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Effects of land-based wind turbine upsizing on community sound levels and power and energy density

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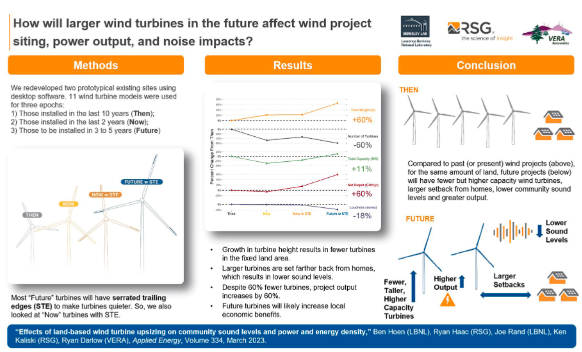
HIGHLIGHTS

- Technological advancement has resulted in larger – and louder – wind turbines.
- Future wind projects will use fewer turbines per unit of land due to setbacks.
- But, project capacity and output will likely increase for those units.
- Average sound levels across future host communities will likely decrease.
- Economic benefits will likely increase as project capacity and output increases.

GRAPHICAL ABSTRACT



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ABSTRACT

Multiple technological, social, and market factors of wind power are evolving rapidly. Most notably, significant wind turbine scaling is occurring and is forecasted to continue. While the larger turbines expected to be deployed in the future are more powerful and efficient, they are also expected to operate at higher sound levels and require larger setbacks than those installed in the last decade. These sometimes-competing deployment trends and impacts cannot be understood via simple extrapolations of past trends. This study analyzes the effect of these future larger turbines on wind turbine micro-siting, project-level power and energy density, and community noise impacts. Due to their taller heights, larger rotors, and higher sound power levels, future wind turbines will require larger setbacks from homes and greater inter-turbine spacing, resulting in fewer turbines deployed for a given land area. This research finds these changes more than offset the effect of the higher turbine sound emissions, significantly decreasing the average sound levels that wind plant hosting communities experience. Yet, simultaneously, plant layouts using future turbine designs also result in projects with higher installed capacities and annual energy output for a given land area. These increases will likely lead to increased tax benefits and local income in the community. The deployment of fewer turbines on a smaller number of parcels could have implications on siting flexibility and landowner payments.

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1. Introduction

The United States and many other countries have aggressive goals to decarbonize their electricity sectors.[1,2] Many of these goals rely on rapidly deploying vast amounts of land-based wind energy. [1,3,4] But various dynamic and inter-related factors influence how and where that deployment will occur. Those factors include, for example:

- Turbine scaling—the continuous growth in turbine height, rotor diameter, and capacity; [5–9]
- Turbine- and plant-level efficiencies—the consistent increase in wind project capacity factors; [5,7,9]
- Market dynamics—e.g., changes to the levelized cost[7,10,11] and grid-system value[6,12,13] of wind energy;
- Transmission and interconnection constraints—the ability to connect and transmit large amounts of wind power via the bulk transmission system; [13–16]
- Land use—the need to find viable land for wind energy build-out; [17–19] and,
- Social acceptance—the acceptance and approval of wind projects by local community members and permitting authorities. [20–23]

Because these factors are evolving during the current rapid deployment of wind energy projects, and are doing so non-linearly and are often competing against or reinforcing each other, many aspects of future wind deployment cannot be understood via simple extrapolations of the past. In order for energy system modelers, wind project developers, policymakers, and local elected officials to accurately anticipate and plan for future wind development trends, a more detailed understanding of the interactions between turbine scaling, plant layout, land use, energy output, and host community benefits and burdens is in order.

Fig. 1 shows trends over the last two decades for rotor diameter, nameplate capacity (i.e., maximum rated electrical power output), tower (i.e., hub) height, and specific power (i.e., rated power output per unit of rotor swept area). Rotor diameter increases have mirrored those of nameplate capacity. Hub height has increased too only not as fast. Together, though, overall turbine height (not shown) has increased dramatically over this period. Swept area (not shown), which is an exponential derivative of rotor diameter (π*(rotor diameter/2) [2]), has increased faster than capacity. This has driven down specific power; the amount of nameplate capacity for a given rotor swept area. A lower specific power is strongly correlated with higher turbine operational efficiency (i.e., capacity factor) allowing greater annual output for a given nameplate capacity. [6,7] The trend toward larger turbines—in terms of rotor diameter, hub height, and rated capacity—is expected to continue well into the future. [11].

These turbine scaling trends also directly affect the available technical capacity (or power density) of wind energy, since wind turbine setbacks from roads, residences, and property lines are commonly based on the total height of the wind turbine. [18] As turbines grow in height, fewer can be placed on the same amount of land.

But setbacks are also often governed, in part, by turbine sounds levels, which have been changing over time too. Indeed, over the last decade, average wind turbine sound power levels (referred to as SWL) have steadily increased, at least based on the US installed wind turbine fleet and the dominant US manufacturers. SWL refers to the inherent sound emissions from a wind turbine, using the international standard IEC 61400–11[24], as reported by a manufacturer or through independent testing. Fig. 2 shows the increase over time of the average SWL of the three major manufacturers of turbines installed in the US. The upward trend in SWL is at least partly related to longer blades, which, unless mitigated, results in increased tip speeds, a major contributor to SWL. Higher SWL can be mitigated by slowing the rotational speed, which has occurred, but not enough to offset the blade-length-related effects. Therefore, fleetwide tip speeds have increased (Fig. 3) (based on calculations derived from data collected for Wiser et al., 2022[7] from manufacturers turbine brochures).

It should be noted that SWL is different from sound pressure level (SPL) that refers to the amount of sound measured at receiver locations such as homes or property lines near a wind project. SPL is strongly influenced by SWL but is also influenced by local factors such as topography, wind speed and direction, turbine layouts, and project operational characteristics. The upward trend in SWL over time, does not imply the same for SPL surrounding wind projects in the US, which are often governed by local regulatory limits. A recent study reviewed 50 US counties with active wind development and showed that SPL limits measured from property lines or residences are common. [25] Therefore, higher SWL, all else being equal, will tend to result in increased SPL, which, in turn, will result in increased setbacks for any given regulatory SPL limit. Thus, as turbines increase the SWL their setback distance from residences increases accordingly, potentially further reducing available capacity for a given land area.

In addition to the direct impact of sound level setbacks on available land for wind development, wind turbine sound can negatively affect attitudes toward existing projects and community support for proposed

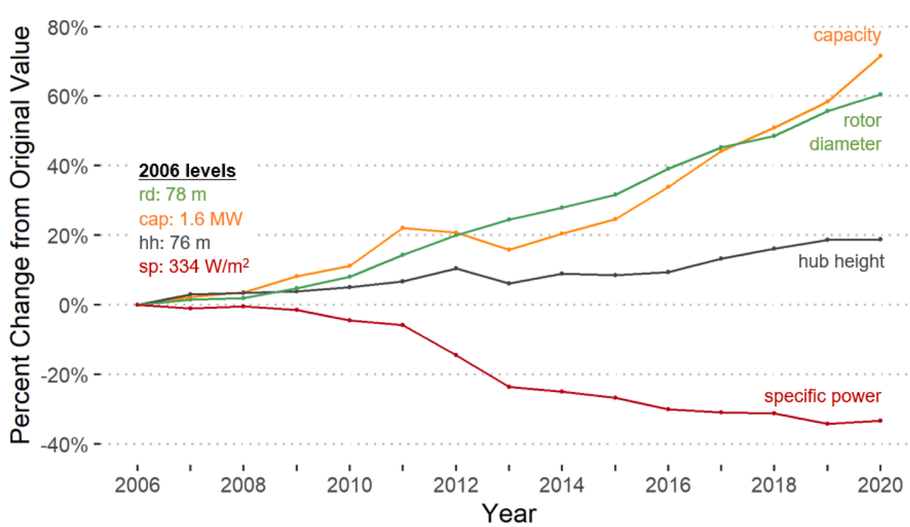

Fig. 1. Average annual fleetwide US wind turbine rotor diameter (rd), capacity (cap), hub height (hh) and, specific power (sp) percentage change trends over time. 2006 original levels shown at left. Fig. A1, in Appendix A, shows the same trends but with underlying units rather than percentage changes. Source: Based on calculations derived from data collected for Wiser et al., 2022[7].

