Accurately quantifying long-term, site-specific, operational icing losses

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Winterwind 2025

For the best energy projects

Management
Part of Ramboll

WHY IS ICING IMPORTANT FOR PROJECT FINANCES?

Understanding production variation

- Market spot prices and the volumes available amplify the risks
- Long-term, mean P50 (P90) over X years
- Seasonal variation…
  … inter-annual variation
- If we measure operational performance, is a snapshot enough to give confidence?

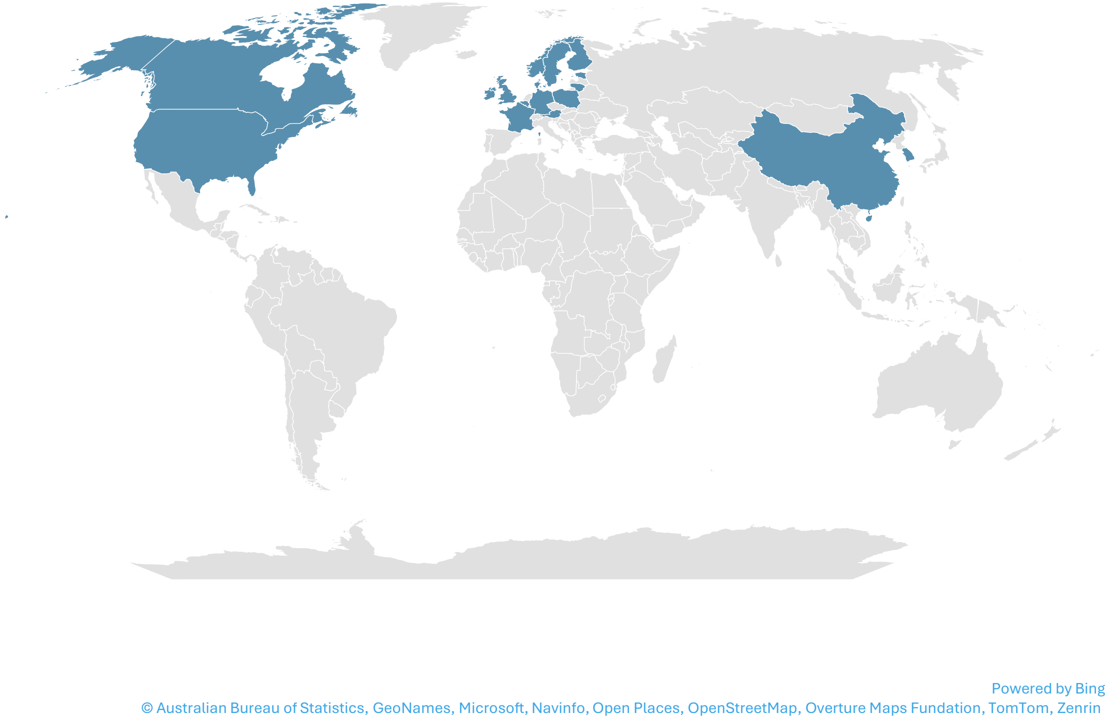
First cold snap is no sweat for Europe's energy markets

[…] underscore the inherent risks associated with fixed-price baseload PPAs for renewable power plants, particularly in the face of heightened volatility and elevated spot power prices. Meanwhile, **icing issues presented another risk** factor for wind turbines, forcing developers to turn to the spot market to cover lost production volumes.

