How Does Wind Project Performance Change with Age in the United States?

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Today's Agenda

1. Overview: Key results, context and implications
2. Methods and uncertainties
3. Future research directions

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How Does Wind Project Performance Change with Age in the United States?

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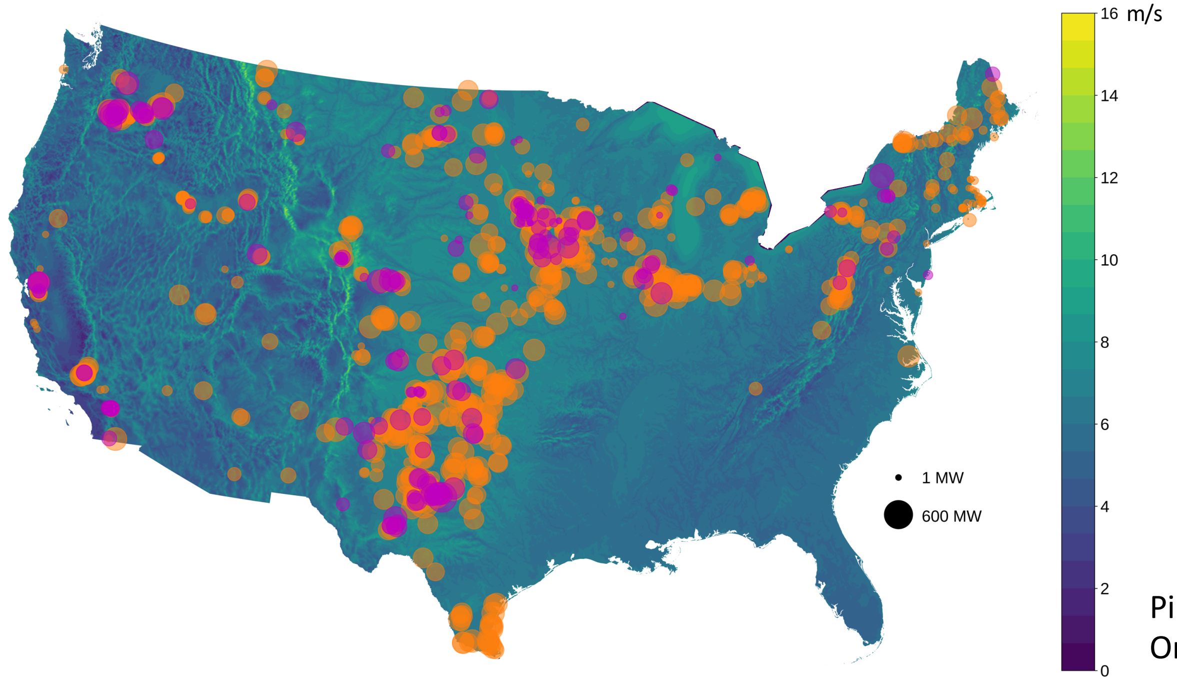
Or at emp.lbl.gov:

https://emp.lbl.gov/projects/cost-benefit-and-market-analysis

The first comprehensive study of how U.S. wind plant performance changes with age

- Research on turbine component reliability does not provide generalizable insight into plant or fleet-wide performance decline with age
- Performance changes are not typically accounted for in levelized cost of energy assessments (Stehly 2016)
- *Note: All machinery (including other power generation technology) shows performance decline with age*

Performance calculated across 917 plants



Two part approach:

