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Out With the Old: Empirical Trends in U.S. Land-Based Wind Turbine Decommissioning and Repowering

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ABSTRACT

A growing number of wind turbines (WTs) across the globe are now reaching or exceeding their expected service lifetime; WT decommissioning is on the rise. Accordingly, questions pertaining to WT end-of-life have risen in importance in policy and practice. Yet, research on the various factors relating to WT decommissioning is relatively sparse. Moreover, the key assumptions underpinning that prior research (e.g., the lifespan of WTs, characteristics of WTs being decommissioned, and whether the site is repowered with new WTs) have never been empirically tested across a large set of decommissioned WTs. Leveraging a uniquely comprehensive and spatially explicit dataset of decommissioned WTs in the United States, this research analyzes spatial, technological, and temporal trends in WT decommissioning and develops a novel predictive model for WT decommissioning. Our analysis pinpoints more than 12,400 WTs that have been fully decommissioned in the United States., the majority of which have been relatively old (> 30 years) and small (< 200 kW). While a WT's age alone is a good predictor of the likelihood of decommissioning, other factors such as the size of the WT and recent performance are also important and significant predictors. Most sites where decommissioning has occurred have seen subsequent repowering, with repowered plants featuring substantially fewer WTs (−86 on average) and higher rated plant capacity (+62 MW on average). Many existing WTs in the U.S. are approaching the end of their expected life with roughly 7500 being 20 or more years old. Findings can help policymakers and stakeholders begin preparing for this potential wave of future decommissioning and repowering.

1 | Introduction and Background

As of May 2025, there were over 76,000 wind turbines installed across the United States, widely varying in size (i.e., hub height and rotor diameter), rated generating capacity, and age [1]. U.S. wind power installations have been especially strong over the past two decades [2], but thousands of turbines were installed in California in the 1980s, beginning as early as 1981 [1, 3, 4]. While the U.S. *installed* power plant fleet has been well characterized through mapping and spatial analysis [1, 5] as well as analysis of technology, performance, and cost trends (e.g., [2]), critical questions remain with regard to the end-of-life for wind turbines, particularly in terms of decommissioning and/or repowering stage.

A growing number of wind turbines across the globe are now reaching (or exceeding) their expected service lifetime. Typically, wind turbine lifespans have been assumed to be approximately 20–25 years [6–9], though a survey of U.S. wind industry professionals found expected lifespans to be increasing over time—up to 30 years for more recent projects [10]. Multiple alternatives exist for wind plants at the end of their operational life, including full decommissioning (i.e., complete removal of equipment without replacement), full

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repowering (i.e., complete dismantling of old turbines and replacement with new turbines at the existing project site), or partial repowering (i.e., retrofitting existing turbines with new components like generators, gearboxes, and/or blades) [11, 12]. Repowering is of growing interest to wind plant operators, not only because it provides an opportunity to increase site productivity and profitability, but also because it can reduce barriers to wind development such as grid interconnection, social opposition, and permitting [13].

Notably, as this research finds, more than 12,400 turbines have already been fully dismantled in the United States alone. As such, these end-of-life questions have risen in importance in policy and practice. Yet, in comparison to the vast body of literature focused on the installation and expansion of wind energy infrastructure (and the challenges and barriers therein), research on the various (e.g., economic, technical, and social) factors relating to wind turbine and plant decommissioning is relatively nascent and sparse. Perhaps coinciding with the early fleets of wind turbines reaching their retirement age, research interest in wind decommissioning and repowering is evidently increasing.

Recent research has explored a variety of subtopics within decommissioning and repowering, which we distill into four overarching thematic groups, briefly described below:

1. Several researchers have conducted techno-economic modeling to assess scenarios of decommissioning and repowering, for example examining the cost of decommissioning and repowering or impacts to energy generation, resource planning, and electric-sector scenarios [9, 11, 14–17].
2. A growing body of research focuses on wind turbine waste, recycling, and circular economy considerations. In particular, prior studies have quantified and/or forecasted the volume and mass of waste and recyclable material as turbines are decommissioned [6, 18–23].
3. Others have begun to examine the implications of wind plant decommissioning, repowering, or even abandonment on local host communities and related stakeholders with regard to social acceptance [24–28], landscape impacts [29], extending local consent and acceptance [30], and/or fair and participatory planning processes for decommissioning [31].
4. Finally, and most broadly, another set of research has attempted to examine or characterize wind plant end-of-life decisions across a wide array of factors, encompassing economic, technological, legal, social, and environmental considerations [7, 13, 32–35]. Toering and Heun [36] took this a step further by developing a framework for "smarter" decommissioning policies and requirements. Relatedly, some reports focus on translating these broad end-of-life considerations for key stakeholders like local permitting officials or host communities [37, 38].

Underpinning all of this prior research are assumptions about future wind plant decommissioning, including the lifespan of turbines before dismantling, the size and types of turbines being dismantled, the extent to which material is recycled versus sent to landfills, and whether the site is repowered with new wind turbine models or restored to previous conditions (i.e., without turbines).

Yet, these assumptions and questions have never been empirically tested across a large or representative set of decommissioned turbines. Leveraging a uniquely comprehensive, detailed, and spatially explicit dataset of decommissioned turbines in the United States, this research fills important knowledge gaps by analyzing spatial, technological, and temporal trends in wind turbine decommissioning. Through the development of the U.S. Wind Turbine Database (USWTDB) [1, 5] over the past 8 years, the research team has utilized aerial imagery and other sources to identify more than 12,400 U.S. wind turbines that have been fully dismantled and removed, recorded their exact locations (latitudes and longitudes), and, to the extent possible, documented important attributes about them such as the turbine make, model, nameplate capacity, hub height, rotor diameter, installation year, and year of decommissioning.

This unprecedented dataset of decommissioned turbines—which is publicly available through the Lawrence Berkeley National Laboratory and the U.S. Geological Survey—allows us to examine a variety of important research questions, such as: (a) Has the rate of land-based wind turbine decommissioning changed over time in the United States? (b) What are the technical specifications and attributes of wind turbines that have been decommissioned, and how has that changed over time? (c) How old are wind turbines when they are fully decommissioned? (d) How does the decommissioning age compare with the age of the *existing* wind turbine fleet in the United States? (e) How well can we predict wind turbine decommissioning, based on available wind turbine and plant characteristics? (f) How frequently are decommissioned wind plants repowered—i.e., do we see new wind turbines installed in the plant footprint where old turbines were removed?

