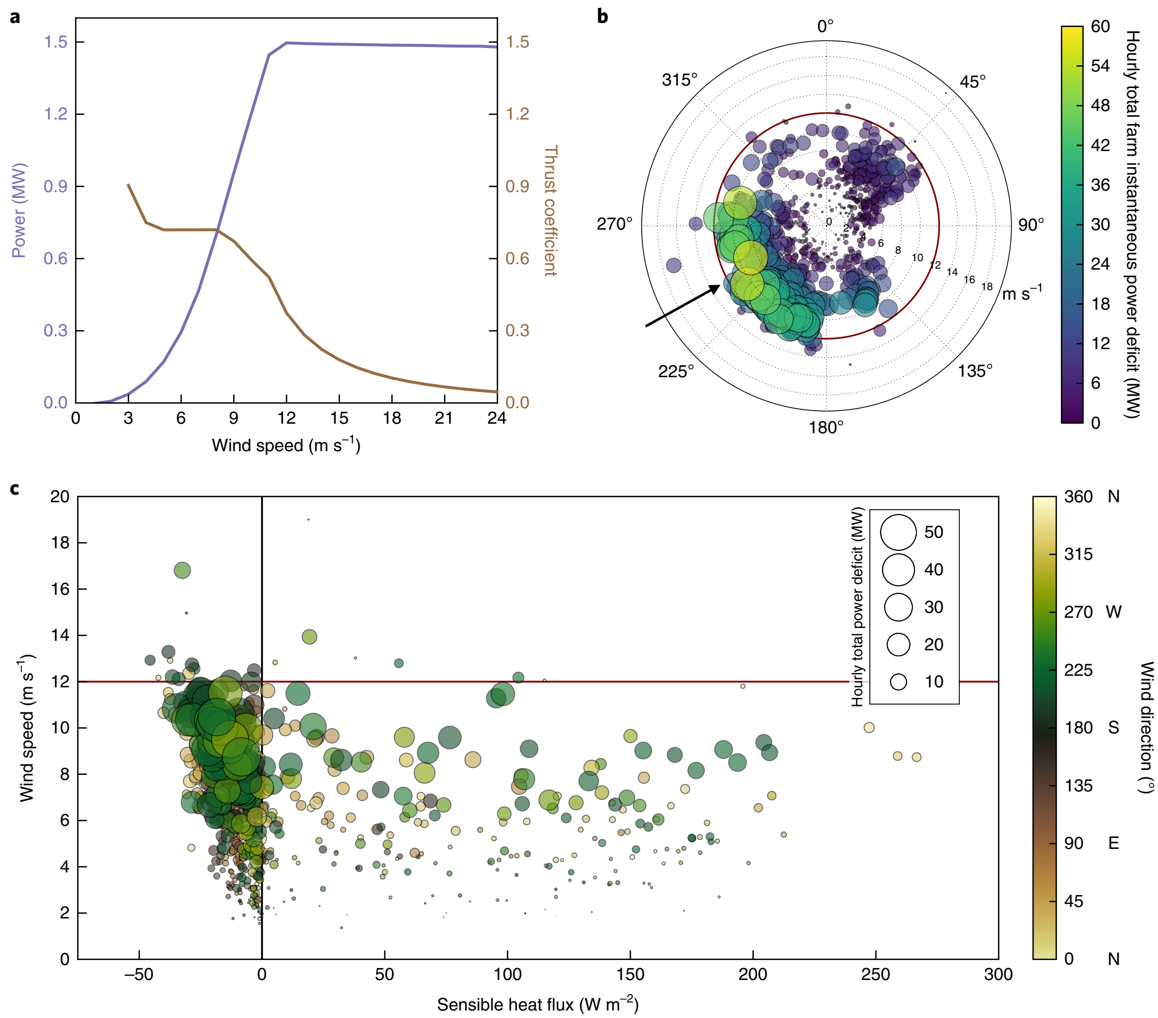

Fig. 5 | Wind turbine characteristics and wind farm wake variability. a, The power curve and thrust coefficient curve of the 1.5 MW turbine used in the simulations. **b**, The wake rose, in which each circle represents one hourly WRF-simulated power deficit at the downwind farm (Roscoe). The colour and the size of the circle represent the WRF-simulated power deficit throughout the downwind farm (Roscoe) for that hour with the size as given by the legend in panel **c**. The WRF-simulated wind speed is denoted by the circle's distance from the origin, and the WRF-simulated wind direction is denoted by the angular location around the origin. The largest wakes of 60 MW (yellow circles) occur for south-southwesterly or westerly winds of 8–10 m s^{-1}. **c**, The relationship between stability as defined by heat flux, wind speed and resulting wake.

potential generation based on capacity MW_{mt} for each wind farm. Second, using the latitude/longitude data for each wind farm, we calculate the directional vector in degrees between the upwind and downwind farms as a measure of the spatial orientation of the wind farms. Third, for every hour in the surface wind dataset, we calculate the difference between the wind farm orientation and the observed wind direction in Abilene, TX, 100 km to the east of this complex of wind farms (Supplementary Fig. 1). This hourly value is normalized by 180°, such that a wind direction that perfectly aligns with the wind farm orientation is equal to 1, and a wind direction exactly opposite the orientation (180° off) is equal to 0. This value for each hour is then averaged for each month and year to generate a proxy index of wind direction Dir_{mt} relative to the wind farm orientation. Larger values of this index imply that winds during the month were more frequently in a direction that would generate wake effects.

Econometric model. We first examine whether wake effects are detectable in monthly generation data by estimating the monthly capacity factor at the downwind (Roscoe) wind farm before and after the construction of the upwind (Loraine) wind farm from March 2008 to December 2013. Simply comparing pre- and post-construction average capacity