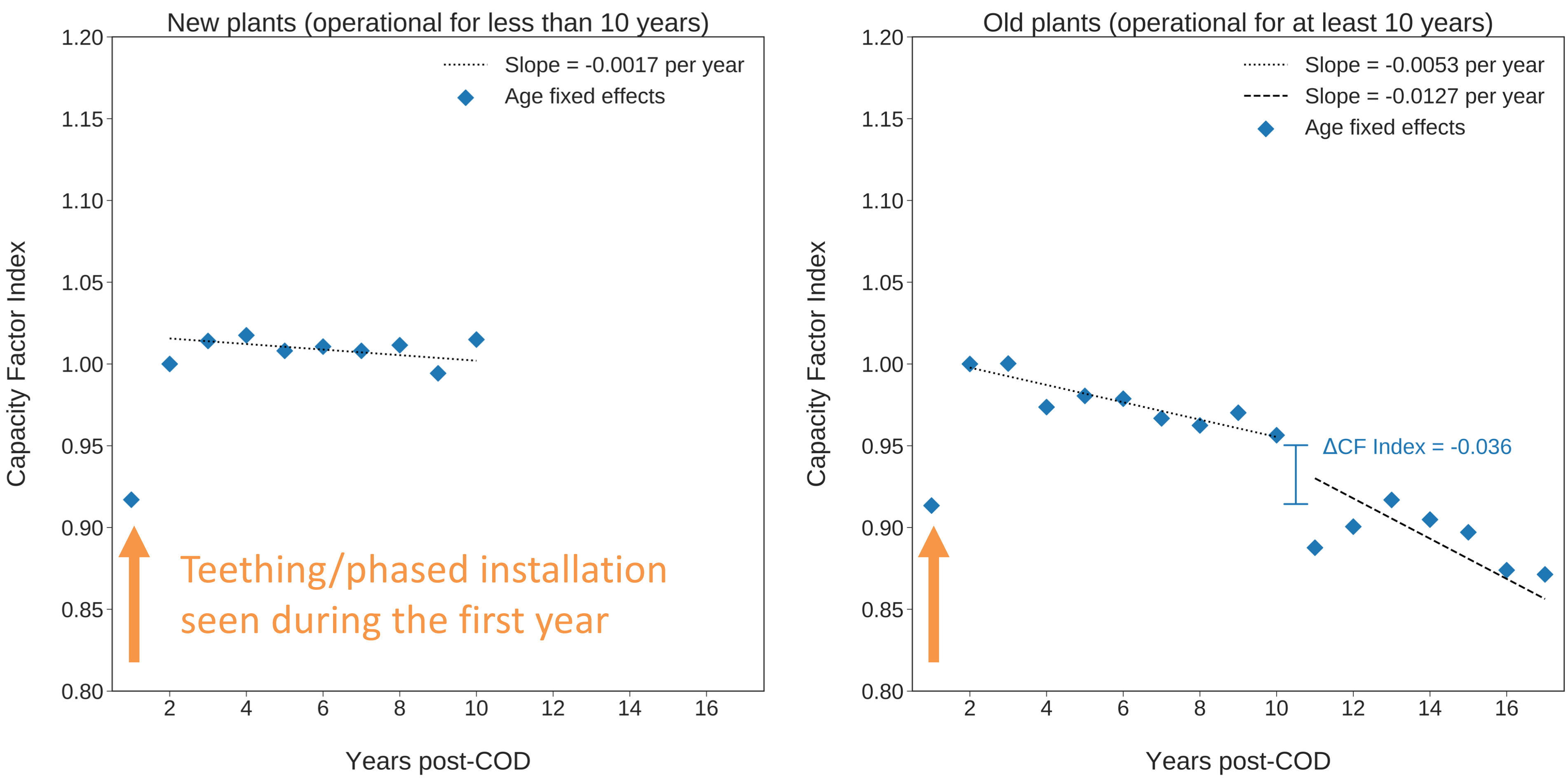
1. ‘Fixed-effects’ regression: to isolate the impact of age on performance (approach follows Staffell and Green 2014)
2. Multivariate regression: to explore correlation between performance changes and plant characteristics

Performance was adjusted for weather variation and curtailment

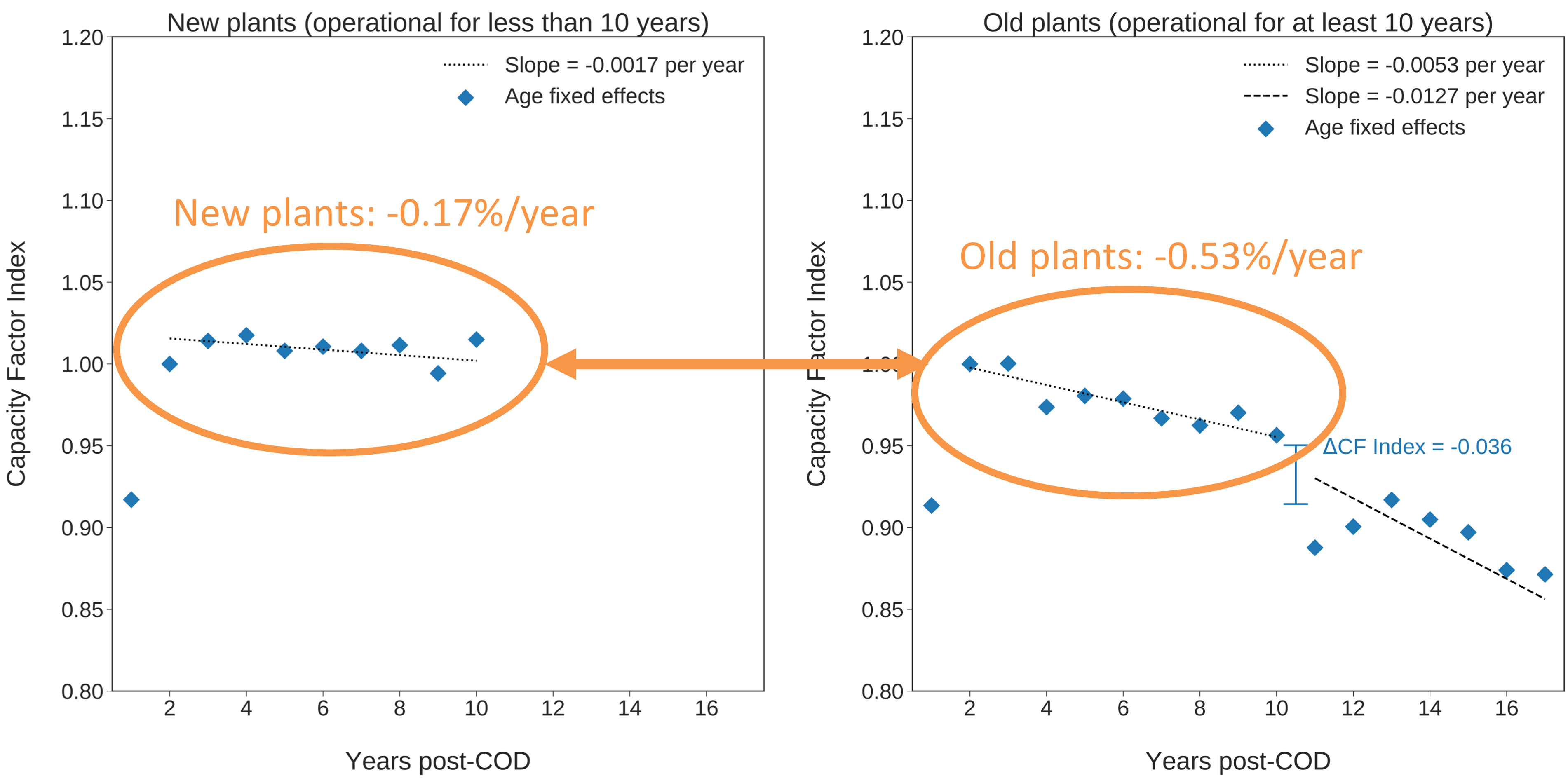
- Potential generation was estimated for each plant on an hourly basis
  - Reanalysis wind speeds at hub-height (ERA5) were combined with a power curve (specific to each project)
- Curtailment was estimated for each plant on an hourly basis
  - Curtailment was based on ISO-reported curtailment, distributed across plants based on local nodal pricing and whether the plant was receiving production tax credits