2 | Methods

2.1 | Developing the Dataset of Decommissioned Turbines

The dataset of decommissioned turbines (henceforth abbreviated as D-USWTDB) is the culmination of more than 10 years of data compilation and human visual verification of U.S. wind turbine locations, which began before 2013 for a (now deprecated) U.S. Geological Survey dataset of wind turbine locations [39] and continues to this day for the quarterly-updated USWTDB [1, 5].

As described in Rand et al. [5], the USWTDB incorporated five source datasets to identify wind turbine locations and technical specifications; three of those source datasets are regularly updated: the American Clean Power (ACP) Association's member-only turbine dataset, the Federal Aviation Administration (FAA) Digital Obstacle File (DOF), and the FAA Obstruction Evaluation—Airport Airspace Analysis (OE-AAA) file. After incorporating, merging, and geospatially matching turbine points from these sources, human analysts visually verify the location of wind turbines using high-resolution aerial imagery.

As part of the visual verification process, analysts identify and flag records of wind turbines that have been dismantled and removed. They document the closest obtainable year of dismantling, the imagery source, and the accessible image date confirming the decommissioning. In some locations, annual imagery may not be available and a turbine may be removed during a year or years without associated imagery. In these cases, analysts utilized existing imagery and, when possible, ACP data to make the best possible estimate of the year of decommissioning.

While USWTDB analysts focus visual verification efforts on *newly constructed* turbines, quarterly efforts are made to identify decommissioned turbines. For example, data from ACP may indicate that a wind plant has been decommissioned, so analysts would check that site to verify whether turbines had been dismantled in the available imagery. Similarly, they periodically check the oldest turbines in the USWTDB to see if they have been removed. As of the date of analysis for this article (June 2025), all turbines installed with a marked online year before 2005 had been visually inspected for decommissioning. Additional sites have also been checked periodically through normal quarterly verification processes.

Notably, the D-USWTDB only includes turbines that have been fully dismantled and removed. Because it relies on imagery to determine if a turbine is decommissioned and not on operational characteristics, it does not capture turbines that are still standing and no longer operational or producing power. Those still-standing turbines remain in the USWTDB; therefore, the D-USWTDB might underestimate the number of decommissioned turbines by excluding those that are standing but not operational. This distinction highlights that the D-USWTDB focuses on dismantled turbines based on available imagery rather than their power generation status.

Similarly, where we describe “repowering” in this paper, we are only referring to full repowering as opposed to “partial” repowering or retrofits. Under partial repowering, some components of the original turbine are left intact (e.g., the tower and nacelle) while others are replaced (e.g., the rotor and generator) [12]. Partial repowering can provide access to tax incentives, increase energy production, and extend project life [2]. In this analysis, we only examine “full” repowering, wherein older turbines are fully removed and entirely new turbines are installed at the same site.

Missing data values are another noteworthy limitation of the D-USWTDB. Despite best efforts, key data fields remain missing for some records. For example, the year of decommissioning is missing for 1.8% of records; installation year is missing for 4.5%; turbine nameplate generating capacity is missing for 27.0%; turbine manufacturer is missing for 28.3%; rotor diameter is missing for 33.2% and hub height is missing for 63.4%. In general, missing data are more problematic for the oldest turbines in the dataset, while newer turbine data are more complete.

2.2 | Summary Analysis

A variety of basic statistics are summarized to characterize the historical trends of decommissioned turbines. These included: counts of decommissioned turbines by installed year and decommissioned year; the sum of decommissioned nameplate generating capacity by installed year and decommissioned year; summary statistics of capacity, hub height, rotor diameter, and installed year by decommissioned year; summary statistics of turbine age upon decommissioning; and summaries of turbine capacity groupings (i.e., “bins”) by turbine age groupings. Turbine age is calculated as the year of decommissioning minus the year of installation for decommissioned turbines, and 2025 minus the year of installation for existing turbines. These summary results are presented in Sections 3.1–3.4, and a table of basic summary statistics is included in the appendix.

2.3 | Classification of Site Repowering vs. Full Removal Without Replacement

The source data for turbine attributes do not reliably indicate whether a new wind plant is actually a repowering of an old project. Therefore, assessing the frequency with which decommissioned wind project sites are repowered with new turbines requires creative spatial analysis; we employed two distinct methods to explore this question.

First, we examined the question at the individual turbine level. We compared the decommissioned dataset to existing turbines in the USWTDB. Starting with the decommissioned turbine dataset, we used the “geonear” function in Stata statistical programming software to calculate the geodetic distance to “near neighbors” (within 1 km) in the USWTDB. To be considered a repowering, the “new” turbine also had to be constructed in the same year or after the nearby “old” turbine was decommissioned. Turbines decommissioned in 2024 or 2025 were excluded from this analysis, since their recency might not allow sufficient time for potential new turbine construction at the site.

Second, we explored the question at the plant level. This was less straightforward; accurately associating individual decommissioned turbines with their respective plants can be challenging, particularly for the oldest vintages of turbines, which have less available information. We generated a plant-level identifier to group decommissioned turbines using available data such as the plant name and turbine locations. Through this method, we successfully assigned a plant ID to 11,892 of the 12,428 total decommissioned turbines (96%), resulting in 189 unique wind plants that have been at least partially decommissioned. We then imported the decommissioned dataset into ArcGIS and created a 1 km buffer around each decommissioned plant (i.e., around all the decommissioned turbines with a shared plant ID). We overlaid the existing turbines from the USWTDB on top of the buffered decommissioned plant layer and performed a spatial join to identify sites where existing turbines are sited within the 1 km buffer of decommissioned plants. Finally, we excluded cases from that spatial join where the “existing” turbine within the buffer was installed in a year prior to the year during which decommissioning started for that site to align with our definition of repowering (i.e., new turbines built within the site footprint where older turbines were removed).

Results of this analysis are presented in Section 3.6.

