Data-driven characterization of performance trends in ageing wind turbines

ALESSANDRO MURGIA, HENRIQUE CABRAL, ELENA TSIPORKOVA, DAVIDE ASTOLFI, LUDOVICO TERZI
25/04/2023

innovation forward

Poster: 237

Context

- Ageing wind turbines can experience performance decay (e.g. due to wear) or improvement (e.g. due to control optimization)

- Performance is influenced by multiple factors:
  - ageing
  - maintenance
  - operative mode
  - environmental conditions
  - seasonality

Factors not influencing long-term performance

Motivation and Goal

- Monitoring and quantifying the long-term performance is required to evaluate the return on investment

➔ Isolating the impact of ageing on turbine performance is fundamental to make informed decision on turbine lifetime extension

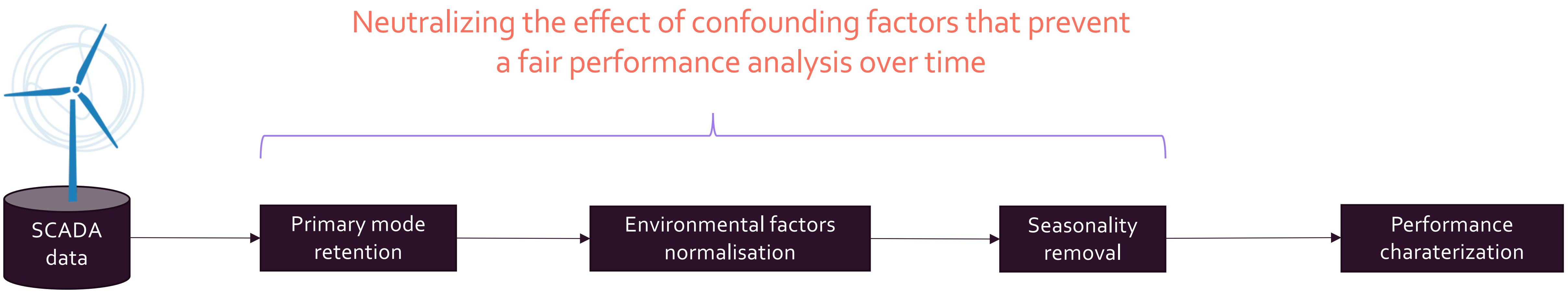
- Due to the complex dynamics in which the turbine operates, there is no knowledge-based model able to describe the effect of ageing on performance

➔ data-driven model are a viable solution for analyzing the aging effect

Goal: Develop a data-driven model to characterize the performance trend of a turbine **due to aging**

Methodology

Workflow


Neutralizing the effect of confounding factors that prevent a fair performance analysis over time
SCADA data
Primary mode retention
Environmental factors normalisation
Seasonality removal
Performance charaterization

Primary mode retention

Turbines can operate in multiple operating modes

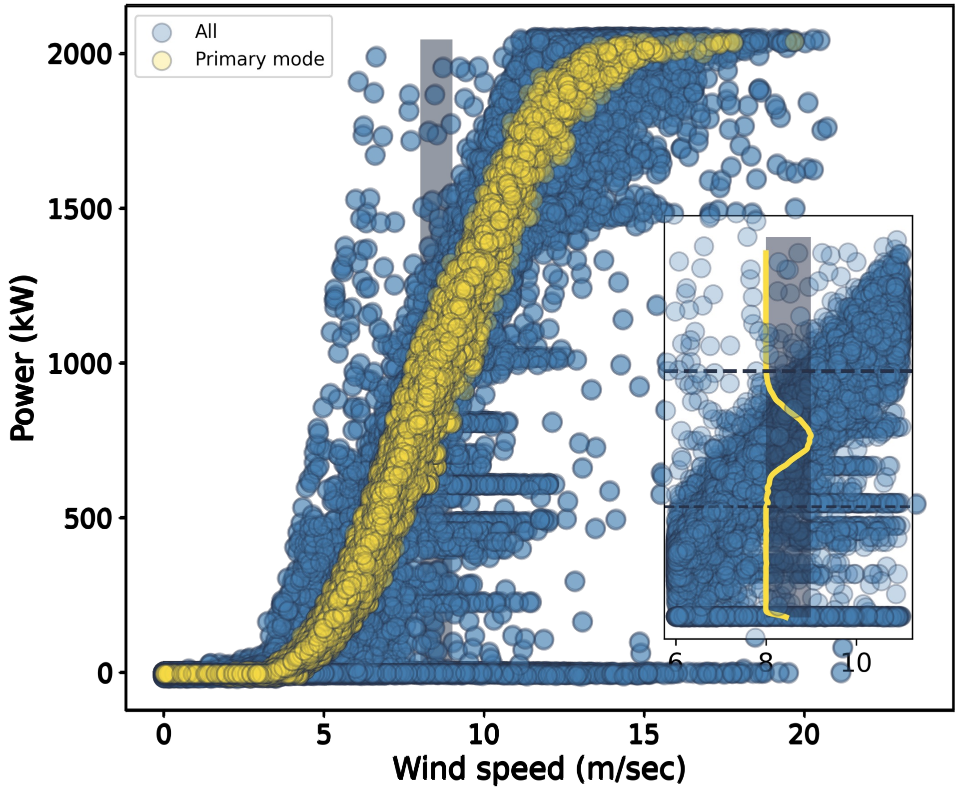
- Primary mode: the turbine can extract the maximum possible energy
- Secondary modes: the turbine extracts energy in a suboptimal way (e.g. due to curtailment, failures)