The rate of age-related performance decline in the United States wind fleet

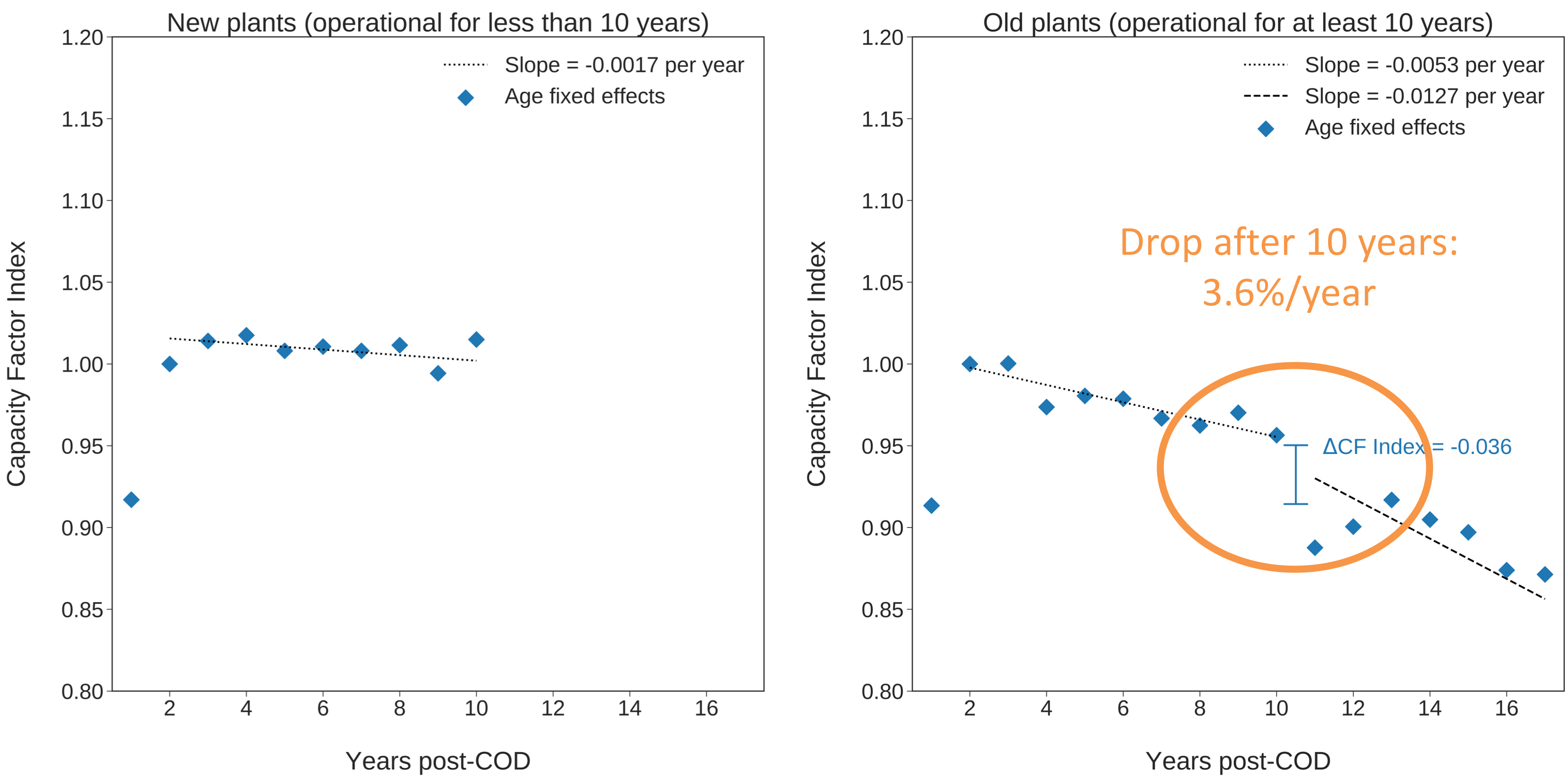
Fleet-wide results split by cohort: overall decline in performance is relatively small