factors would be naive, as those averages may be confounded by any number of factors. As such, we consider three models and several variants that model wake effects while controlling for omitted variable biases in different ways. Importantly, all three models include the capacity factor at the neighbouring control (Champion) wind farm as a control variable to capture the natural variation in wind conditions over time. The discussion below focuses on our preferred model, with additional model descriptions and results in Supplementary Note 3 and Supplementary Table 1. Results for other locations appear in the Supplementary Information: Iowa in Supplementary Table 3 and Supplementary Fig. 4, Illinois in Supplementary Table 4 and Supplementary Fig. 5, and Kansas in Supplementary Table 5 and Supplementary Fig. 6.

The outcome variable of interest is CF_{mt}^{down}, which is the capacity factor in month m and year t at the downwind site. We estimate the following model:

$$CF_{mt}^{down} = \beta_1 MW_{mt}^{up} + \beta_2 Dir_{mt} + \beta_3 MW_{mt}^{up} Dir_{mt} + \gamma CF_{mt}^{cont} + \theta_t + \varepsilon_{mt} \quad (1)$$

whereby the capacity factor in month m and year t at the downwind site is regressed on the capacity MW_{mt}^{up} at the upwind site, the capacity factor CF_{mt}^{cont} at the control site and fixed effects for each year θ_t. The variable Dir_{mt} is an index variable that can vary between 0 and 1, capturing how closely hourly wind directions within a month (weighted by the cube of hourly wind speed to reflect the cubic power curve for wind power generation) match the spatial orientation between upwind and downwind farms (248°).

The coefficients of interest are β_1 and β_3, which capture the wake effect. The marginal effect on the downwind capacity factor of an additional megawatt of upwind capacity (the wake effect) is given by $\frac{\partial CF_{mt}^{down}}{\partial MW_{mt}^{up}} = \beta_1 + \beta_3 Dir_{mt}$. As a larger value for Dir_{mt} implies greater wake effects (reduced capacity factor at the downwind site), it is expected that β_3 will be negative. Standard errors for all models are clustered at the season-year level to address standard heteroscedasticity and serial correlation concerns.