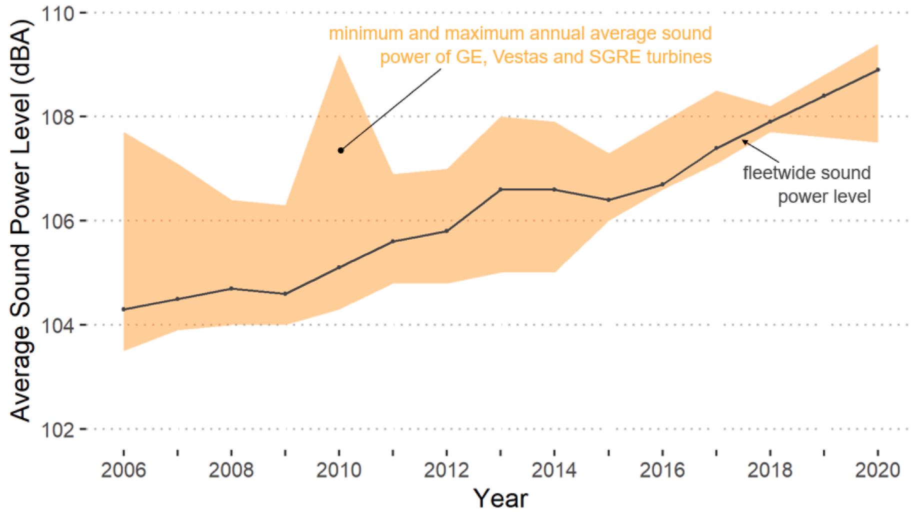

Fig. 2. Annual US fleetwide average and minimum and maximum sound power levels for General Electric (GE), Vestas, and Siemens Gamesa Renewable Energy (SGRE) wind turbines installed in that year, based on data provided to the authors by these manufacturers and data collected as part of the development of the US Wind Turbine Database[26,27]GE, Vestas, and SGRE constitute 95% of US installed capacity over this period.

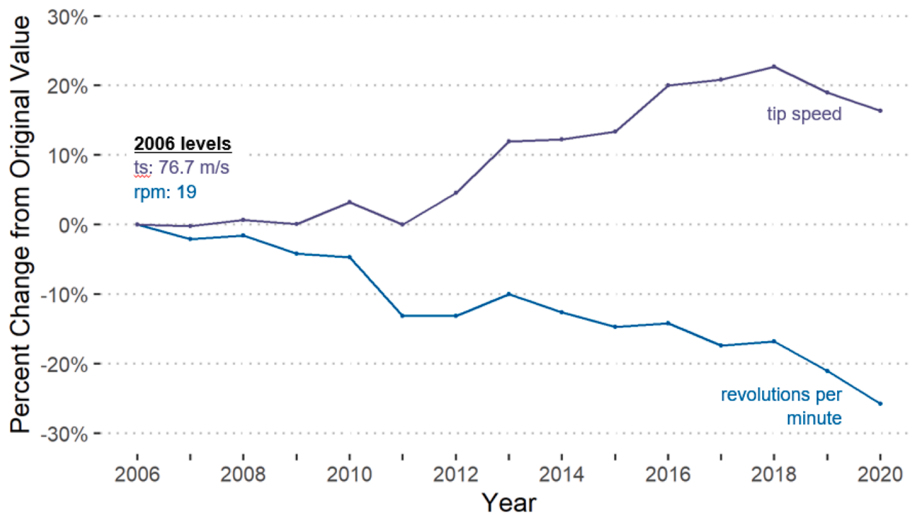

Fig. 3. Average annual fleetwide US wind turbine tip speed (ts) and revolutions per minute (rpm) percentage change trends over time. 2006 original levels shown at left. Source: Based on calculations derived from data collected for Wiser et al., 2022 from manufacturers turbine brochures.

projects. [22] Some individuals report being annoyed by wind turbine sound, [28–31] and being able to hear turbines leads to less favorable attitudes among local residents toward existing wind projects. [32] Prior research identified social acceptance—specifically, sound impacts—as a leading challenge for the continued scaling of wind turbines. [33] The potential sound impacts of future wind turbines and plant layouts are therefore directly tied to the speed and success of local permitting as influenced by community opposition. With wind project developers citing local acceptance and permitting as a key challenge to project success, [22,34] wind turbine manufacturers are increasingly supplying turbine blades with serrated trailing edges (STE) (as reported to the authors by representatives from the three largest wind turbine manufacturers in the US and discussed more in Section 2.5). STE is a simple technology that places physical serrations (or chevrons) on the trailing edge of airfoil blades to reduce turbulent airflow. STE is highly effective at reducing sound emissions by 0.5 to 3.2 dBA, on average, with minimal (and theoretically positive) impacts to turbine power output. [35,36].

Social acceptance can be partially understood through the lens of distributive justice (i.e., by how the benefits and burdens of wind projects are socially and spatially distributed within the local community). [37–40] Local benefits may include job creation, the sustaining of rural economies, and financial benefits (e.g., landowner payments, local ownership or investment, local tax revenues, and, if applicable, reduced electricity costs). Local burdens may include economic impacts (e.g., negative property value impacts, increased wealth inequality) or sensory impacts (e.g., sound, viewshed, or shadow flicker). [22,37] Numerous studies have shown that the fair distribution of these benefits and burdens is an important aspect of local acceptance. [41–44] It is therefore important to examine the impact of future land-based wind turbine scaling (and resulting wind plant layouts) within the framework of distributive justice. This necessitates examining the implications of larger turbines on community impacts such as local landowner payments, tax revenues, community sound levels, and viewshed.