2.4 | Predictive Model of Turbine Decommissioning

We developed a logistic regression model to estimate the maximum likelihood of the binary (“yes”/ “no”) outcome of wind turbine decommissioning. To construct a dataset that included both outcomes, we combined the D-USWTDB with the USWTDB (i.e., the set of existing, *not* decommissioned turbines), resulting in 87,750 total observations. We examined and report here four different model specifications (Models 1–4), which increase in sophistication as additional independent variables are added. The final model (Model 4) includes four unique independent variables: the age of the turbine, the turbine's rated capacity, recent wind plant performance (i.e., capacity factor), and a binary (dummy) variable for turbines in California.[1]

The wind plant capacity factors were calculated using annual generation data from the U.S. Energy Information Administration (EIA) form 923. Annual capacity factors were calculated based on each wind plant's total rated capacity and the reported annual generation, as shown in Equation (1).

$$CF_y(\%) = \frac{G_y}{p_{cap} \text{ x } 8760} \text{ x } 100 \tag{1}$$

where:

- $CF_y(\%)$ = the capacity factor for year (y), expressed in percentage terms
- G_y = the reported energy generation (Megawatt-hours [MWh]) for year (y)
- p_{cap} = the total rated capacity (MW) of the wind plant
- 8760 = the number of hours in a year (y)

For *decommissioned* turbines, it uses the capacity factor from 2 years[2] prior to the year of decommissioning. Accordingly, for *existing* turbines, the regression model uses the capacity factor from the year 2023, i.e., approximately 2 years from today.

Our primary independent variable—age—was missing in 3799 (4.3%) of records in the combined existing + decommissioned dataset, resulting in a usable sample of 83,951 observations. Turbine capacity was missing in an additional 2236 (2.7%) records, while plant capacity factor was missing in an additional 10,916 (13%). To include these latter two variables in the model, yet retain records in which they were missing (because those records still had useful information for the “age” and “California” variables), we generated categorical variables to enable the use of an “unknown” or missing category in the regression. Turbine capacity was, therefore, split into three categories (“unknown,” “< 1 MW,” and “1 + MW”) to distinguish between smaller turbines and larger (“megawatt-class”) machines. Capacity factor was also split into three categories (“unknown,” “< 20%,” and “20+%”) to distinguish plants with lower performance (i.e., < 20% capacity factor).

We tested the four independent variables for collinearity by measuring Variance Inflation Factors (VIF). The highest VIF was between the “age” and the categorical “<> 1 MW” capacity, but the VIF of 2.39 is sufficiently low for inclusion.

The logistic regressions were run in Stata statistical software, producing odds ratios for each independent variable. The odds ratios represent the change in likelihood of decommissioning for a unit change in the independent variables, e.g., a 1-year increase in age. The equation for the final, full model (Model 4) is shown in Equation (2).

$$y(X) = \frac{e^{(\beta_0+\beta_a A+\beta_{tc} TC+\beta_{ca} CA+\beta_{cf} CF)}}{1 + e^{(\beta_0+\beta_a A+\beta_{tc} TC+\beta_{ca} CA+\beta_{cf} CF)}} \tag{2}$$

where:

- $y(X)$ = the probability that a turbine with X attributes will be decommissioned
- β_0 = intercept term
- A = age of the wind turbine (years)
- β_a = coefficient for age
- TC = turbine capacity category (“unknown,” “< 1 MW,” and “1+ MW”)
- β_{tc} = coefficient for turbine capacity category
- CA = california binary (dummy) indicator
- β_{ca} = coefficient for California binary indicator
- CF = capacity factor category (“unknown,” “< 20%,” and “20+%”)
- β_{cf} = coefficient for capacity factor category

Results from the predictive model are presented in Section 3.5.

3 | Results

3.1 | What Is the Rate (Volume) of Wind Turbine Decommissioning Over Time in the United States?

As of June 2025, we identified a total of 12,428 decommissioned wind turbines in the United States, representing more than 2500 MW of nameplate generating capacity. Some decommissioning occurred as early as 1992, but decommissioning volume was minimal until 2011 when over 1000 turbines were dismantled. In 2015 alone, more than 2600 turbines were dismantled and removed. Despite fewer turbines being removed in recent years (Figure 1A), the larger nameplate capacity (Figure 1B) of more recently removed turbines means that annual decommissioned capacity has remained high, with at least 200 MW removed annually since 2019 (peaking in 2021 with 377 MW decommissioned) (Figure 1B). The number of turbines decommissioned annually has varied considerably.

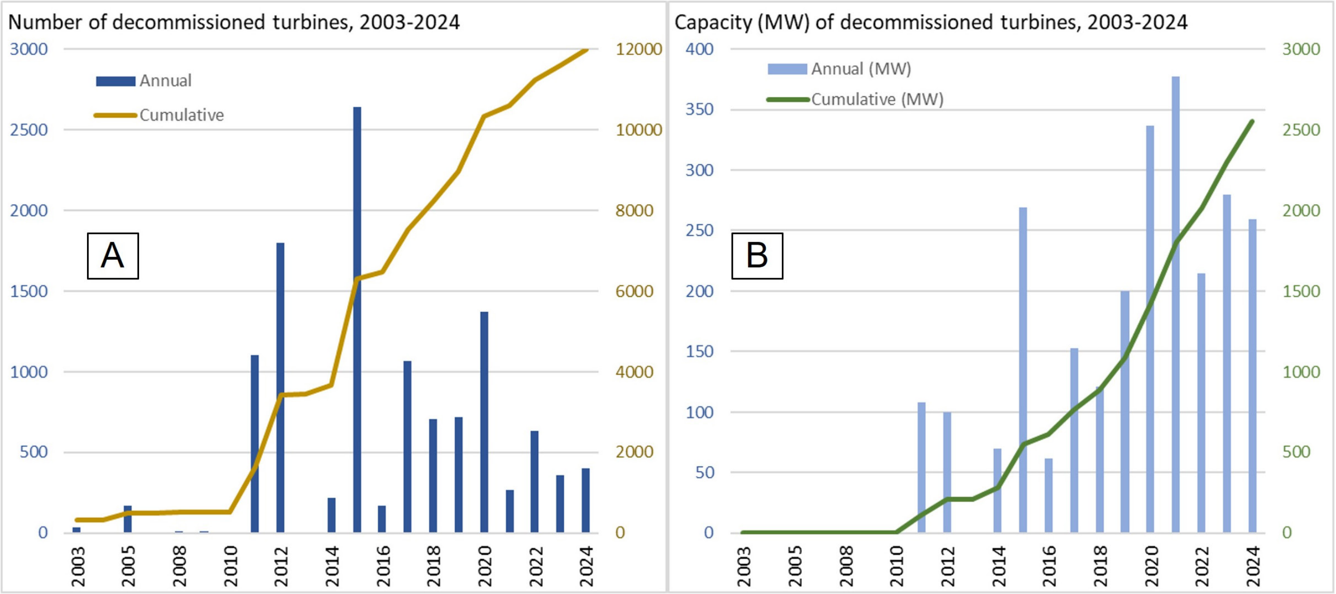

FIGURE 1 | Annual and cumulative number (A) and capacity (B) of wind turbine decommissioning. Note that decommissioned year is missing (unknown) for ~2% of all records in the dataset; turbine capacity is missing for ~27% of records.