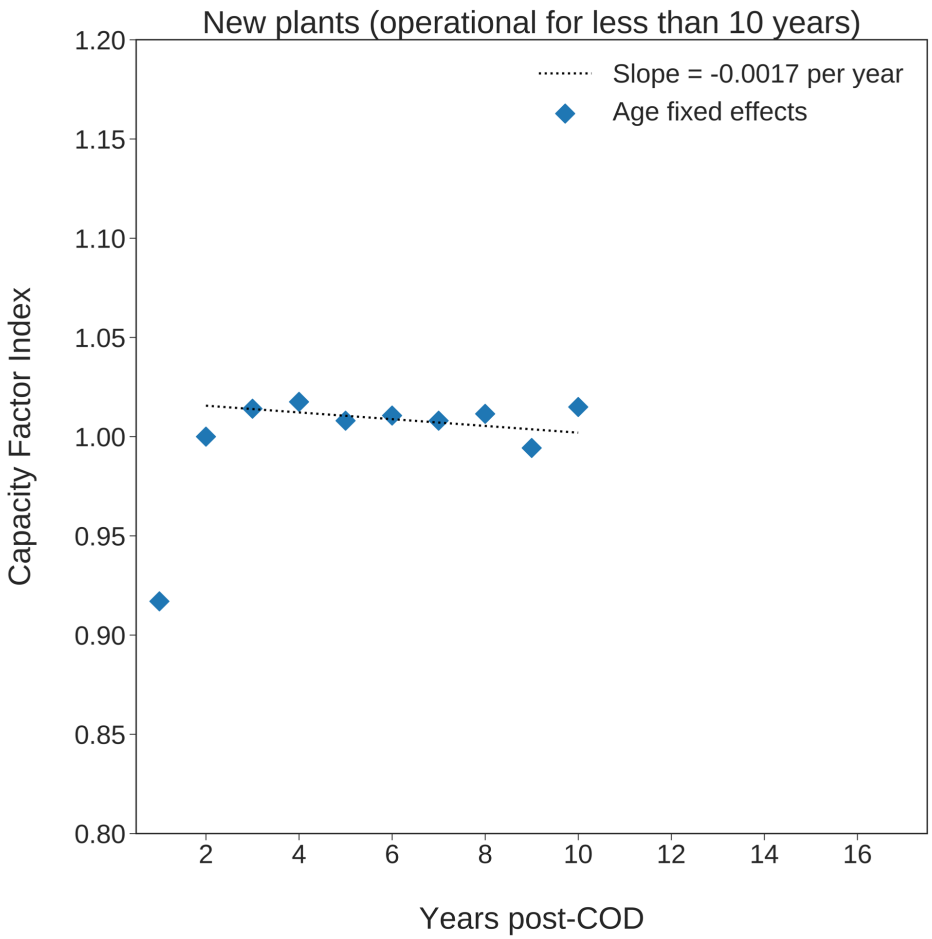
Newer plants have less age decline during first 10 years of life