A rich and growing body of literature examines the impacts of turbine technology, [17,18,33] land use, [17,18,45–47] and social and environmental constraints[19,34,48,49] on available technical potential, electricity system costs and emissions, and pathways for the buildout of wind energy and other energy technologies at a macroscale. Rinne et al. (2018), for example, showed that modern, taller turbines with lower specific power ratings substantially increase land-based wind

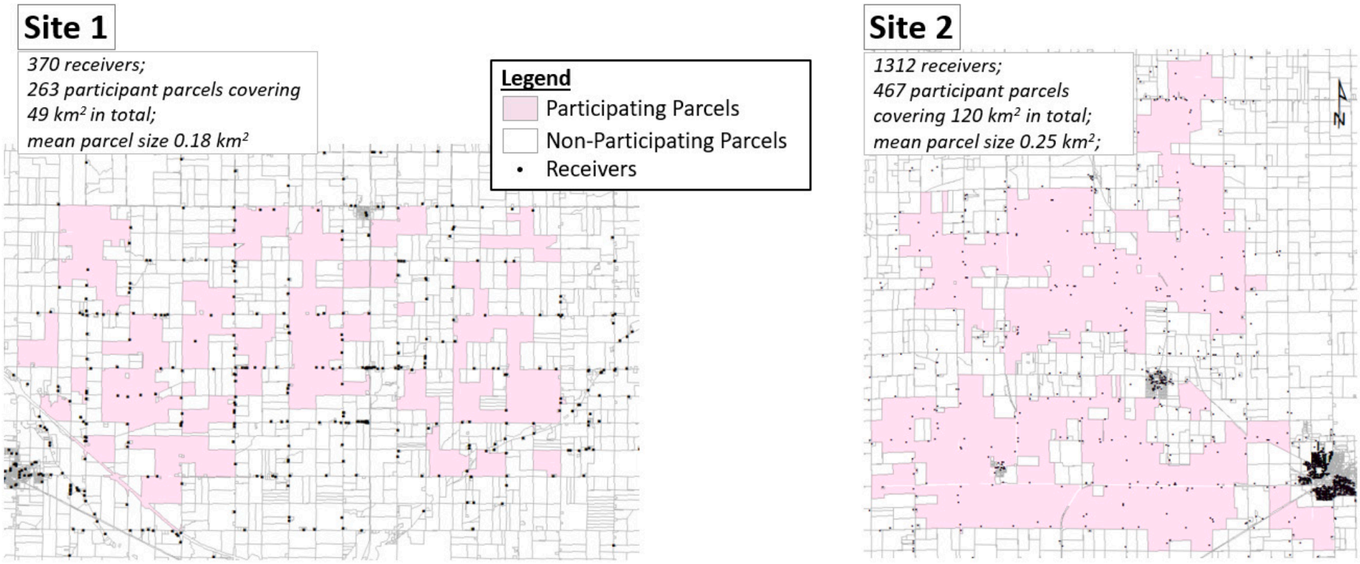

Fig. 4. Parcel maps of Site 1 and Site 2 showing participating (pink) and nonparticipating (white) parcels, and locations of homes (i.e., receivers, black dots).

power potential, despite the decreased installation density of larger machines. [17] Lopez et al. (2021) similarly found that the increased energy generation from these larger turbines mostly offsets the effect of reduced available capacity potential due to increased setbacks, though they still found a small net negative effect to generation. [18] These findings have important implications for the economics and available potential of land-based wind, but these macroscale models are too coarse to capture local land-use and social impacts. [48] Ultimately, little is known with respect to how future land-based wind turbine technology may affect plant layouts, energy generation, land-use, and social impacts at the local level.

Thus, there is a need for research that examines these impacts with a finer resolution. Specifically, how will expected changes in turbine heights, rotor diameters, rated capacities, power curves, and sound power levels affect: (1) total installed project capacity; (2) annual energy generation; (3) land use; and distributive justice factors, such as (4) sound levels as experienced at residences in the community; and, (5) local financial benefits such as landowner payments and tax revenues.

2. Material and methods

The analysis was conducted by siting wind projects via desktop software (WindFarmer, discussed below in more detail) using two prototypical wind development sites; and, three wind turbine models representing three temporal epochs entitled Then, Now, and Future (TNF) for three turbine manufacturers. Each project was modeled to maximize the number of wind turbines that could be installed within the project footprint of each site, thus also maximizing total power output, while also respecting setback and maximum SPL requirements. A detailed description of the sites, epochs, manufacturers, models and methods follows.

2.1. Site selection

The analyses were conducted at two prototypical sites in the Midwestern United States. The two sites currently host operating wind turbines, so they represent realistic developable land configurations (Fig. 4). They were chosen to represent a set of characteristics contemporary sites often share, including: a large developable land area; [50] multiple parcels requiring trade-offs between energy density and setback requirements; areas where the predominant wind direction is either parallel to property development (e.g., roads and parcels) (Site 2, south wind direction) or askew (Site 1, southwest wind direction); and, both participating and nonparticipating landowners intermixed within the project footprint as well as roads and wetland areas.

2.2. Parcel data

The authors assembled the project and neighbor footprints shown in Fig. 4 using property parcel maps surrounding the two existing wind projects. The parcel data, sourced from Digital Map Products (https://www.digmap.com/platform/parcel-data-coverage-map), provided detailed geospatial boundaries to identify parcels that hosted a turbine and those that did not. That distinction allowed the authors to distinguish participating (i.e., hosting a turbine) from nonparticipating landowners. The participating landowners would be in contract with the project owner and not only host a turbine but likely allow higher sound levels at their residences than nonparticipating landowners. For example, nonparticipating residences might have SPL maximums of 45 dBA L_{1h} while participating residences would allow up to 50 dBA L_{1h}. The metric "L_{1h}" is the equivalent continuous sound pressure level, which is a pressure weighted average, over a one-hour period and is a commonly-used metric when measuring, limiting and reporting SPL around US wind projects, such as at property lines and residences. Because these projects were already built, the authors were able to model the sound levels from each existing turbine to nearby residences to check average SPL at those residences. Many turbine-hosting parcels had higher SPL as expected but so too did some parcels that did not host a turbine. Any residence on a parcel without a turbine but with SPL above required limits, was, for the purposes of this research, considered a participating landowner. It is common for developers to have arrangements with more landowners than end up hosting. Therefore, although these parcels did not host a turbine in the existing project, they were allowed to do so in the projects developed for this research.

2.3. Receiver data

Receiver data (i.e., residences) shown in Fig. 4 were obtained and verified via three sources: CoreLogic (https://www.corelogic.com), Melissa Data (https://www.melissa.com/), and Microsoft's Bing Maps Building Footprint Layer (https://www.microsoft.com/en-us/maps/building-footprints). The CoreLogic data comprised all single-family homes, condos, duplexes, and apartments with complete addresses located within 2 km of any single turbine of the existing