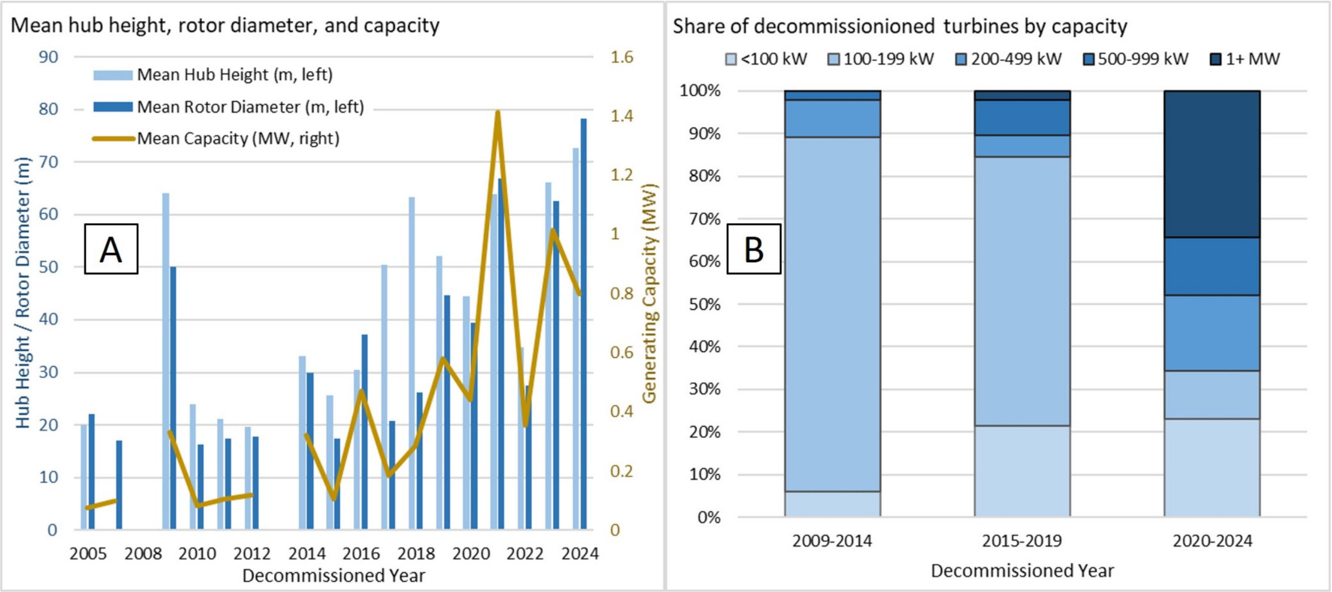

FIGURE 2 | Average turbine hub height, rotor diameter, and nameplate generating capacity by year of decommissioning (A) and share of capacity groups by decommissioned year (B). Note that decommissioned year is missing (unknown) for ~2% of all records in the dataset; turbine capacity is missing for ~27% of records; rotor diameter is missing for ~33% of records; and hub height is missing for ~63% of records. Insufficient data for turbines decommissioned in 2008 and 2013.

3.2 | What Are the Technical Specifications/Attributes of Wind Turbines That Have Been Decommissioned, and How Has That Changed Over Time?

The vast majority of turbines that have been decommissioned to date in the United States have been very small by modern standards. Whereas the average turbine installed in the United States in 2023 had a nameplate generating capacity of 3.4 MW, a rotor diameter of 134 m, and a hub height of 103 m [2], the average decommissioned turbine in our dataset had a generating capacity of 0.29 MW, a rotor diameter of 27 m, and a hub height of 38 m.

But, as shown in Figure 2, the average size of decommissioned turbines has increased over time with a some data variability.

Most recently, in 2024, the average decommissioned turbine was 0.8 MW in capacity, with a rotor diameter of 78 m and a hub height of 73 m.

From 2009 to 2024, turbines with a nameplate capacity of 100–199 kW represented 55% of all decommissioned turbines, but were 83% of decommissioned turbines from 2009 to 2014 and 63% from 2015 to 2019 (Figure 2b). Turbines rated 1 MW or larger, on the other hand, account for only 10% of the total decommissioned. Moreover, the 1 MW and larger machines represented a negligible portion of decommissioning activity until recent years, accounting for 34% of turbines decommissioned from 2020 to 2024, compared to just 2% of turbines decommissioned from 2015 to 2019. The 2020–2024 period saw a more even distribution of decommissioning activity across all turbine capacity groups.

3.3 | How Old Are Wind Turbines Typically When They Are Fully Decommissioned?

Our analysis reveals that the average decommissioned turbine in the United States was dismantled 30 years after installation, with the median being 31 years. Furthermore, less than 20% of all decommissioned turbines were dismantled within 25 years of being installed, whereas over 70% were removed after at least 30 years. These findings are illustrated in Figure 3, which shows the distribution of turbine age upon decommissioning.

We also characterized the size (capacity) of decommissioned turbines based on their age at the time of decommissioning (Figure 4). The oldest turbines that have been decommissioned are also predominantly the smallest, which aligns logically from installation trends. That is, the turbines installed 30 or more years ago were much smaller by all dimensions, including generating capacity, and therefore turbines reaching 30+ years of service prior to decommissioning are guaranteed to be smaller. Although fewer in total, it is noteworthy that turbines decommissioned after less than 23 years of service are predominantly larger (500 kW or more). Thus far, the dismantling of megawatt-class turbines has occurred only after a shorter-than-expected lifespan (i.e., less than 23 years).