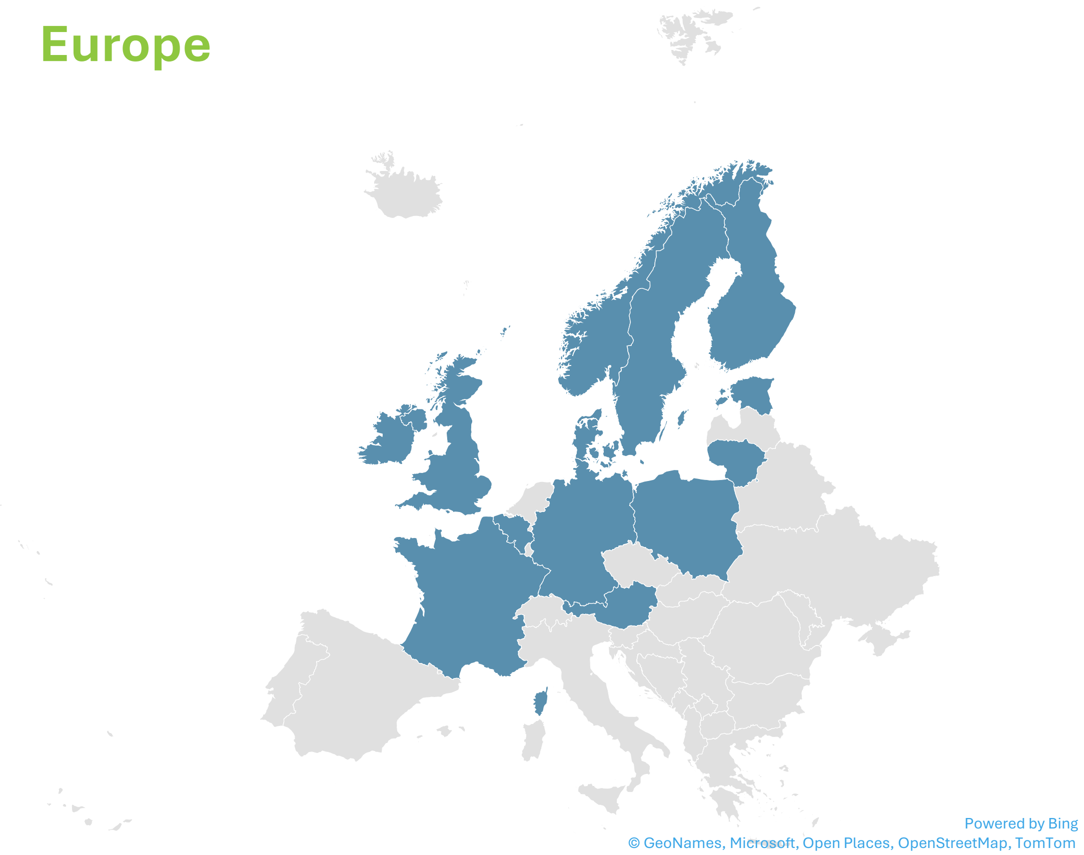
Axpo, European Energy Markets Monthly
December 2023

WHERE HAS K2M SEEN ICING IN OPERATIONAL WIND DATA?