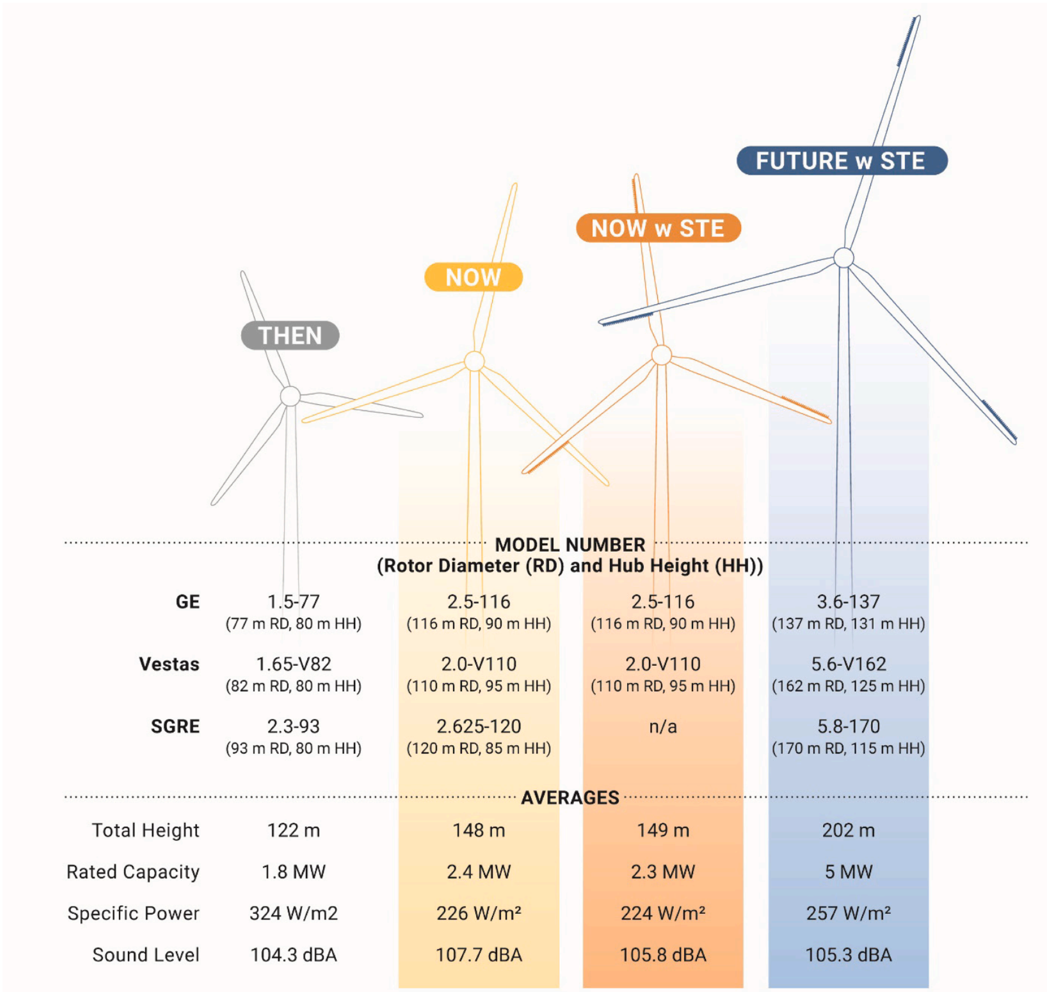

Fig. 5. Then, Now, Now with STE, and Future with STE wind turbine models for each manufacturer. Sound level refers to SWL.

projects in each respective project area. Initially, this yielded a sample of 400 receivers for Site 1 and 1,420 receivers for Site 2.

A variety of quality control measures were used to verify the receiver location data, including removing duplicate location records and location validation using multiple sources. For Site 1, addresses were geocoded using Melissa Data. Points at locations that were determined to be area centroids rather than residential rooftop coordinates were dropped from the final dataset, and points farther than 40 m from a "building" in Microsoft's open-source building footprint data were excluded from the dataset also. For Site 2, all residential parcels within 2 km of a turbine were matched to Microsoft's open-source building footprint data. [51] The centroid of all buildings on a residential parcel was used. The final cleaned sample for Site 1 included 370 receivers and 263 participating parcels covering 49 km^2 in total, and a mean parcel size of 0.18 km^2. Site 2 contained 1,312 receivers and 467 participating parcels covering 120 km^2 in total, and a mean parcel size of 0.25 km^2.

2.4. Wind turbine data

Structural, operational, and sound characteristic data for the various turbines used for this analysis were assembled using two primary sources. The US Wind Turbine Database[26,27] (https://eerscmap.usgs.gov/uswtdb) supplied the turbine structural and wind project data for turbines already installed in the US. Sound power level and operational characteristics for each turbine were collected via WindPro.[52] These data include physical turbine specifications and normal operation power curve, thrust curve, and sound curve (medium turbulence intensity). Additionally, missing information was infilled via data obtained directly from the manufacturer.

2.5. Manufacturers and epochs

Three manufacturers— General Electric (GE), Siemens Gamesa Renewable Energy (SGRE), and Vestas—were chosen for the project because they represent the overwhelming majority of historical installed capacity in the United States and worldwide (at least outside of China). Combined GE, SGRE, and Vestas account for 92 % of the US installed capacity from 2011 to 2020, and 96 % from 2019 to 2020.[26] They accounted for 46 % of the total global installed capacity through 2019, with Vestas, GE, and SGRE ranked first, second, and third, respectively. In 2020, many Chinese OEMs had made inroads capturing the second and fourth spots, but those projects were almost entirely concentrated in China. Outside of China, thru 2020, Vestas, GE, and SGRE make up 92 % of the market.[53].

Three temporal epochs of turbines were examined. The three turbine epochs were chosen to represent, respectively; Then: turbines most frequently installed in the last decade in the US (2011–2020); Now: turbines most frequently installed in the last two years in the US (2019–2020); and, Future: turbines most likely to be installed in the next three to five years in the US (i.e., 2023–2025). The US Wind Turbine Database was used to select individual turbine models for the Then and Now epochs. Manufacturers provided information on their expectations for Future turbine models. These Future models were cross-checked against wind project developer reports provided to the American

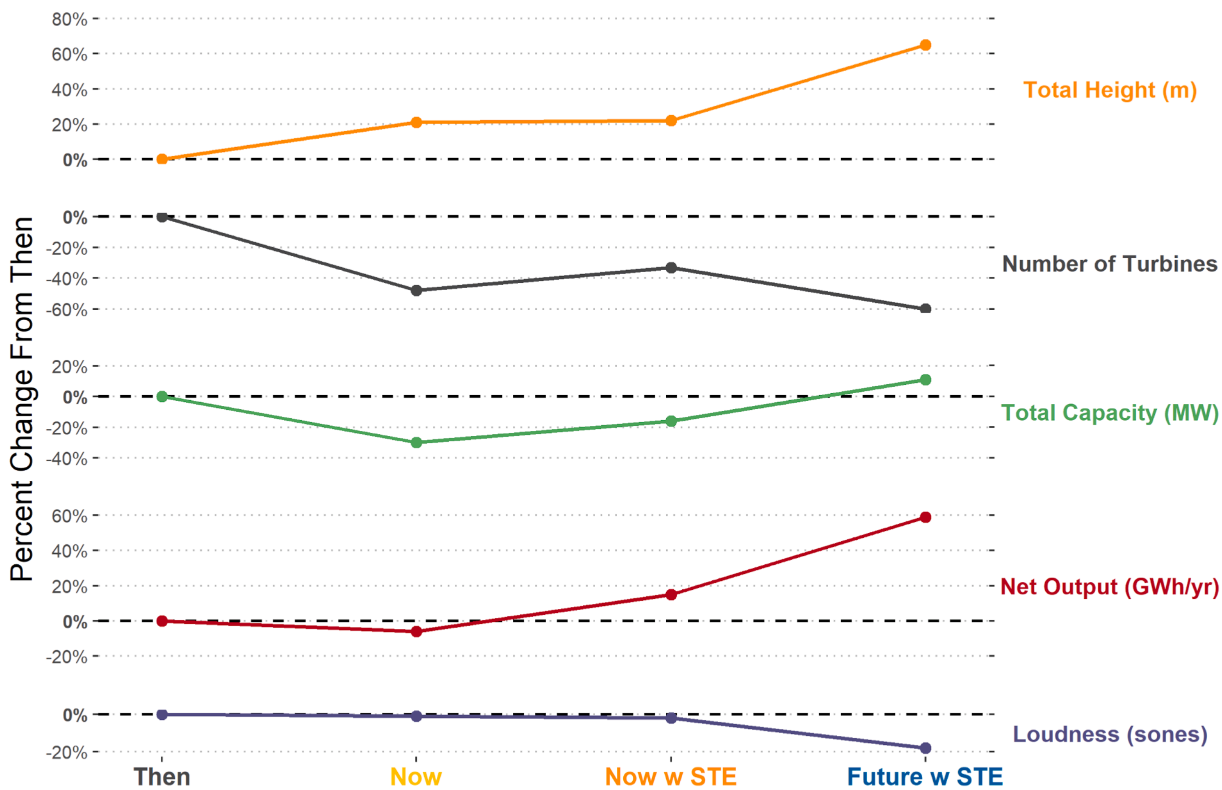

Fig. 6. Mean total wind turbine height, numbers of wind turbines, total project capacity, project output, and loudness among Then to Future w STE wind projects.