➔ The operating mode needs to be fixed to analyze performance trend

The operating mode is often not recorded by the SCADA system

Goal: Filter raw sensor data to retain only data points in the primary mode

Power curve



Environmental factors normalization

To evaluate a turbine's performance, the following factors need to be considered:

- active power
- environmental conditions

Once the environmental conditions are fixed, the turbine performance is described as efficiency:

$$efficiency = \frac{actual\ active\ power}{expected\ active\ power}$$

The expected active power is computed using a machine learning model

Goal: Factor out environmental factors from turbine performance

Seasonality removal

Turbine performance can present a seasonal variability:

- Not all seasonal factors are known or tracked (e.g. icing)

Seasonality is removed via two state-of-the-art methods:

- Year-over-Year degradation detection (YoY) [1]
- Seasonal and Trend decomposition using Loess (STL) [2]

Goal: Factor out the seasonal component from turbine performance

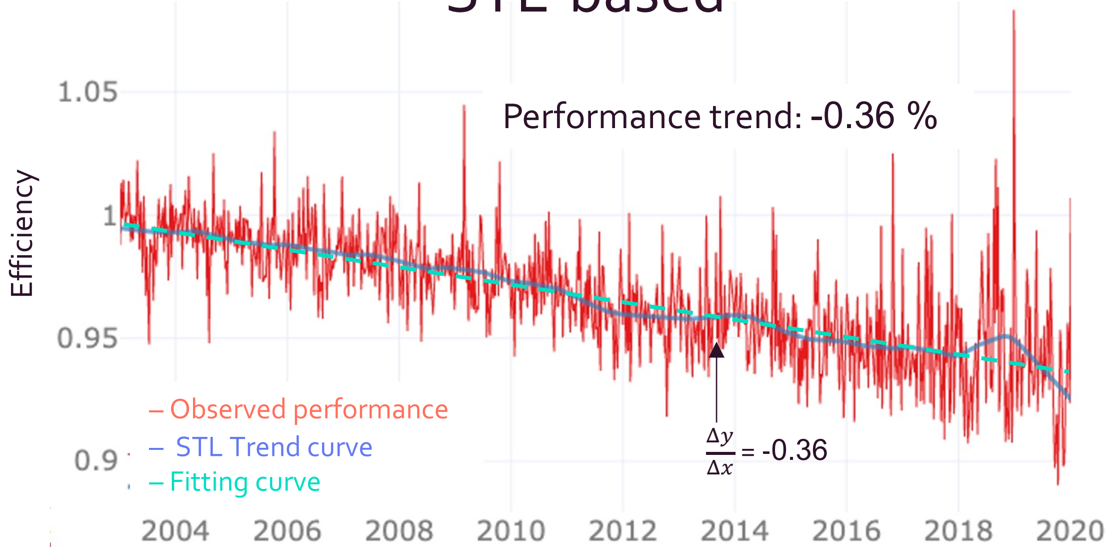
Picture taken from: The conceptual design of a safety system: For the 5MW Deepwind offshore floating vertical-axis wind turbine

[1] Validation of the PV Life model using 3 million module-years of live site data. Hasselbrink, E.F. et al., 2013
[2] Cleveland, R.B., Cleveland, W.S., McRae, J.E., and Terpenning, I. (1990). STL: A seasonal-trend decomposition. Journal of Official Statistics *6*, 3–73