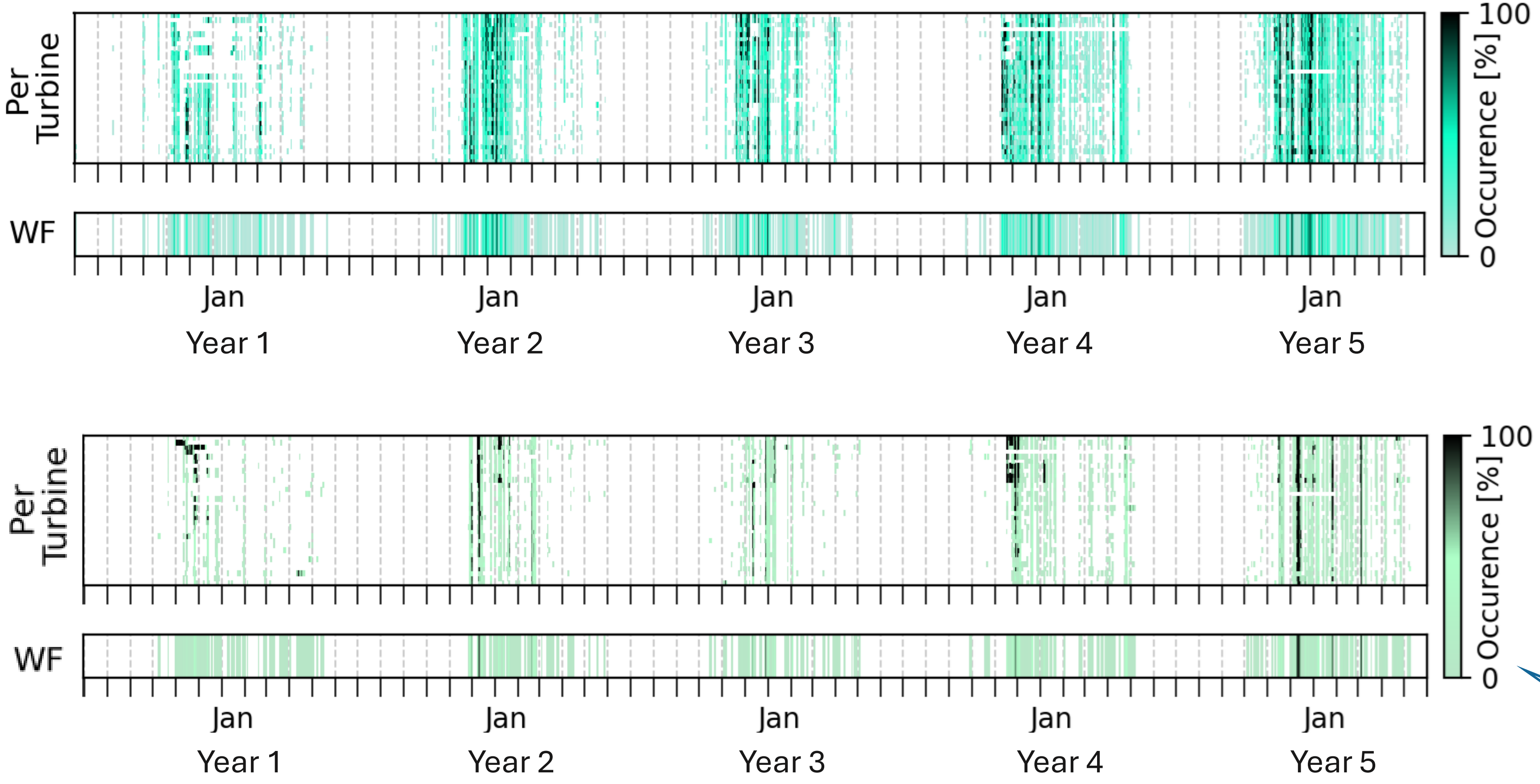
Worldwide

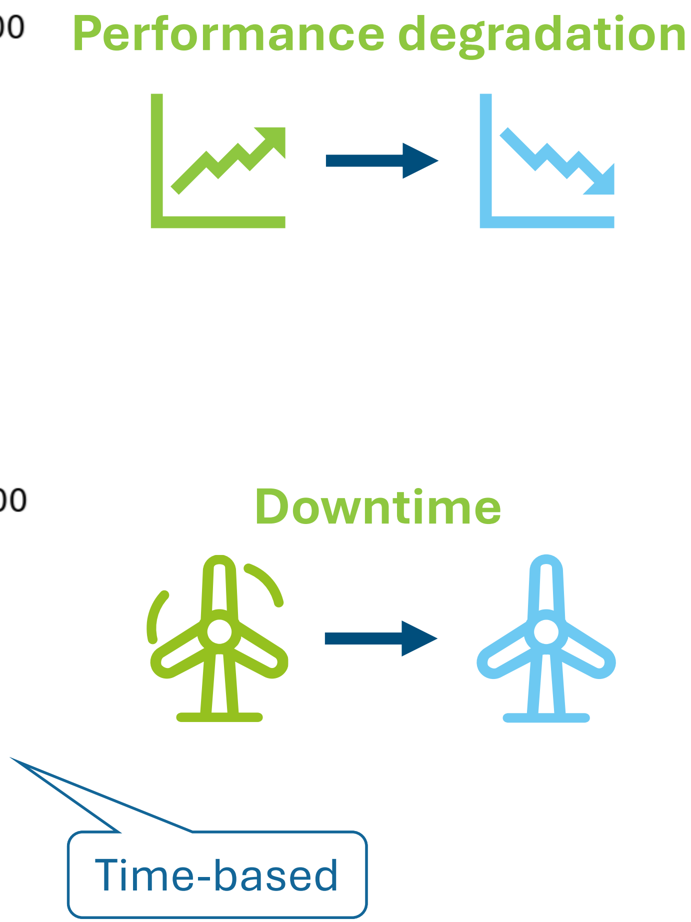


Europe



HOW DO WE SEE ICING IN SCADA DATA?