Clean Power Association (ACP) and appearing in their CleanPower IQ under construction and in advanced development database (https://cleanpower.org/cleanpower-iq). Future turbine models for each manufacturer appeared in the ACP database. Finally, the model characteristics were also compared to estimates derived from an expert elicitation of future turbine characteristic trends,[11] which also aligned.

This research is focused on the sound from turbines and seeks to determine how SPL change at homes surrounding a wind project as turbines in that project get larger and louder. As noted in the Section 1, one tool manufacturers use to reduce the sound level of turbines is the application of serrated trailing edges (STE) on their wind turbine blades. STE are highly effective at reducing sound emissions by 0.5 to 3.2 dBA, on average, with minimal (and theoretically positive) impacts to turbine power output.[35,36] Manufacturers reported to the authors that STE were not employed except in only the rarest of circumstances in the Then epoch nor for the most part in the Now epoch, but are expected to be employed as a standard feature for all turbines to be installed in the Future epoch, including the models chosen for this analysis. This significant change appears to be happening quickly. One of the manufacturers reported to the authors that > 50 % of turbines shipped in the US in 2021 contained STE as compared to < 10 % in 2019. Because STE would have an effect on several variables of interest, most notably community sound levels and sound related setback requirements, and because all Future turbines are expected to have STE, the authors wanted to examine the effect of STE alone. To do so, separate projects were designed using turbines representing the Now epoch with STE (Now with STE) for two of the three manufacturers, Vestas and GE. SGRE did not have a STE version of their Now turbine. Further, all Future turbines contain STE to align with manufacturer expectations. For the purposes of the text, tables and figures below, and because all Future also have STE, they are interchangeably referred to as "Future" and "Future with STE".

The average wind turbine characteristics and specific makes and models for the TNF epochs are shown in Fig. 5. Moving from Then to Future, average total height increases from 122 m to 202 m while rated capacity increases from 1.8 MW to 5.0 MW and specific power decreases from 324 W/m^2 to 257 W/m^2. Mean sound levels (i.e., SWL) rise from 104.3 dBA to 105.3 dBA despite the application of STE; sound power levels are in fact highest in the Now epoch at 107.7 dBA. In the Now w STE epoch, STE decrease the sound power by 1.6 dB, on average, compared to the same turbines without STE.

2.6. Wind resource

In total, given 11 turbine models and 2 sites, the authors developed 22 TNF projects. A wind resource grid (WRG) was calculated for each project dependent on wind speed and direction characteristics at the unique turbine hub heights. WRGs were calculated for hub heights of 80 m, 85 m, 90 m, 95 m, 115 m, 125 m, and 132 m (see Fig. 5). WAsP[54] software was used for a single "met mast" with a horizontal resolution of 30 m, 16 wind direction sectors, with a coverage encompassing the largest project footprint of each site.

The meteorological data were extracted from six-year modeled point data from the US Wind Toolkit[55] dataset from 2007 to 2013. The US Wind Toolkit data includes hourly wind speed at heights of 10 m, 40 m, 100 m, 120 m, and 140 m and hourly wind direction at 100 m. The 100 m wind direction data were applied to all hub heights, which was binned monthly for each of 16 wind direction sectors. The hub height data were exported into a .tab file that represents a meteorological mast located at the calculation point of the US Wind Toolkit data. The density, temperature, and other "climate context" data were retrieved by WAsP using its location-based barometric reference dataset.

The elevation and surface roughness data used by WAsP to calculate the WRG were extracted from the National Elevation Dataset Digital Elevation Model (DEM)[56] and the 2011 National Landcover Dataset (NLCD).[57] The DEM data were exported as 3 m elevation contours for an area several kilometers larger than the largest of the 22 project footprints, while the NLCD was extracted covering 5 km beyond the DEM coverage.

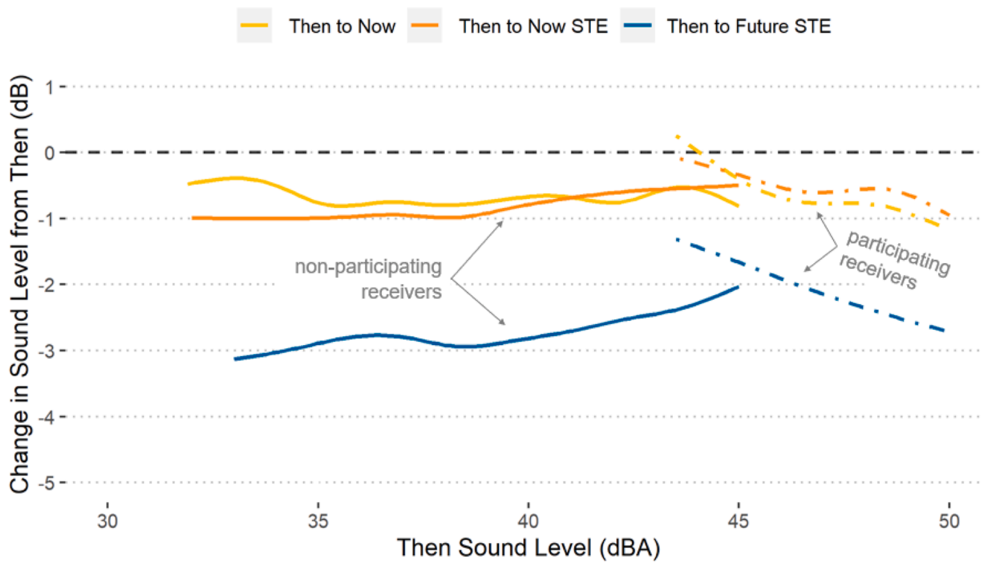

Fig. 7. Average change of overall A-weighted SPL referenced to Then (i.e., starting) SPL by participation. Nonparticipants are shown as solid lines and participants are shown as dashed.

2.7. Model Basis

The data described above were combined in WindFarmer[58] wind project design software to form a "Model Basis" for each of the 22 projects. Boundary areas representing the extent of the parcel footprint for each site were combined with participating and nonparticipating receptor points, the DEM and NLCD data, and the WRGs calculated by WAsP. In addition, turbine specifications and operation performance were added. WindFarmer combines these data to calculate the hourly wind energy production, including losses from wind turbine wake effects and turbulence from surface interactions to generate annual energy production values for each scenario. WindFarmer also checks to ensure that the layout of the wind turbines meets siting requirements such as setback distances and sound limit constraints as described below. These procedures are identical to those used by practitioners, including some of the authors, when developing a wind project site for clients.

2.8. Preliminary layout and constraints

The three turbine locational constraints used for this analysis were: 1) a boundary setback of 1.3x total turbine height from any property line or roadway; 2) maximum sound levels of 45 dBA L_{1h} at nonparticipating receivers (residences) and 50 dBA L_{1h} at participating receivers (residences); and 3) an elliptical spacing constraint of 8 rotor diameters row to row and 5 rotor diameters side to side with the major axis facing the primary wind sector. (As noted in Section 2.1, Site 1′s primary wind sector is southwest and Site 2′s is south.) These constraints were determined through consideration of standard requirements in several jurisdictions across the United States.

Once a draft layout was achieved for each project, the layout was optimized for energy production as described below.