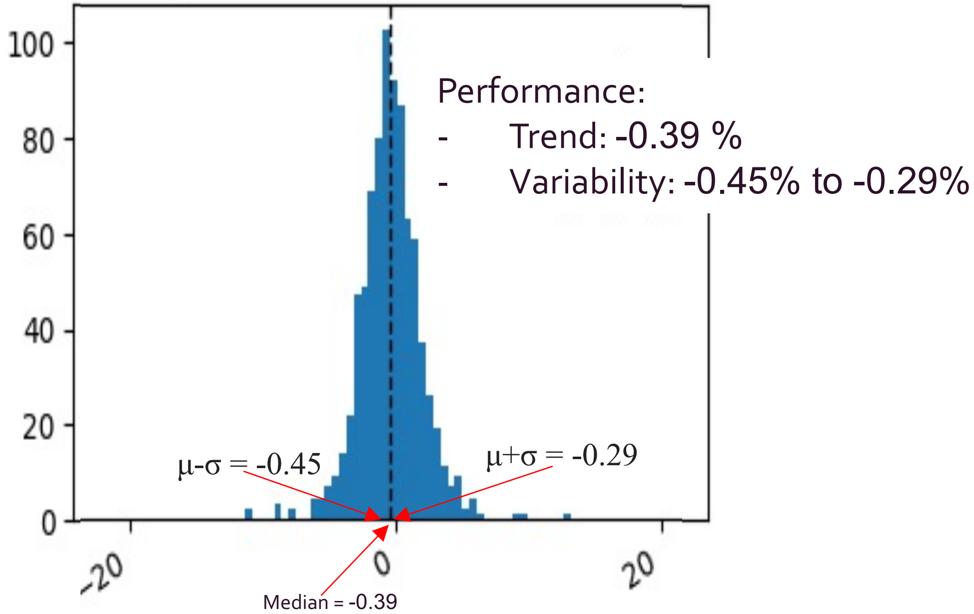
Performance charaterization

- Performance is reported in terms of trend and variability

STL-based



YoY-based



Goal: Summarize actionable information from the evolution of turbine performance in terms of performance trend and performance variability per year