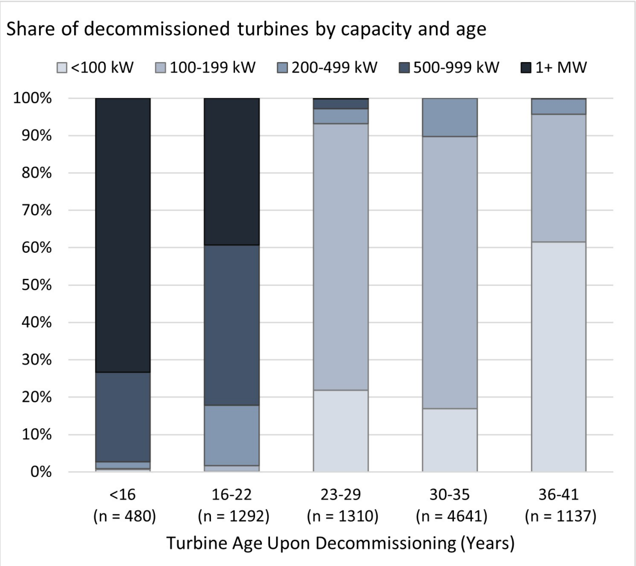

FIGURE 4 | Share of capacity groups by turbine age upon decommissioning. Note that decommissioned year is missing (unknown) for ~2% of all records in the dataset; installation year is missing for 4.5% of records. Both data points are required to calculate turbine age. Turbine capacity is missing for ~27% of records.

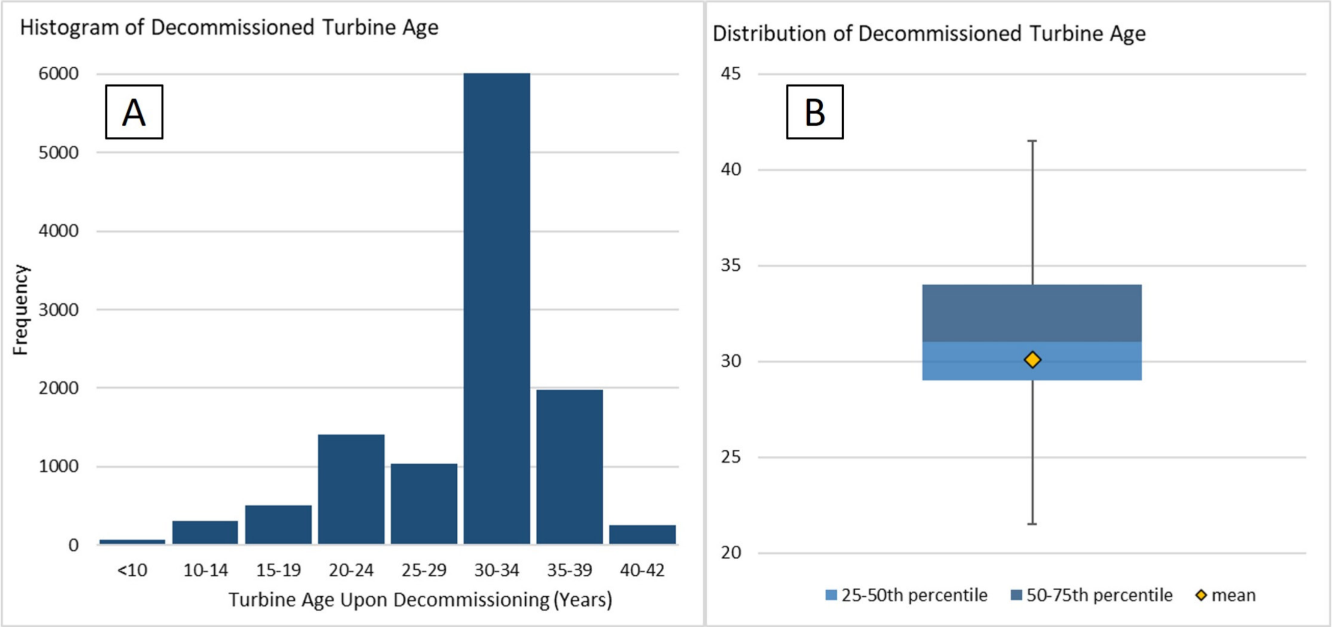

FIGURE 3 | Distribution of wind turbine age upon decommissioning. Note that decommissioned year is missing (unknown) for ~2% of all records in the dataset; installation year is missing for 4.5% of records. Both data points are required to calculate turbine age. Error bars (whiskers) in right plot represent 1.5 times the interquartile range.

However, a longer time series of data will be needed to assess the durability of these larger machines, as relatively few have been decommissioned to date.

3.4 | How Does the Typical Decommissioning Age Compare With the Age of the *Existing* Wind Turbine Fleet in the United State?

We calculated the age of more than 75,000 *existing* wind turbines using the USWTDB [1] to understand potential near-term future decommissioning volume. There are more than 2250 turbines that are 35–43 years old and that are still standing today (according to the most recently available aerial imagery); these are very likely to be dismantled imminently. However, 97% of currently installed wind turbines in the United States are less than 30 years old (the average age of decommissioned turbines), 96% are less than 25 years old, and 90% are less than 20 years old (see Figure 5). This suggests that annual decommissioning volumes are likely to remain relatively low at least for the next 5–10 years. However, more than 17,500 existing turbines are 15–19 years old, so decommissioning volume may increase substantially 10 years from now.

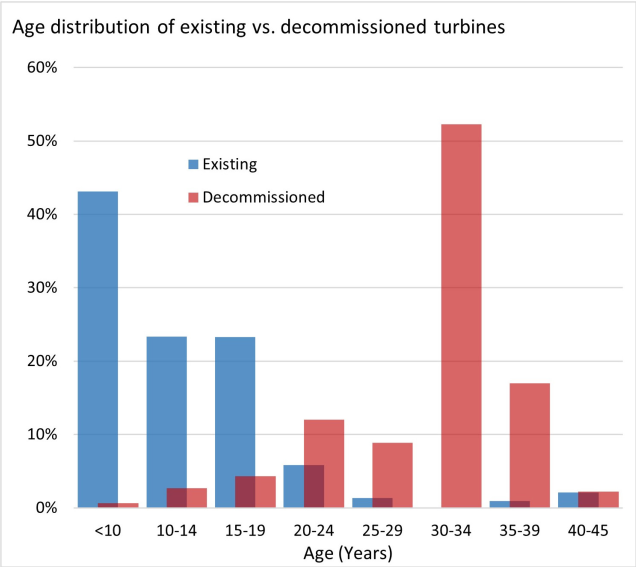

FIGURE 5 | Distribution of age of existing wind turbines compared to age of turbines upon decommissioning.