2.9. Micrositing and optimization

Draft project layouts were optimized for annual energy production (i.e., output) using a single WindFarmer procedure based on the eddy viscosity model with a maximum of 200 iterations or until 20 "fruitless" iterations were reached, while still respecting the various design constraints.[i] After optimization, total nameplate capacity, annual output, net capacity factor, and array efficiency for each scenario were calculated.

2.10. Sound pressure level estimates

As noted above, SPL limits were applied as a design constraint in WindFarmer with each project having SPL limits of 45 dBA_{L1h} for non-participating residences and 50 dBA_{L1h} for participating residences. Once a final layout was determined, final SPL estimates were modeled for each participating and non-participating residence. SPL modeling was conducted using CadnaA 2022[59] following the procedures laid out in ISO 9613–2[60] and ANSI/ACP 111-1-2022[61].

SPL was converted to Loudness for one of the figures in this report (Fig. 6). SPL is measured in decibels, which is a logarithmic scale. As such, it is difficult to use the SPL to estimate how people perceive differences in sound level. For example, a doubling in SPL is not a doubling in the perceived loudness of a sound. Thus, to determine the percent change in the perceived level of wind turbine sound in the community, which is used in Fig. 6, epoch-averaged octave band sound levels were converted to loudness using the Stevens' Mark VI calculation.[62] Loudness is a psychoacoustic parameter that better represents the human perception of the level of sound than dBA. It is measured in sones and is a linear quantity, not logarithmic, and can therefore be expressed as percent change.

3. Results

The key results from our analysis are described in percentage terms in Fig. 6 (the data used to construct these percentages, which is shown below in parentheses, are provided in Table A2 in the Appendix). From the Then to the Future epoch, wind turbine heights are expected to increase an average of 60 % (from 122 m to 202 m). This increase, along with sound power level increases, decreases the number of turbines that

[i] Based on the considerable development experience of the authors, 200 iterations is more than adequate to examine differences among micro-siting options. Moreover, specifying 20 "fruitless" iterations ensures the procedure was not able to improve outcomes despite a large number of attempts.

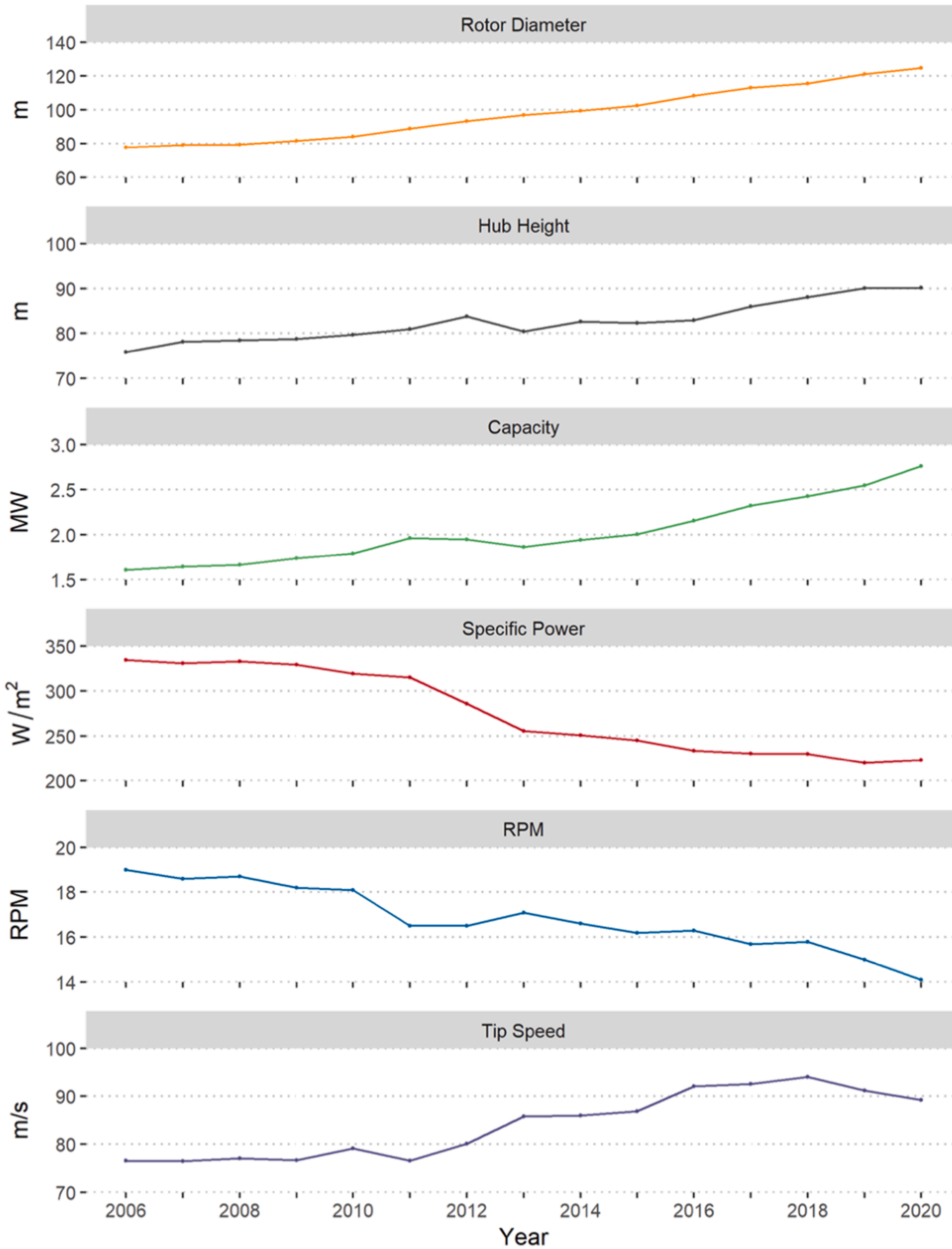

Fig. A1. US fleetwide turbine characteristic trends displaying units. This figure uses the same data as Fig. 1, which is shown as percentage changes. Y-axis unit abbreviations are as follows: meter (m), megawatts (MW), watts per square meters (W/m^2), revolutions per minute (RPM), and meters per second (m/s).

can be developed. The average number of turbines at these two project sites decreases by 60 % (from 222 to 89). Despite this, the total installed nameplate capacity increases by roughly 11 % (from 395 MW to 437 MW), and estimated annual energy output increases by almost 60 % (from 1,146 GWh/yr to 1,825 GWh/yr).

These average trends are shared among all the manufacturers and across both sites, with some variation in the size of those trends (see Fig. A2 in the Appendix for details on each project).

Despite increasing wind turbine SWL (i.e., sound emissions) moving from Then to Future epochs (Fig. 5), the average community SPL – experienced at receiver locations (i.e., homes) - decreased between those two epochs. The average SPL surrounding the wind turbines decreases by 3.3 dB (not shown – dB converted to sones for Fig. 6). Average loudness decreased from 2.84 sones in the Then epoch to 2.31 sones in the Future epoch, representing an 18 % reduction in average loudness between Then and Future.