The key control variable is CF_{mt}^{cont}, and the coefficient γ represents how the capacity factor at the control site moves with the capacity factor at the downwind site. It is expected to be positive and near 1. The inclusion of year fixed effects θ_t helps control for potential omitted variable bias in identifying our coefficients of interest, but at the cost of reduced degrees of freedom and variation. Specifically, year fixed effects control for any systematic differences in year-over-year capacity factor between the control site and the downwind site, such as differential degradation in performance or increased maintenance due to age. Month fixed effects were also considered, but inclusion led to overfitting concerns, and a joint test that all month fixed effects are equal to zero cannot be rejected ($P > 0.07$). By contrast, year fixed effects are jointly significant, and examining out-of-sample predictions based on training datasets does not indicate overfitting.

Numerical weather prediction model set-up. The focus of the atmospheric modelling component of the study is to provide temporal and spatial granularity to the wake effects suggested by the econometric analysis of the Texas complex of wind farms. Using numerical weather prediction, we simulate wake effects at fine temporal (every 10 min) and spatial (every 1 km) resolution and then aggregate those effects to compare with the monthly farm-wide econometric analysis.

The simulations use the WRF model[31,32] version 3.8.1, with four one-way nested domains (170×138, 187×160, 217×199 and 76×76 grid cells at 27 km, 9 km, 3 km and 1 km resolution, respectively) (part of the finest domain appears in Fig. 1; all domains appear in Supplementary Fig. 7). Topographic data are provided at 30-s resolution, and the vertical resolution near the surface is nominally 12 m (Supplementary Fig. 8), stretching aloft following recommendations from other investigations[48] for a total of 58 levels. Boundary conditions for winds, temperature and other meteorological variables on the boundaries of the simulation domain are with the ERA-Interim reanalysis data[49]. Physics options selected include cloud microphysics[50], RRTM long-wave radiation scheme[51], Dudhia short-wave radiation[52] with a 30-s time step, a surface layer scheme that accommodates strong changes in atmospheric stability[53], land surface physics with the Noah Land Surface Model[54], the MYNN2 PBL scheme[55] with TKE advection and the explicit Kain–Fritsch cumulus parameterization[56] on the outer two domains. Simulations use a model time step of 30 s on the outer domain. See Supplementary Note 4 for more detail.

January 2013 is selected for simulation on the basis of the high frequency of southwesterly winds that would manifest strong wake effects (Supplementary Figs. 1 and 2). Each day of January 2013 is run separately with 12 h of spin-up time preceding the 24-h analysis period for a total of 36 h. For each day, three simulations are carried out. One simulation includes all three wind farms (upwind, downwind and control; UDC), one simulation includes only downwind and control (DC), and the third simulation includes none of the wind farms (NWF). The turbines are included in the WRF simulations using their latitude and longitude[29] and approximating the turbines all as 1.5-MW GE SLE turbines[33] (Supplementary Fig. 9). Some cells include a mix of upwind and downwind turbines.

The effects of turbines are represented in WRF as elevated drag elements[20–22,24,48] that also produce turbulent kinetic energy at the centre of the model grid cell, as large-eddy simulations suggest that the inclusion of turbulence is critical for the wind farm parameterization[57]. The power produced by each turbine in the simulation is a function of the wind speed at the rotor-containing levels in the grid cell in which the turbine is located, and downwind cells show a reduced wind speed because of the removal of momentum by the turbine as it produces power. The exact locations of the effects of individual turbines (of rotor span ~80 m) cannot be represented in a mesoscale model at 1-km horizontal resolution, so it is possible that the wake effect is underestimated when the flow is directly from an upwind turbine to a downwind turbine. Regardless, these simulations capture the diurnal cycle of stability and the rotation of the winds as cold fronts move through the region and their effect on wind power production (Supplementary Fig. 13).