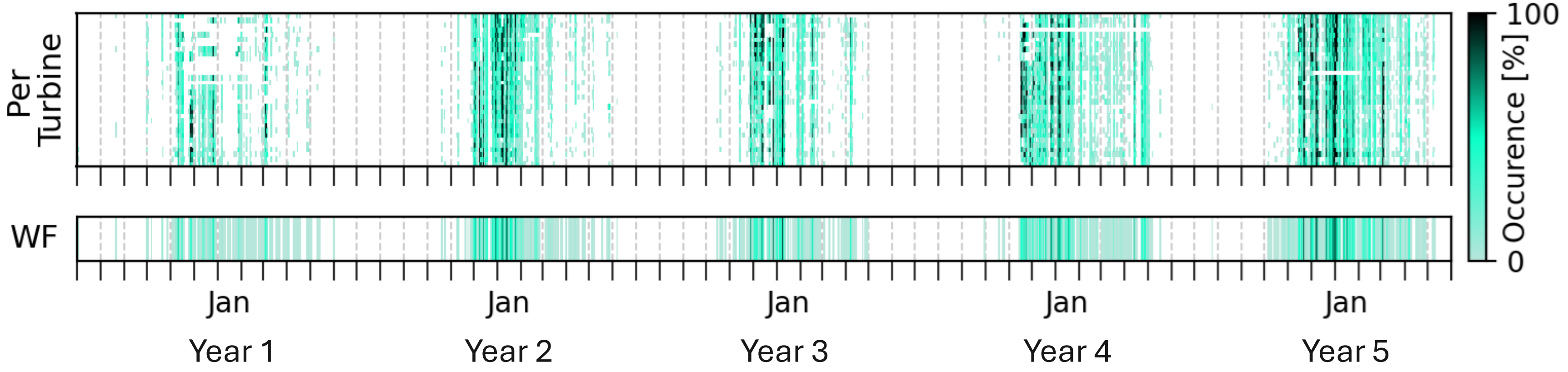


Subset of WTGs from example cold-climate wind farm

① ICING PERFORMANCE DEGRADATION

- **Environmental**
  - Temperature
  - Humidity
  - ...
- **Turbine placement**
  - Elevation
  - Exposure
  - Wakes
  - ...
- Turbine O&M
  - Icing shutdown strategy
  - Availability
  - ...
- Wind resource