A more detailed look at the SPL decrease experienced at participating and non-participating residences is described in Fig. 7 (using dB). The

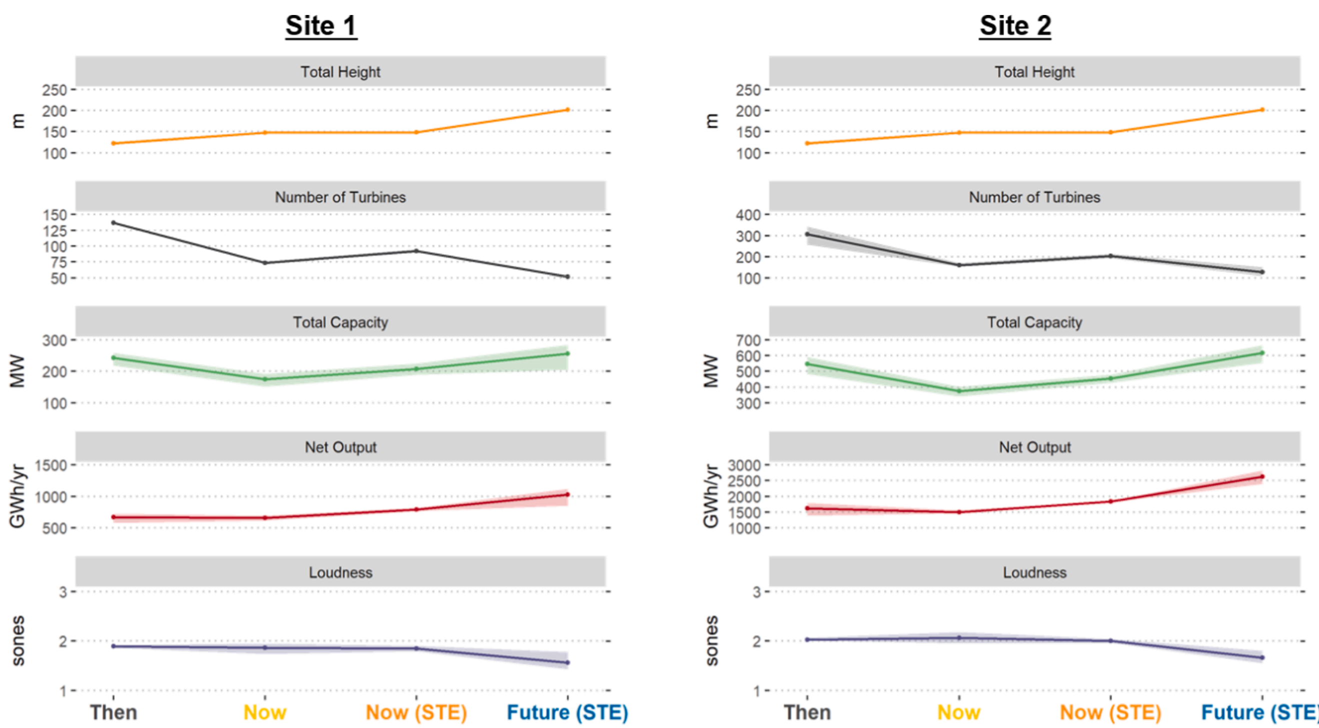

Fig. A2. Site 1 and 2 outcome averages and ranges across all manufacturers showing units. This figure uses the same data as Fig. 6, which is shown as percentage changes and with Site 1 and Site 2 combined into a single average. Y-axis unit abbreviations are as follows: meter (m), megawatts (MW), gigawatt hours per year (GWh/yr), and sones (sones). Shaded areas represent the range between minimum and maximum among the three manufacturers for that metric and Site.

Table A1
Details of manufacturer wind turbine models used in the analyses. Many of these data are shown and/or summarized in Fig. 5.

Manufacturer	GE				SGRE				Vestas			
Project	Then	Now	Now w STE	Future w STE	Then	Now	Now w STE	Future w STE	Then	Now	Now w STE	Future w STE
Turbine Details												
Model	1.5-77	2.5-116	2.5-116	3.6-137	2.3-93	2.625-120	n/a	5.8-170	V82	V110	V110	V162
Rotor Diameter (m)	77	116	116	137	93	120	n/a	170	82	110	110	162
Hub Height (m)	80	90	90	131	80	85	n/a	115	80	95	95	125
Total Height (m)	119	148	148	199.5	127	145	n/a	200	121	150	150	206
Rated Capacity (MW)	1.5	2.5	2.5	3.6	2.3	2.625	n/a	5.8	1.65	2	2	5.6
Specific Power (W/m^2)	322	237	237	244	339	232	n/a	256	312	210	210	272
RPM	20.4	15.7	15.7	11.4	16	13.5	n/a	8.8	14.4	17	17	12.1
Tip Speed (m/sec)	82	95	95	82	78	85	n/a	78	62	98	98	103
Tip Speed (mph)	184	213	213	183	174	190	n/a	175	138	219	219	230
Sound Output (dBA)	104	107	105.5	106	105.4	108.5	n/a	106	103.4	107.6	106	104

figure presents the changes in average SPL experienced initially in the Then epoch as compared to the Now, Now with STE, and Future epochs. For each epoch consistent decreases from Then SPL are evident. This is especially pronounced for the Future epoch, where decreases as compared to the Then epoch are between 1.5 and 3 dB. As is discussed in Section 2.2 and shown in Fig. 4, participating homes tend to be closer to wind turbines and are also subject to higher noise limits when designing the projects relative to non-participants' homes. That is indeed what is shown in Fig. 7, but, importantly, a reduction in SPL occurs for both participating homes and their nonparticipating neighbors in each of the three epochs and especially in the Future epoch. In other words, all receivers, regardless of if they are participating or nonparticipating, experience, on average, lower sound pressure levels in all epochs, and especially the Future epoch, as compared to Then SPL.

4. Discussion

These results show that larger turbines in the future will likely lead to a decreased number of turbines per unit of land and lower community SPL, but increased capacity and project energy output. A number of the implications of these findings are discussed below.

Fewer turbines sited farther from homes, resulting in lower average SPL, will likely be a net positive for communities as compared to currently operating projects. The authors calculated the average distance from neighboring homes for Future projects is 1.39 km as compared to 1.17 km, 1.33 km, and 1.22 km for respective Then, Now, and Now with STE projects (corresponding medians are 1.29 km vs 1.02 km, 1.21 km, and 1.07 km). Setbacks from homes and property lines will remain a controlling factor in deployment potential.[18,19] With fewer larger turbines, and larger average distances to residences due to height related setbacks, SPL related setbacks requirements might be imposed less frequently.

Higher wind project sound level exposures are correlated with a heightened awareness of wind turbine sounds by community members.[28] but the opposite is also true. Therefore, at lower average sound levels, wind project neighbors will be less aware of the wind turbine

Table A2
Manufacturer and site-specific results for each epoch. These data are shown in both Fig. 6, as percentage changes as compared to the Then epoch and in Fig. A2 with the y-axis showing units of change.