TABLE 1 | "Life table" for U.S. wind turbines, illustrating decommissioning rates by age interval.

Age interval (years)	Number of existing turbines	Number of decom. turbines	Decom. rate
1–5	16,256	12	0.1%
6–10	17,740	82	0.5%
11–15	16,175	361	2.2%
16–20	16,852	899	5.1%
21–25	3299	1037	23.9%
26–30	942	3122	76.8%
31–35	27	4373	99.4%
36–40	682	1811	72.6%

We further refine this by calculating an age-specific decommissioning rate. This is akin to the idea of the "life table" method utilized to calculate survival rates in medical statistics, population ecology, and other fields (see, e.g., [40]). As shown in Table 1, we calculate the decommissioning rate to be low (0%–5%) for the first 20 years of wind turbines' lifespans, 24% for turbines with 21–25 years of operation, and then increasing substantially to > 70% for each of the three oldest cohorts.

3.5 | How Well Can We Predict Wind Turbine Decommissioning With Available Data?

The logistic regression model estimated the likelihood of a given wind turbine being decommissioned; across the four model specifications we tested four independent variables. Results are displayed in Table 2. Overall, the model performed reasonably well—with a pseudo R^2 of 74% in Model 4. Model 1 is notable in that turbine age alone was found to be a reasonably good predictor of decommissioning likelihood. Nonetheless, Model 4 was superior, so we focus the remainder of the results on that specification. We found all four independent variables to be highly statistically significant ($p < 0.001$).

Unsurprisingly, age had a positive correlation with decommissioning likelihood, with each year of age increasing decommissioning likelihood by about 7%. Higher capacity turbines (1 MW or larger) were substantially less likely (by about 93%) to be decommissioned than those less than 1 MW when controlling for other variables. Turbines located in California, meanwhile, were more than four times more likely to be decommissioned than those in other states. Finally, turbines in plants with lower recent capacity factors (< 20%) were 2.6 times more likely to be decommissioned (while those without capacity factor data were 19 times more so—likely due to missing EIA generation data for the oldest wind plants in our dataset).

Figure 6A illustrates the relationship between turbine age and Model 4's predicted probability of decommissioning. Unsurprisingly, the predicted probability remains close to zero through the first 10 years, increasing slightly to approximately 5% at 20 years, after which the slope increases markedly. Beyond 30 years of service, the predicted probability of decommissioning is above 80%. Figure 6B, meanwhile, shows the same probability but with capacity factor on the x-axis. In this case, the predicted probability is negatively correlated with capacity factor—i.e., higher capacity factors correspond to lower decommissioning probability.

Overall, these regression results (alongside the polynomial line graphs in Figure 6) add more depth, sophistication, and nuance beyond the "life table" presented in Table 1 by examining and controlling for a larger suite of independent variables that influence decommissioning.

TABLE 2 | Logistic regression results for four model specifications. For the "turbine capacity" variable, the < 1 MW category was omitted; turbines with "unknown" capacity were included in the model but that category is not shown in the results table. For the "capacity factor" variable, the "≥ 20%" category was omitted; turbines with "unknown" capacity factor were included in the model but that category is not shown in the results table.

Model	Model 1		Model 2		Model 3		Model 4	
Number of obs.	83,951		83,951		83,951		83,951	
Pseudo R^2	0.6003		0.6573		0.6927		0.7365	
Ind. variables	*Odds ratio*	*p*	*Odds ratio*	*p*	*Odds ratio*	*p*	*Odds ratio*	*p*
1. Age	1.341	0.000	1.143	0.000	1.027	0.000	1.073	0.000
2. Turbine capacity								
1+ MW			0.032	0.000	0.022	0.000	0.068	0.000
3. CA dummy					12.437	0.000	4.379	0.000
4. Capacity factor								
< 20%							2.62	0.000
Constant	0.0004	0.000	0.064	0.000	0.281	0.000	0.038	0.000

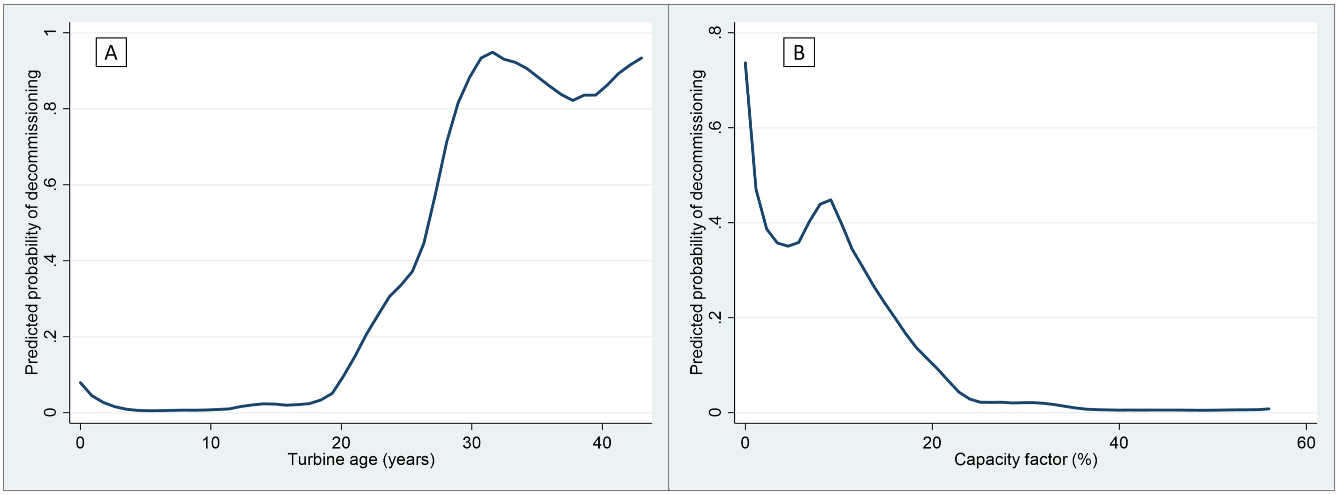

FIGURE 6 | Predicted probability of decommissioning by: (A) wind turbine age and (B) recent wind plant capacity factor.

3.6 | Are Decommissioned Wind Plants Typically Repowered, as Opposed to the Project Site Being Fully Decommissioned Without Replacement Turbines?