Legal investigations. The legal analysis started in 2014, and an update on all of the major research was conducted in January 2018 to make sure the data were current. The analysis involved extensive reviews of primary law sources that have binding authority such as state statutory websites and cases. In addition to primary-source word searches, we also searched statutes state-by-state in all 50 states to see how each might regulate wind. The statutory research was conducted concurrently with legal research into cases and administrative reviews relating to renewable energy development to provide context as to how particular statutes and regulations were interpreted, either by courts or by state or federal agencies. Similarly, we performed word searches to uncover all reported state or federal court cases related to wind development. Although not all county- and local-level regulation of wind conflicts are available for searching on primary source websites, we could find cases not reflected in reported state or federal court databases or information about proposed regulations through news stories (see Supplementary Note 5).

The research also involved heavy use of secondary sources to help locate and explain primary legal sources, including journal articles, wind data websites and national compilations of wind energy regulations. The most comprehensive national compilations were those from the National Council of State Legislatures (2016)[58], the National Association of Regulatory Utility Commissioners (2012)[59] and the Environmental Law Institute (2011)[60]. The secondary source searches provided verification that, as of the time of their publication, no states had specific statutes addressing wind wakes or wind property right protections. However, Minnesota was an exception because its administrative rules 'regulate the distance between turbines in the same project' suggesting some recognition for the need for setbacks[60]. Research specific to Minnesota was conducted on the Westlaw electronic database and directly through Minnesota state websites. We also contacted representatives of the Minnesota PUC directly to ask questions about what their permitting process required in the context of setbacks or wake studies (see Supplementary Note 6).

The Google search engine and Heinonline's portal to www.municode.com were used to find websites or other information from the communities directly impacted by the Roscoe and Loraine projects: Nolan, Mitchell and Scurry counties as well as the towns of Sweetwater, Roscoe, Loraine, Colorado City and Snyder, TX. Not all of these counties or towns had searchable databases, so we also contacted R. E. Wetsel of Wetsel Carmichael & Allen, LLP. R. E. Wetsel has practised wind development law in Sweetwater, TX, for more than three decades, and he is co-author of one of the leading references on wind law[61] (see Supplementary Note 7).

Finally, we searched broadly for journal articles and other materials that might address the topic of wind wakes. For example, searches of 'wind energy regulation[s]', 'wind wake regulation' on Google and 'wind w/10 turbine and wake' in Lexis's Secondary Materials database brought us back to several articles[25,47,62–68] and books[69,70], some addressing wind waking and some offering possible solutions. In conclusion, the legal research showed that there are no state-level or federal statutes or regulations regarding wind waking or relative wind rights. Further, there are no such city- or county-level ordinances in the location of this study—Nolan, Mitchell, Scurry, Sweetwater, Roscoe, Loraine, Colorado City or Snyder, TX. Without such regulatory protection, parties in wake-loss situations have little negotiating power and few recourses other than to lobby local regulatory officials or to file an expensive common-law nuisance lawsuit.

Data availability

The data that support all of the empirical findings in this study are based on publicly available data as referenced herein. National Weather Service Automated Surface Observing System data were accessed via http://mesonet.agron.iastate.edu/ASOS/. The WRF simulations employ the publicly available WRF code (http://www.wrf-model.org) with no custom code. The data that support the plots within this paper are available at https://github.com/julielundquist/NatureEnergyWindFarmWakes. These data, as well as the namelists for the WRF simulations, are also archived at the University of Colorado PetaLibrary (funded by the NSF under grant OCI-1126839) and can be obtained from the corresponding author upon request.

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Author contributions
J.K.L., D.K. and K.K.D. conceived the research. D.K. designed and carried out the econometric study and wrote the economic sections. J.K.L. and J.M.T. designed the atmospheric simulations; J.M.T. carried out the atmospheric simulations; J.K.L. and J.M.T. wrote the atmospheric sections. K.K.D. designed the legal investigation and wrote the legal sections. All authors contributed significantly to writing the joint sections.

Competing interests
The authors declare no competing interests.

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