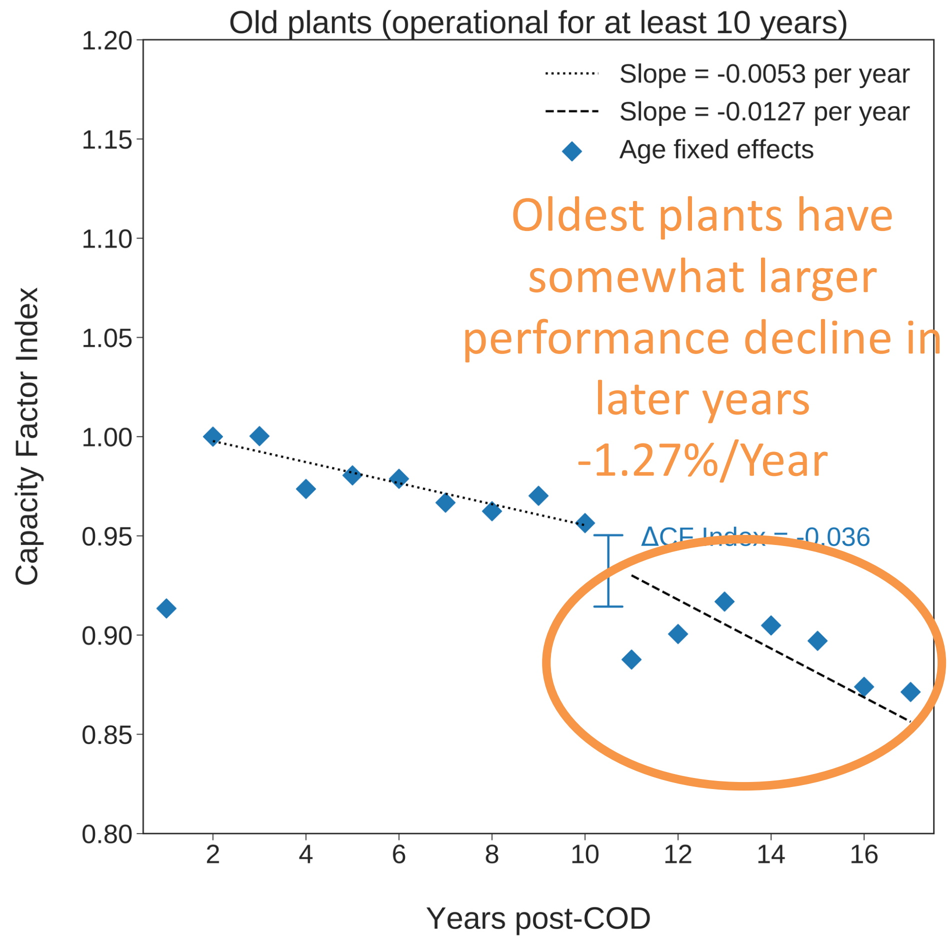


Plants see a performance drop after 10 years of age



The oldest plants have larger performance decline in later years

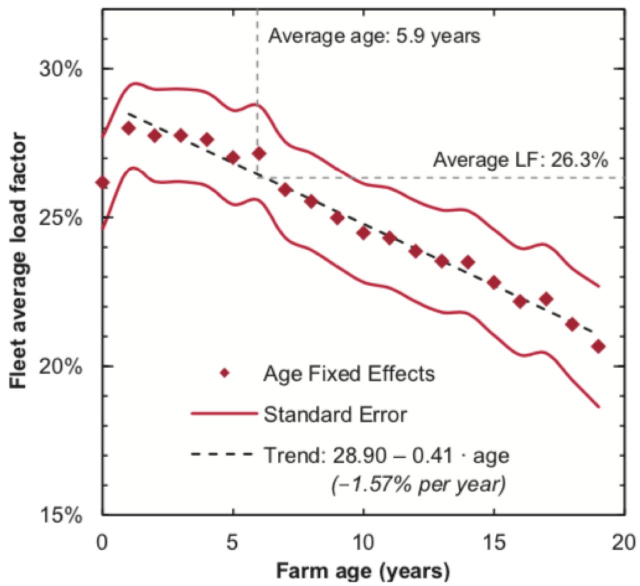


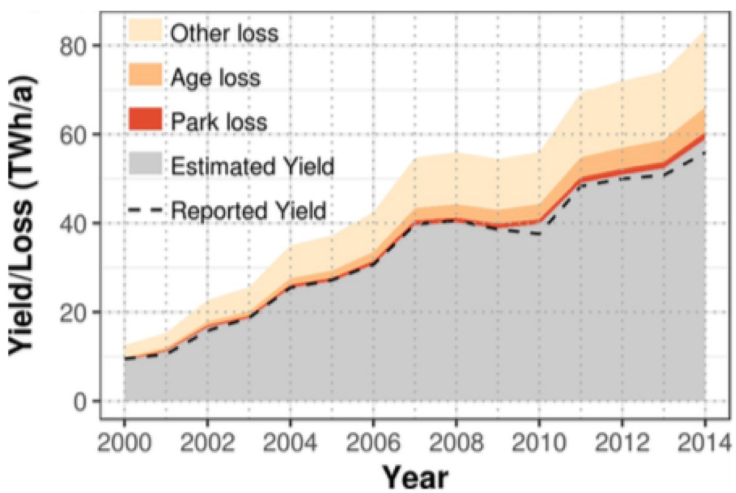


Summary: Fleet-wide performance declines mildly with age, newer plants do better

1. We find very low levels of degradation in newer plants during the first 10 years (-0.17%/year)
2. Older plants degradation during the first 10 years is a bit larger (0.53%/year)
3. Older plants experienced a relatively large drop in performance after 10 years (3.6%)
4. Degradation continues in years 14 and later; by year 17, for older plants, capacity factors are on average ~87% of year-2 performance