Results

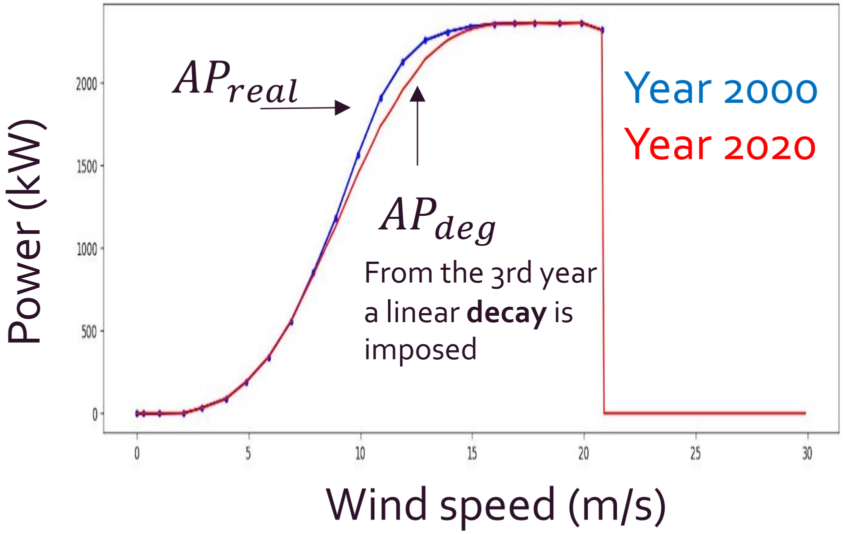
Dataset

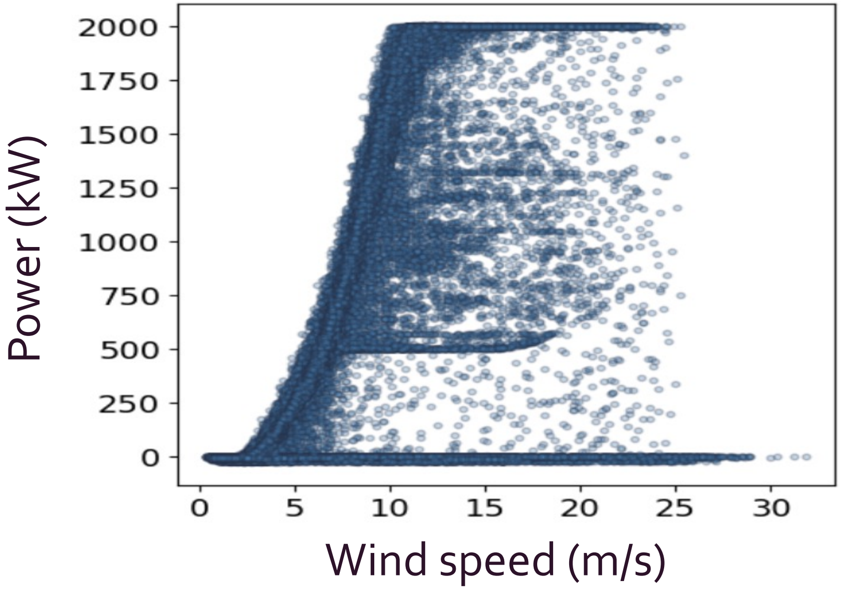
Synthetic dataset

- 20 years data
- Variables
  - Wind Speed
  - Wind direction
  - Air Density
  - Active Power (AP_{real})
  - Active Power_degraded (AP_{deg})
  - Active Power_expected (AP_{exp})

Real-world dataset

- 7 turbines
- 11 years of data
- In 2018 the controller was modified





innovation forward

Results

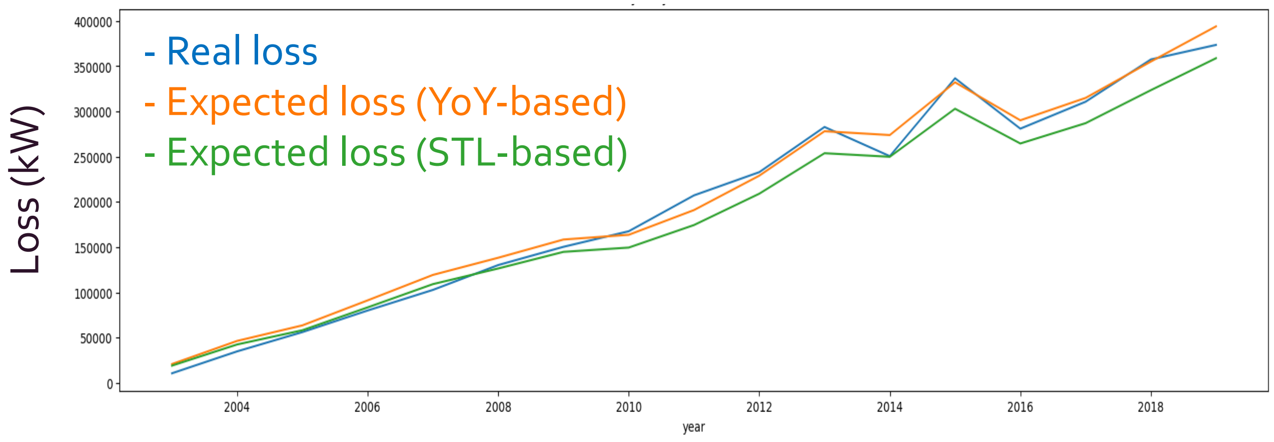
SYNTHETIC DATASET

- Performance Trend (PT):
  - 0.0039 (YoY)
  - 0.0036 (STL)

- Real loss: $AP_{real} - AP_{deg}$
- Expected loss: $AP_{exp} - AP_{deg}$

➔ $AP_{deg}\left(\frac{PT * \# years}{1 - PT * \# years}\right)$

Yearly loss evolution



R^2 between real and expected loss is:

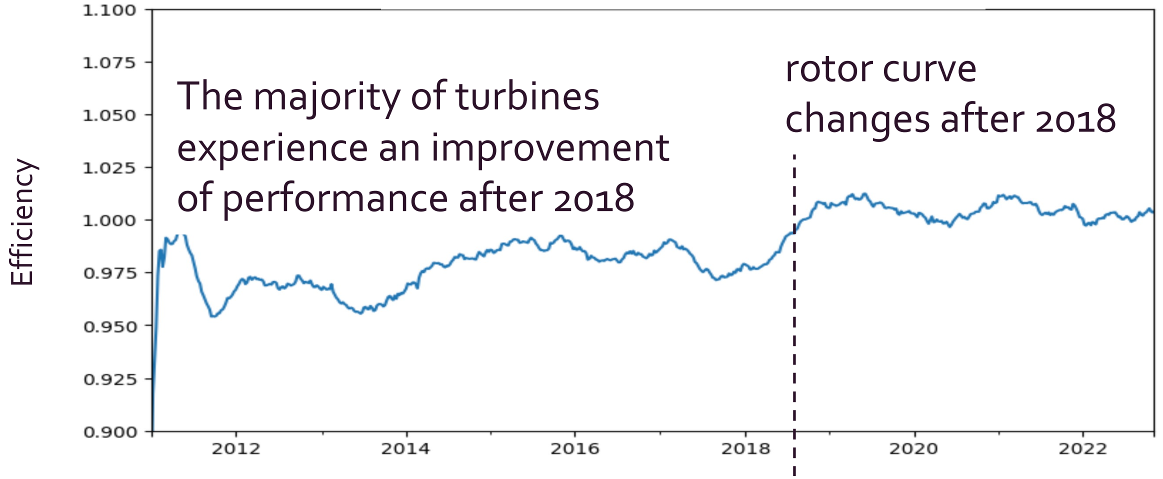
- 0.97 (STL) - 0.99 (YoY)