3.6.1 | Turbine-Level Results

Most decommissioned wind turbines have new wind turbines installed nearby. Out of 11,591 eligible decommissioned turbines (i.e., those that were removed prior to 2024), 7422 (roughly 64% of total) have had new turbines installed within 1 km *after* the original turbine was removed.

3.6.2 | Plant-Level Results

Out of 169 eligible decommissioned plants (i.e., those that had decommissioning activity prior to 2024), 91 had new turbines installed within a 1 km buffer after decommissioning had commenced (54% of plants). However, this does not tell the whole story, because those 91 plants collectively account for 10,200 decommissioned turbines (88% of eligible turbines). To elaborate, the sites for which we confirmed repowering activity averaged 112 decommissioned turbines per plant, whereas the sites where we do not find evidence of repowering average just 18 turbines.

Our interpretation of this finding is that many of the sites *without* repowering represent cases where only a subset (perhaps just a few) of the turbines within the plant have thus far been decommissioned and removed, while many of the old turbines within the plant still remain standing. Hence, resulting in the smaller average number of turbines per plant at nonrepowered sites. In contrast, the repowered sites are much more likely to represent sites where *all* old turbines within the plant were removed, clearing the site for new turbines to be built within the original site footprint.

Regardless, it is clear from turbine- or plant-level analyses that the majority of decommissioning activity is followed up with repowering (i.e., newly installed turbines) at or near the same site.

3.6.3 | Comparison of Wind Plants "Before" vs. "After" Repowering

The plant-level analysis described above enabled us to match 91 decommissioned wind plants with replacement (i.e., repowered) plants, allowing for a comparison of plant configurations before and after repowering.[3] Table 3 shows the average number of turbines, total capacity, rotor diameter, and total turbine height across the matched plants, before and after repowering.

On average, the post-repowering plant configurations had 86 fewer turbines (−77%), but the total rated generating capacity of the plants nonetheless increased by 62 MW (280%) compared to the average before repowering. Summing the differences across all the 91 repowered sites we identified, we find that while repowering has resulted in a decrease of 7849 turbines, capacity increased by 3655 MW. The post-repowering plant configurations naturally featured much larger turbines: rotor diameters increased by nearly 57 m and total turbine height increased by nearly 50 m on average.

Figure 7 shows three aerial images of the same Wind Wall project near Tehachapi, California. Image A was captured in April 2017 (prior to decommissioning), image B was captured in September 2023 (after repowering), and image C was from 2023 but with the locations of the decommissioned turbines shown as red dots and the repowered turbines shown as blue dots. These images are useful to illustrate what repowering can look like; the image frames show roughly 35 old turbines removed and replaced with just four large modern turbines. The decommissioned turbines at this site were Vestas V17 machines, with a rated power of 90 kW each, and were installed in 1985. The new turbines are Vestas V126 machines, with a rated power of 3.45 MW each, and were installed in 2021. Just within this image frame, we can see a net reduction of 31 turbines, and a net capacity increase of ~10.6 MW.

4 | Discussion

More than 12,400 wind turbines representing more than 2500 MW of generating capacity have already been decommissioned in the United States. Although some decommissioning activity began in the 1990s, the scale increased substantially after 2010. During 2011, 2012, 2015, 2017, and 2020 each saw more than 1000 turbines were removed annually, and during other years within the past decade (2015–2025), hundreds of additional turbines were removed as well.

Wind turbine lifespans have commonly been assumed to be 20–25 years [6–9]. In contrast to that assumption, we find that decommissioned turbines in the United States have predominantly been 30 or more years old, which is more in line with expectations from surveyed wind industry professionals [10]. Regarding age, we must again stress the definition of "decommissioned" in this dataset, which requires the turbine to be fully dismantled—i.e., no longer erect. That definition is materially

TABLE 3 | Number of turbines and total capacity comparisons for "before" and "after" configurations of repowered wind plants. The last column ("Total net change") calculates the difference in these two metrics across the full group of identified repowered sites.

	Before repowering		After repowering		
	Mean	**Median**	**Mean**	**Median**	**Total net change**
Number of turbines in plant	112	38	26	17	−7849
Total capacity (MW) of plant	22.2	8	62.3	57.6	3655.5
Average rotor diameter (m)	45.2	45	101.8	112	*n/a*
Average total turbine height (m)	76.8	78	126.2	148	*n/a*

FIGURE 7 | Images from the "Wind Wall" project near Tehachapi, California: (A) Before repowering, (B) After repowering, and (C) Turbine locations for both before (red) and after (blue) repowering. Images A and B from Google Earth Pro. Image C from ArcGIS Pro.

distinct from whether the turbine is "operational," or actually capable of producing power. While preferred, to our knowledge, information on the operational status of turbines is not publicly available, and perhaps not even organized across plants in the United States.

While we find that wind turbines typically stand for 30–31 years prior to being removed, it may still be the case that the useful, productive lifespan is closer to 25 years, with a period of reduced or no energy generation prior to being dismantled. This is an important question for future research to pursue. Nonetheless, the finding of a 30-year expected lifespan for wind turbines is valuable for informing both waste (and recycling) volume forecasts as well as power sector modeling.

The finding that most decommissioned turbines have been small in rated capacity (and other dimensions—e.g., hub height, rotor diameter) follows logically from the fact that they have been old, given the evolution of wind turbine technology and design over the past 40 or more years that has resulted in larger and larger machines being manufactured and installed [2, 3, 41, 42]. Nonetheless, it is noteworthy that megawatt-class machines were not dismantled in high numbers until after 2015, and still relatively few of them have been removed as of today (< 900 turbines). Moreover, those 1+ MW machines that have been decommissioned to date were removed after shorter-than-expected lifespans (less than 23 years).

These preliminary trends for 1+ MW turbine decommissioning may be poised to change, however, as the fleet of turbines installed in the early 2000s approaches 30 years of operational life. Although 96% of existing turbines in the United States are less than 25 years old, more than 7500 turbines are 20 or more years old, and another 17,500 turbines are 15–19 years old. This suggests that a larger wave of decommissioning may be approaching in the next 10 years or so—one that not only entails larger sheer numbers of turbines being removed, but also larger machines themselves (e.g., the mean capacity of turbines 20 years old today is 1.5 MW). This has important implications for waste management (i.e., recycling facilities and landfill capacity), repowering considerations (e.g., permitting, social license, and interconnection), and power sector modeling.