International context: US performance loss with age is relatively mild





Staffell and Green 2014 (*Top figure*)

- Study of the UK wind fleet
- Performance decline of **-1.6 %/year**
- For an older set of turbines (2002 – 2012)

Germer and Kleidon 2019 (*Bottom figure*)

- Study of the German wind fleet
- Performance decline of **-0.6 %/year**
- For an older set of turbines (2000 – 2014)

Olauson et al (2017) study the Swedish wind fleet and also find relatively low levels of performance decline (similar to the -0.6%/year above)

Interpretation: Tax credits and technology

Hypotheses for the performance drop after year 10:

- Loss of PTC reduces profit-incentives for aggressive monitoring and maintenance
  - Operating profit drops in year 11 with the loss of the PTC, and so too does the rigor of the maintenance protocols; consistent with recent LBNL OpEx survey of wind professionals
- Deferred maintenance and component lifetimes of roughly 10 years
- Some uncertainty related specifically to plant-level curtailment

Hypotheses for newer and older plants differences:

- Component reliability: e.g., older turbines have faced a higher rate of gearbox issues
- Technical and O&M maturity: e.g., newer turbines have additional sensors & controls
- Turbine design: e.g., newer turbines have lower specific power (should reduce degradation via aerodynamics because operate at rated power more often)
- Contracts: e.g., trend over time toward stricter turbine availability and project performance guarantees

These findings and various explanations illustrate that aging, while inevitable at some level, is a managed process for mechanical equipment. Degradation can be influenced by turbine design, O&M protocols, operational strategies, policy incentives, and contracts→ ultimately related to the profit incentives of project owners, and tradeoffs between O&M costs and degradation rate

Plant characteristics that influence performance changes with age

Project metadata was used to investigate drivers of performance over time

1. Select new projects (441 projects between the age of 5 and 10 years)
2. For each project, we found the rate of performance change with age
3. We ran a multivariable regression across all the projects to determine which plant characteristics influenced the performance change with age

- Project vintage
- Project nameplate capacity
- Project ownership type
- Size of project owner
- Turbine specific power
- Turbine OEM
- Terrain roughness
- Average wind speed
- Density of other projects in the region: wake effects from new upwind plants
- Density of other projects in the region: O&M network efficiencies gained from regional concentration
- Merchant plant or non-merchant
- Production tax credit or 1603 grant
- Drive type (gear box vs. direct drive)

Prior hypotheses about the possible impact of a subset of characteristics (8 of 13)

- **Project nameplate capacity**: larger projects may have lower degradation rates due to heightened O&M monitoring and on-site personnel
- **Project ownership type and size**: large owners, or owners with dedicated wind knowledge, may establish more-effective O&M programs to reduce degradation
- **Turbine specific power**: more time spent at rated power means less time with aerodynamic efficiency losses, leading to lower levels of degradation
- **Average wind speed**: More time at rated power means lower degradation, but possible higher turbulence may increase degradation
- **Turbine OEM**: differences is turbine design, component reliability, and maintenance contracting may lead to variations in performance between OEMs
- **Terrain roughness**: increased terrain roughness (and associated turbulence) may increase degradation due to greater mechanical stresses on the turbines
- **Status of PTC vs. 1603 grant**: projects that receive the PTC have higher incentives for aggressive O&M and therefore lower degradation than projects that received the 1603 up-front grant