Manufacturer	GE				SGRE				Vestas			
Project	Then	Now	Now w STE	Future w STE	Then	Now	Now w STE	Future w STE	Then	Now	Now w STE	Future w STE
Project Site 1 Details												
Number of Turbines	146	72	90	57	112	73	n/a	49	152	76	95	50
Total Capacity (MW)	219	180	225	205	258	192	n/a	284	251	152	190	280
Net Capacity Factor	30%	42%	41.6%	47%	32%	42%	n/a	45%	32%	46%	46.0%	45%
Net Output (GWh/yr)	583	661	819	852	728	698	n/a	1121	702	618	766	1110
Array Efficiency	94%	96%	94.9%	96%	93%	95%	n/a	95%	94%	96%	95.3%	95%
Mean dBA	34.8	34.6	34.4	31.1	34	33.4	n/a	28.9	34.2	33.7	33.3	29.1
Median dBA	37.2	37.1	36.5	32.9	36.3	35.9	n/a	32.5	37.2	36	35.4	32.9
Project Site 2 Details												
Number of Turbines	323	152	192	150	257	153	n/a	109	342	171	214	119
Total Capacity (MW)	485	380	480	555	591	402	n/a	632	564	342	428	666
Net Capacity Factor	33%	45%	44.1%	49%	35%	44%	n/a	48%	34%	49%	48.4%	48%
Net Output (GWh/yr)	1387	1482	1854	2389	1786	1559	n/a	2656	1692	1462	1813	2819
Array Efficiency	92%	94%	93.4%	95%	91%	94%	n/a	94%	91%	95%	93.7%	94%
Mean dBA	41.2	40.3	40.6	40	40.7	39.8	n/a	36.2	41	40.4	40.1	36.6
Median dBA	40.4	39.6	39.8	39.1	39.9	38.9	n/a	34.5	40.2	39.6	39.2	34.9

sounds. Sound levels of wind turbines are regularly cited as one of the most significant impacts on neighboring homeowners.[28–31] Other sensory impacts of wind turbines—such as viewshed, shadow flicker, or aviation lighting—are also a concern for many community members.[25,29,63] Turbines in the future will be larger (by 65 % in this study) as compared to their previously installed versions, and therefore will be more visible from a larger distance. But, an estimated 60 % fewer turbines will be installed given the same land area. An open question remains as to whether fewer larger turbines are less aesthetically impactful compared to more plentiful smaller turbines.

These results indicate a significant amount of land will be freed from direct land use (pads, roads, collector systems, and inter-turbine electric lines), which will lead to less clearing and disturbing of farmland or forests, and a reduction of impervious ground cover. This will minimize the wildlife and ecological impacts of these installations.

Local economic benefits are tied, in part, to project costs and revenue. A significant portion of local benefits are derived via tax payments tied either to installed capacity, total capital costs, or revenue the project generates.[64,65] Tax revenue, whether paid through an established tax policy/structure or via payment in lieu of taxes (PILOT), will likely be higher in the future across the US, on average, given considerable Future turbine increases in energy output and capacity. That average will likely be partly offset by the historic and forecasted reductions in wind project capital expenditures (CapEx).[7,11] But these CapEx decreases, forecasted to be roughly 3 % to 5 % in the next three to five years (not considering recent supply chain constraints, inflation, and interest rate hikes) will likely be more than offset by the 11 % increase in rated project capacity modeled in this study. Therefore, even taxes based on the installed cost of the project will likely increase in the future. Though, the tax outcomes in individual states, counties, and other taxing districts will, of course, differ dramatically based on their unique taxation policies. Of course, tax payments are only a part of local income. According to one wind project developer the authors consulted, the largest payments are made to participating landowners that host a turbine. Although amounts or specifics regarding payments to landowners are not well documented in the literature, it is assumed that they are at least partially tied to installed capacity or output, and therefore would potentially further add to local community benefits as turbines scale.

Importantly, though, the result of this analysis shows that dramatically fewer landowners will be required for future projects. Therefore, fewer landowners will receive these payments, concentrating that income among fewer community members. This could lead to perceptions of winners and losers, intracommunity conflict, and distributive injustice.[41,66] Further, since participating landowners are afforded more meaningful opportunities to engage with and influence wind project planning processes,[67,68] community perceptions of fairness of the planning process could be adversely impacted as well.

In addition to lower community sound levels and potentially higher community tax revenue, the significant increase in output, with dramatically fewer turbines might allow greater siting flexibility. Researchers have found that allowing community stakeholders to have a greater say in the planning and siting process might lead to increased community acceptance of proposed projects.[37,68,69] With greater siting flexibility, a set of different equally compelling options (from the developer's perspective) might be considered in concert with the community. This could provide them an opportunity for input and a greater sense of control of the development outcome.

The authors believe this study will provide useful information for stakeholders considering projects in the next three to five years both inside and outside the US. Wind development has occurred and likely will occur in landscapes and atmospheric conditions, and under similar design constraints that were studied here, including in the European context. [70] Experts around the globe, including Europe, Asia, and North America, forecast similar turbine growth trends to those utilized in this study. [9,11] Notwithstanding, there are several caveats that should be considered. This study used only two sites and three future turbine models. The sites used do not represent all existing and potential sites for wind turbine development. These sites were located in the Midwestern United States, in relatively flat and simple terrain with fairly consistent and predictable wind conditions. There are other types of sites (e.g., ridgelines, hills, or other forms of complex terrain) and other types of wind flow patterns which promote different development strategies that were not represented here. Additionally, there can be permitting or electrical interconnection constraints that would encourage alternative development strategies that were not represented here. Therefore, future research should explore these impacts across a variety of sites and possible turbine makes and models.

Other follow-on research is also recommended. Detailed comprehensive ex-post economic analyses would be useful in empirically exploring the drivers to net local economic benefits and costs given larger future turbines. Further, although the authors see a clear pattern of decreasing numbers of turbines when future larger and louder turbines are sited, the individual contribution of sound level setbacks versus total height related setbacks was not explored. Such exploration would provide more clarity as to how various future changes will impact development outcomes. Finally, the authors suggest it would be fruitful to research the perceived aesthetic tradeoffs of fewer larger turbines versus more plentiful smaller turbines.

5. Conclusions

The technological advancement of wind turbines over the course of decades has resulted in higher operating efficiencies, increased reliability, and lower levelized energy costs. This advancement has manifested in much larger machines: the average wind turbine installed in the U.S. in 2020 had approximately 70 % higher rated capacity, a 60 % larger rotor diameter, and a 20 % taller tower than the average turbine installed just 15 years prior. This upsizing is expected to continue into the future. These larger turbines, alongside their evolving operating characteristics and wind plant layouts, have resulted in considerable and ongoing changes to wind projects' capacity, energy generation, and community impacts. Because these technological factors are evolving rapidly and often non-linearly, future wind project trends and impacts cannot be assessed via simple extrapolations of the past.

Although average turbine rotational speed has decreased over time, blade tip speeds have continued to increase (due to larger blades) and therefore turbine sound power levels have likewise increased across the installed US wind fleet. Larger wind turbines necessitate increased inter-turbine spacing to optimize energy production and reduce maintenance costs. One might hypothesize that the increase in turbine sound power levels and tip speeds would result in communities hosting wind turbines in the future experiencing higher levels of turbine sounds than communities that are hosting older turbines, but this study reveals the opposite.

Wind turbines anticipated to be deployed in the next three to five years will, potentially, substantially decrease the SPL communities experience (by 3.3 dB), while simultaneously increasing installed capacity (by 11 %) and annual energy output (by almost 60 %) for a given land area. Increases in capacity and output will likely lead to increased tax benefits in the community. The deployment of fewer turbines, on fewer (and larger) parcels, might create greater siting flexibility which could enable greater opportunities for community input in the planning process. However, the concentration of wind turbines (and therefore, landowner payments) on fewer parcels may also exacerbate potential disparities between those receiving and those not receiving substantial benefits.

Collectively, these changing wind project characteristics could dramatically impact the economics (cost and value), technical potential, and social acceptability of wind energy.

CRediT authorship contribution statement

Ben Hoen: Conceptualization, Methodology, Project administration, Validation, Formal analysis, Visualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Ryan Darlow:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Ryan Haac:** . **Joseph Rand:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Ken Kaliski:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix

See Figs. A1 and A2 and Tables A1 and A2.

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