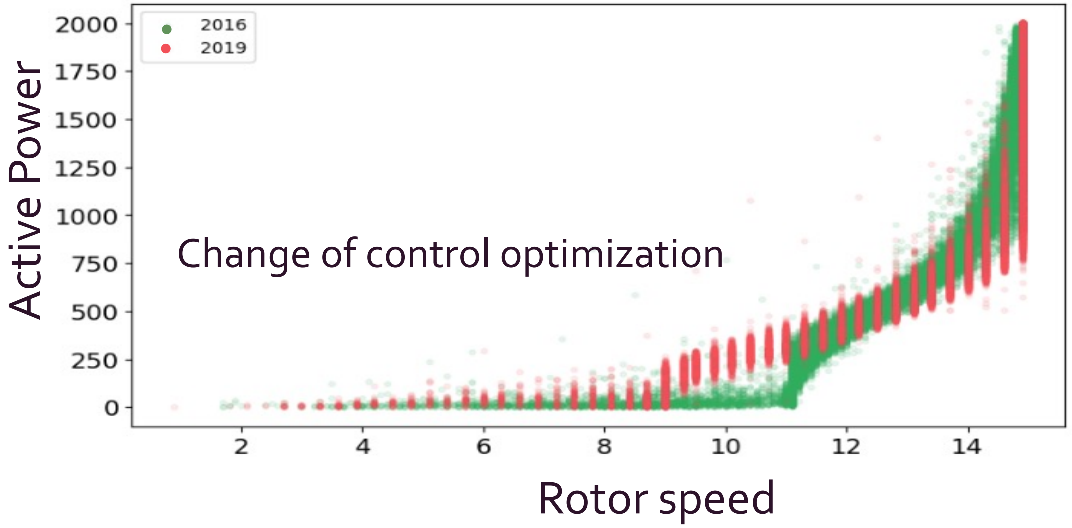
The methodology provides a good estimation of the real loss, i.e. it correctly estimates the induced performance decay