Only a few characteristics were found to be correlated with performance changes

- **Project nameplate capacity**: larger projects may have lower degradation rates due to heightened O&M monitoring and on-site personnel
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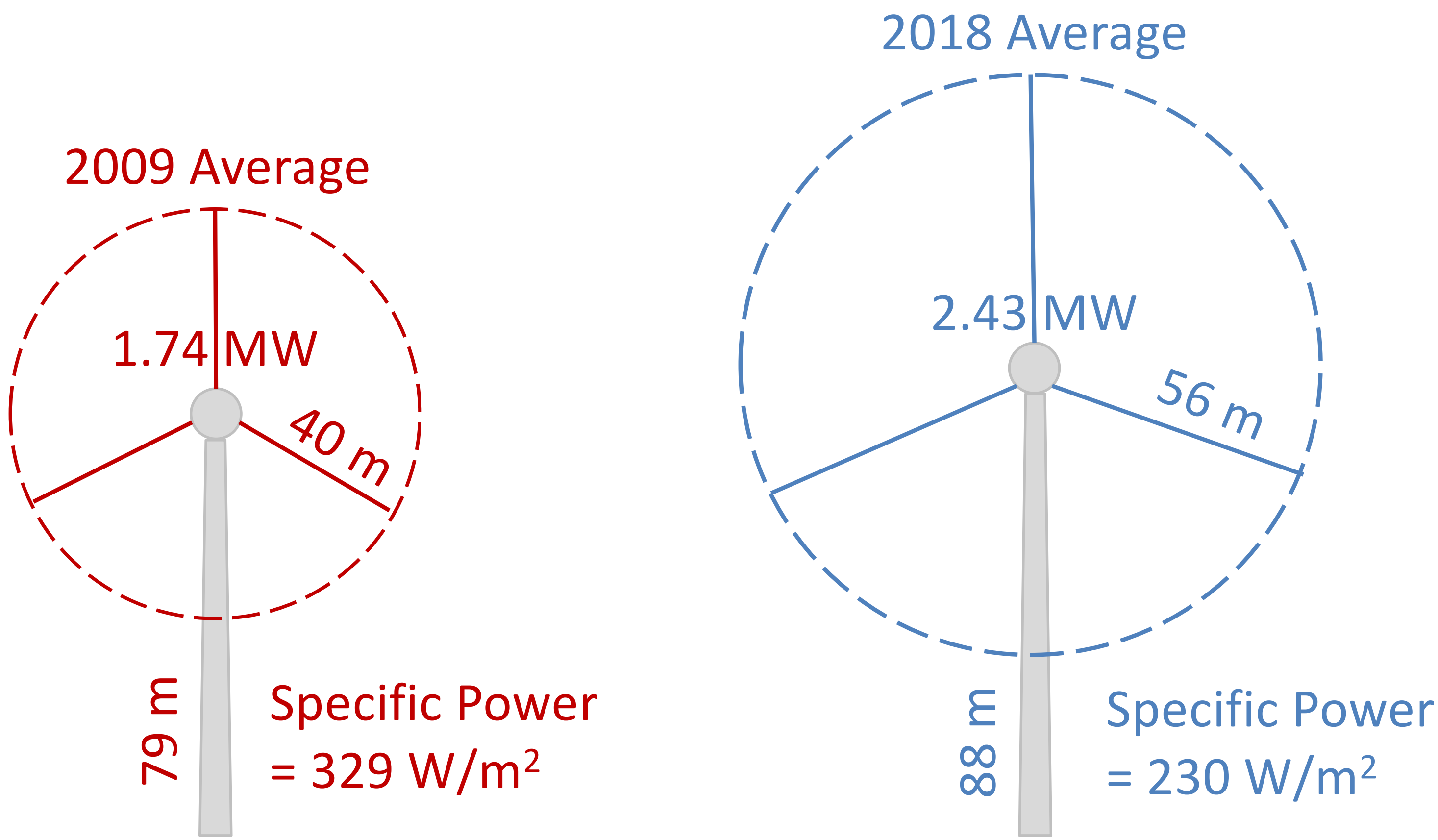
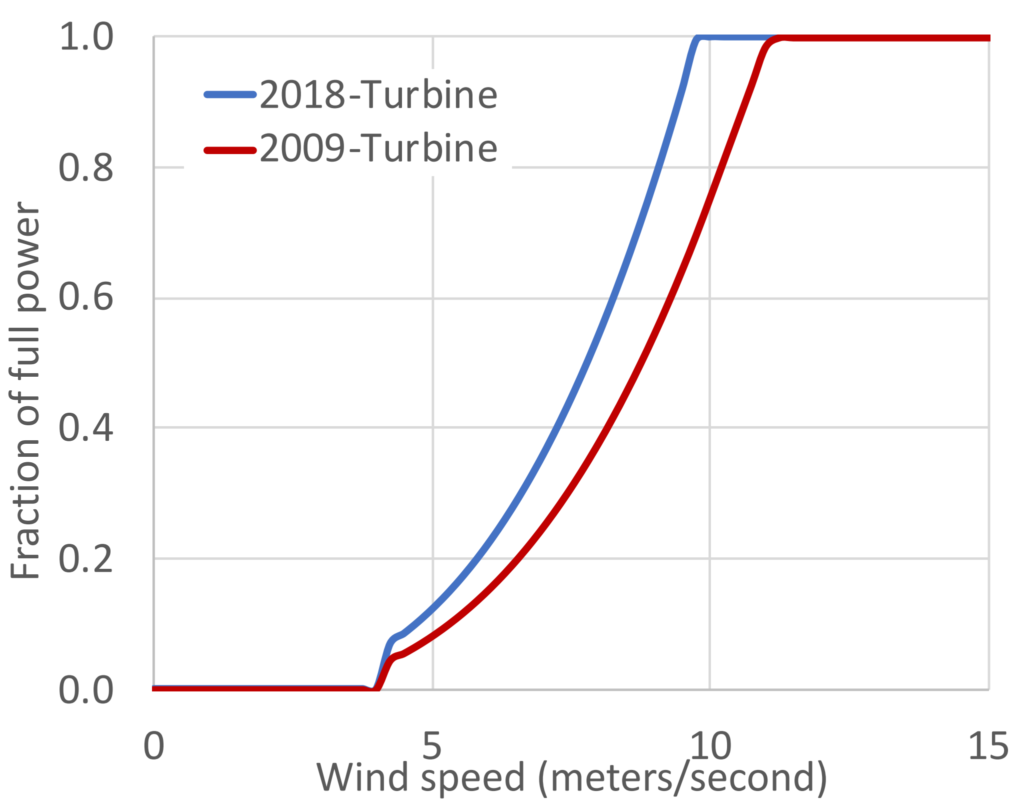
Lower specific power means: larger blades relative to turbine capacity