On the other hand, there has been a notable recent trend of partial repowering, with over 8000 turbines undergoing significant retrofits since 2017 to increase energy generation, extend lifetimes, and qualify for tax credits [2]. The old turbines predominantly decommissioned in the United States to date were too small and dated to be retrofitted, whereas operators of megawatt-class turbines may increasingly choose to do so. It is not yet known how partial repowering affects the lifespan of the turbine, because none of these have been decommissioned.

It follows logically that a turbine's age is a good predictor for the likelihood of decommissioning, but adding additional independent variables (turbine capacity, a binary indicator for California, and recent capacity factor) resulted in a substantially better model fit. All four independent variables tested were found to be significant, with turbine age and "California" being positively correlated with decommissioning likelihood, while larger (1+ MW) turbines and higher capacity factors (20+ %) were negatively correlated. The model predicts a very low (< 5%) likelihood of decommissioning through the first 20 years of operation, increasing to > 80% likelihood after 30 or more years of operation.

Other variables beyond those four included in this analysis could also influence decommissioning decisions. To the extent possible, future research could incorporate additional variables such as the quality of the local wind resource, the duration of the plant's power offtake agreement, nearby nodal average wholesale electricity prices, transmission constraints, and characteristics of the plant owner to better predict decommissioning. In addition, future research could refine the model by predicting repowering and full decommissioning (to prior site conditions) as separate outcomes.

In the 1980s and '90s, U.S. wind developers tapped into some of the best wind resources in the country to build wind plants. Today, greenfield wind development (built on undeveloped land) has become more constrained: the windiest sites have already been built out, and meanwhile transmission/interconnection, land-use, and social (e.g., ordinances) constraints have increased. Therefore, it comes as no surprise to find that the majority of decommissioning activity in the United States has been accompanied by repowering—developers and owner/operators do not wish to let those prime wind resource sites go to waste. While it was challenging to develop a reliable metric to quantify repowering, our two approaches (turbine-level and plant-level) both reach the same conclusion that the majority of sites are indeed repowered.

Perhaps even more interesting than the frequency of repowering is the magnitude of changes we observed when comparing plant configurations before and after repowering. Repowered sites resulted in a drastic reduction in the number of turbines (by 86, or −77% on average), yet a substantial increase in the rated capacity of the plant (by 62 MW, or 280% on average) due to the use of larger turbines. This suggests that modern wind turbine and plant designs enable a more efficient use of space—i.e., higher power densities. Coupled with the higher average capacity factors enabled by modern wind turbines [2, 43], one could infer that repowered sites also achieve higher energy densities—i.e., higher annual energy generation for a given footprint of land. These empirical findings on power and energy density of repowered wind plants corroborate the modeled (theoretical) findings in Hoen et al. [44].

The findings pertaining to repowering have important implications, for example: How will local communities hosting wind plants respond to repowering—in particular their perceptions of a plant layout that utilizes many fewer, but much larger, turbines? Moreover, will communities feel they were misled about the "temporary" lifetime of wind plants in their communities (which repowering effectively doubles) [28, 30]? And how will community opposition toward repowering compare to that of greenfield development, which developers cite as a leading cause of project delays and cancellation [45]? Will permitting officials treat repowering differently than land-use permit applications for greenfield wind plants? How will repowering be treated amidst backlogged interconnection queues [46], especially if developers seek to increase the nameplate capacity of the plant?

How, specifically, will repowering impact the power and energy density of wind plant sites, and therefore affect the transmission system more broadly? These and other questions will become more pressing with the pending wave of decommissioning and repowering that approaches in the next 10 years.

5 | Conclusion

This research developed a novel, comprehensive, and spatially explicit dataset of land-based decommissioned wind turbines. To date, more than 12,400 wind turbines have been fully decommissioned in the United States the majority of which have been relatively old (> 30 years) and small (< 200 kW). Although relatively few turbines 1+ MW in capacity have been decommissioned thus far, those removed had a shorter-than-expected lifespan. Many existing turbines are approaching the end of their expected life with roughly 25,000 turbines currently installed in the United States that are 15 or more years old, and 7500 of those being 20 or more years old. And while a turbine's age alone is a predictor of the likelihood of decommissioning, other factors such as the size of the turbine, recent performance (i.e., capacity factor), and whether the turbine was sited in California were also important and statistically significant predictors.

Most sites where decommissioning has occurred have subsequently been repowered with new turbine construction in or around those same sites. The repowered wind plants have markedly different characteristics than the original plants they replace—most notably regarding the number of turbines (86 fewer on average), the rated plant capacity (+62 MW on average), and the larger scale of turbines themselves (i.e., height and rotor diameter). The implications of these repowering trends on host communities, wind project cost, value, and profitability, energy affordability, and grid system planning and operations are important areas for additional research.

A potential wave of wind turbine decommissioning and repowering approaches in roughly 10 years and is likely to entail both larger numbers of decommissioned turbines and larger physical machines. Awareness of these potential changes can help policymakers, project developers and owners, grid operators, permitting officials, waste management industry members, original equipment manufacturers, and host communities to plan how to prepare for this wave and its implications, some of which are described above. Researchers can help to support those stakeholders in this planning, utilizing the empirical trends reported here alongside the D-USWTDB data to refine assumptions and improve research designs to analyze those end-of-life implications with greater depth, accuracy, and relevance.

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Data Availability Statement

The datasets underlying this research are publicly available.

The D-USWTDB (decommissioned turbines) is available via the Lawrence Berkeley National Laboratory here: https://emp.lbl.gov/publications/us-wind-turbine-database-files.

The USWTDB (existing turbines) is available via the US Geological Survey here: https://energy.usgs.gov/uswtdb/.

Endnotes

[1] To date, over 85% of decommissioned turbines in the United States were in the state of California. The California dummy variable was used to control for that state's dominance in the context of other independent variables.

[2] The decision to use generation data from 2 years (as opposed to one) accounts for the fact that some decommissioning activity may have begun in the year prior to the plant's final recorded decommissioning year. Moreover, because turbine-level decommissioning year is sometimes based on available aerial imagery dates, minor errors in decommissioned year are possible.

[3] Note that this analysis does not include so-called "partial repowering," in which some components of the original turbine are left intact (e.g., the tower and nacelle) while others are replaced (e.g., the rotor and generator).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** U.S. decommissioned wind turbines: Summary statistics.