Results

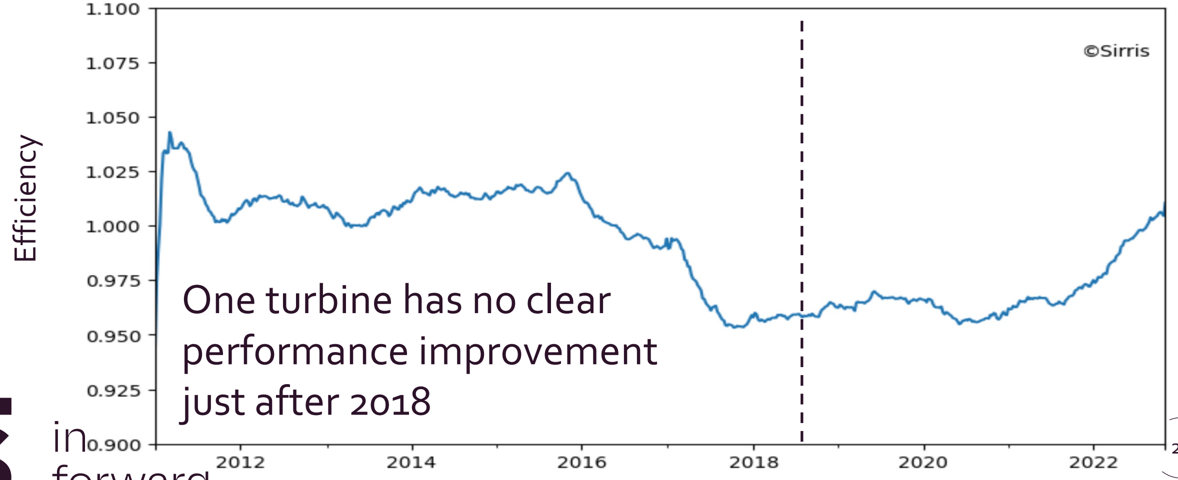
REAL-WORLD DATASET

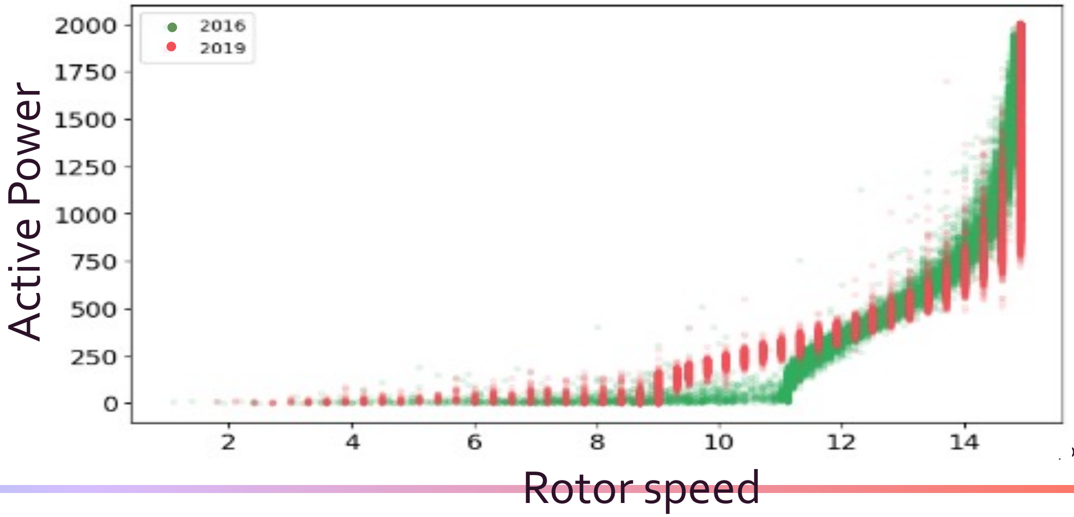
Performance evolution – **Turbine 07**





Performance evolution – **Turbine 01**





Results

REAL-WORLD DATASET

Turbine performance during 2011-2022

Wind Turbine	YoY-based performance trend	YoY-based performance variability	STL-based performance trend
T01	0.02	[-0.26; 0.20]	-0.38
T02	-0.04	[-0.53; 0.31]	0.00
T03	0.10	[-0.30; 0.61]	0.11
T04	-0.20	[-0.52; -0.01]	0.06
T05	-0.04	[-0.53; 0.31]	0.15
T06	-0.18	[-0.43; 0.06]	0.10
T07	0.42	[0.08; 0.60]	0.52

YoY-based and STL-based performance trends are generally aligned

Results

REAL-WORLD DATASET

Turbine performance during 2011-2022

Wind Turbine	YoY-based performance trend	YoY-based performance variability	STL-based performance trend
T01	0.02	[-0.26; 0.20]	-0.38
T02	-0.04	[-0.53; 0.31]	0.00
T03	0.10	[-0.30; 0.61]	0.11
T04	-0.20	[-0.52; -0.01]	0.06
T05	-0.04	[-0.53; 0.31]	0.15
T06	-0.18	[-0.43; 0.06]	0.10
T07	0.42	[0.08; 0.60]	0.52

In the long-term, performance remains rather stable

Results

REAL-WORLD DATASET

Turbine performance

Wind Turbine	YoY-based performance trend (2011-2022)	YoY-based performance trend (2016 vs 2019)
T01	0.02	-1.92
T02	-0.04	1.44
T03	0.10	2.74
T04	-0.20	-0.05
T05	-0.04	0.45
T06	-0.18	1.01
T07	0.42	1.07

In the short-term, maintenance activity clearly improves performance

Conclusions

- We presented a methodology to characterize turbine performance in the long- and short-term
  - The methodology can factor out confounding effects that can affect turbine performance (e.g. weather, operative mode)
- On a synthetic dataset, the methodology identified the induced performance decay
- On a real-case dataset, the methodology provided insights in performance evolution in the long- and short-term
  - Control optimization may not always have a positive effect on turbine performance
  - Turbine performances tend to be rather stable over the years