- Swept area is increasing faster than capacity
- Low specific power allows turbines to generate at full power at relatively low wind speed

Low SP turbines spend much more time at rated capacity (full power)



Operating at full power minimizes aerodynamic losses and thus minimizes performance decline with age due to aerodynamic losses

- At full power turbines are already shedding some of the potential energy from the wind, thus they can make up for some losses just by harvesting more of the potential energy
- One example of an aerodynamic loss is blade edge erosion

Multivariate regression: Limited correlation between degradation rates and project characteristics

- **Specific power:** Lower specific power increases time at rated power reducing impacts of aerodynamic losses, and leads to lower level of degradation
- **Terrain roughness:** A proxy for turbulence, potential for increased stress on turbines and thus greater degradation
- **Mean wind speed:** Statistically significant only when outliers removed—higher wind speeds may lead to greater periods of time at rated power, thus lower aerodynamic degradation

Sensitivity, uncertainty, and future research directions

Lack of publicly available plant-level data adds uncertainty

- Monthly generation for wind plants is reported by the Energy Information Administration (EIA)
  - EIA does not report curtailment for each plant
  - We estimate curtailment for each plant using data about hourly pricing, regional curtailment, and plant status related to the production tax credit
  - The size of the 10-year decline in performance is most sensitive to our estimates of curtailment
- Recorded generation was weather corrected – i.e. adjusted to account for the variability in wind speeds between years
  - Because measured wind speeds at wind plants are not publicly reported we are forced to use modeled data
  - The modeled data adds some uncertainty to the fleet-wide results
  - In particular, if the data was not weather normalized, the difference between the newer plants and older plants was removed

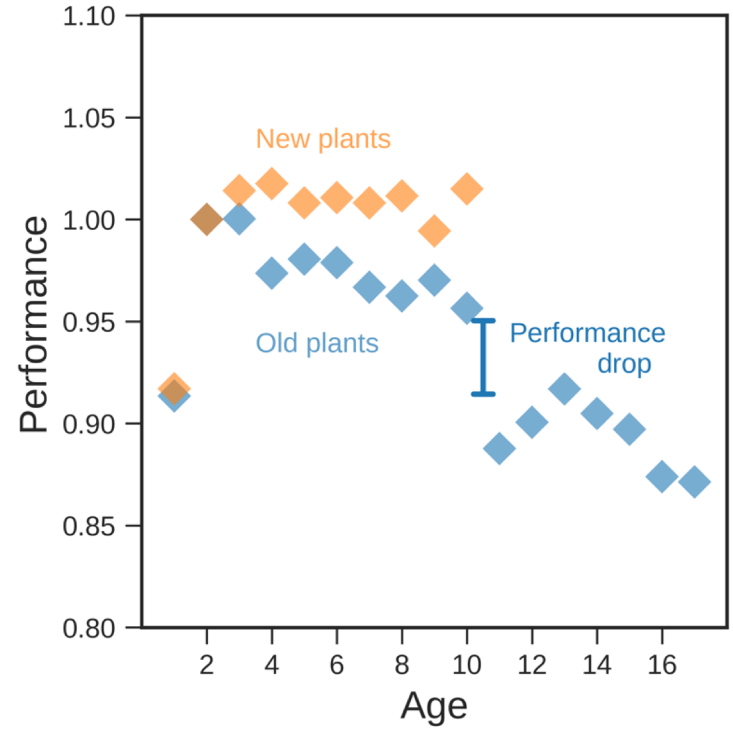
Future research questions:

- Will newer projects maintain low levels of performance decline into their second decade of life?
- Improved estimates of curtailment and wind speeds may help refine the results and build confidence
  - More data sharing?
- Can we further diagnose the driving factors of performance decline?
  - For example, can we refine the terrain roughness characteristic
    - What is actually causing performance degradation – turbulence, wind sheer, extreme winds?
  - Improved proxies for inter-plant wake effects
- Inter-fleet comparisons: what is different between the US fleet and European fleets

Summary

Core Findings

- First comprehensive study of how performance changes with age in US wind plants
- New plants have little performance degradation over their first decade
- US plants have mild performance degradation compared to other regions
  - Performance declines to 87% in year 17
  - Performance drops at the close of the PTC window
- Plants with lower specific power, flat-terrain, and high average wind speed tend to have lower levels of performance decline with age



While aging is inevitable, it is a managed process for mechanical equipment, impacted by turbine design, O&M protocols, operational strategies, policy incentives, and contracts: ultimately related to the profit incentives of project owners, and tradeoffs between O&M costs and degradation rates

Thank you!

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This research is open access:

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