Significant inter-annual variability



① ICING PERFORMANCE DEGRADATION

Each WTG is an individual

- **Environmental**
  - Temperature
  - Humidity
  - …
- **Turbine placement**
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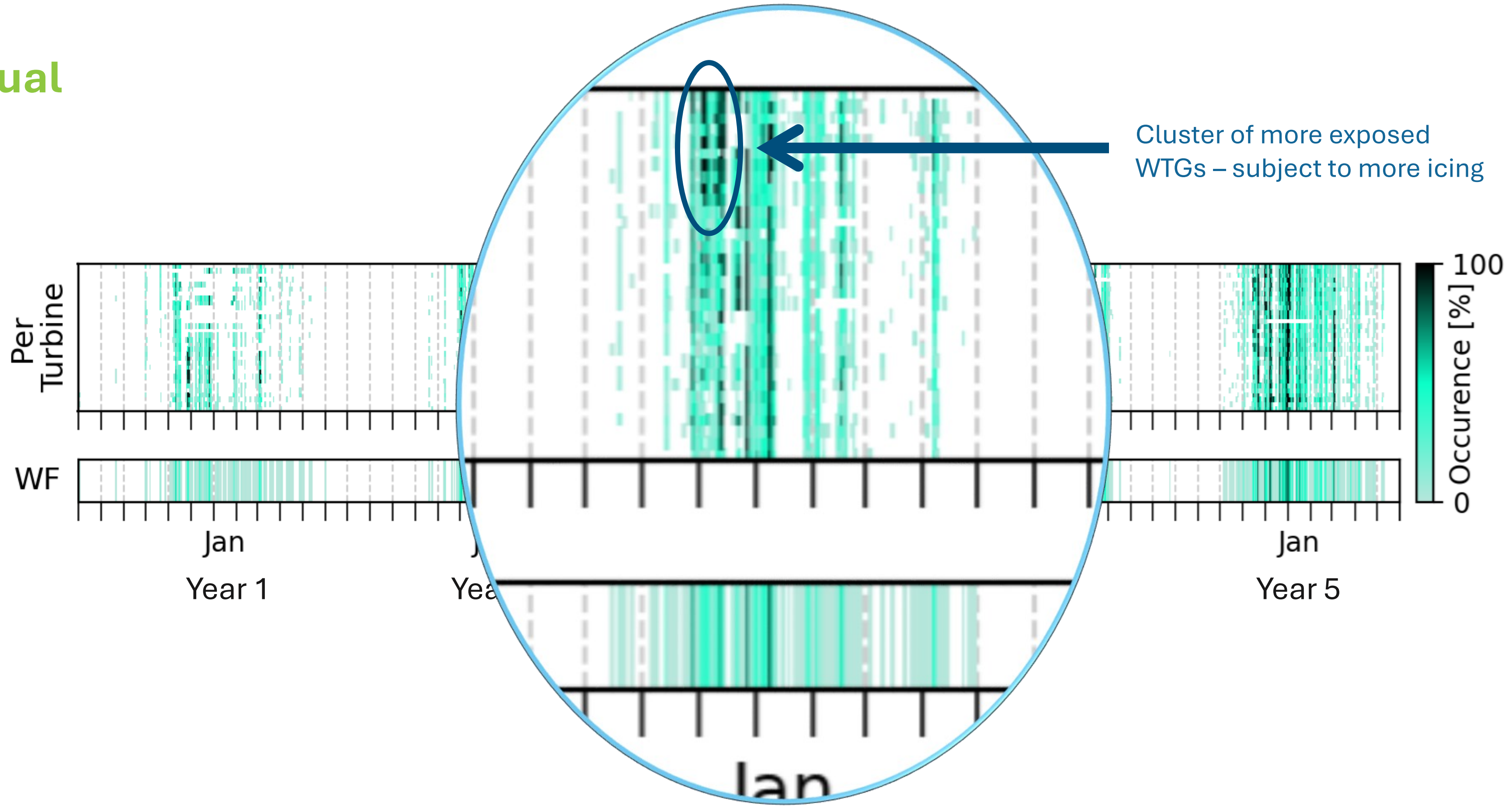

② OPERATIONAL STRATEGY

- Environmental
  - Temperature
  - Humidity
  - …
- Turbine placement
  - Elevation
  - Exposure
  - Wakes
  - …
- **Turbine O&M**
  - Icing shutdown strategy
  - Availability
  - …
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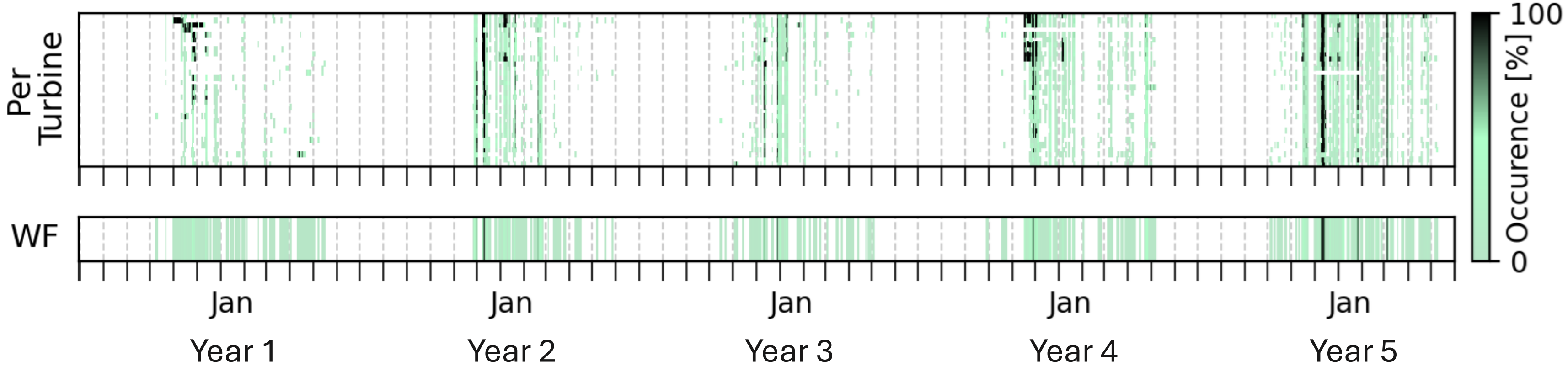
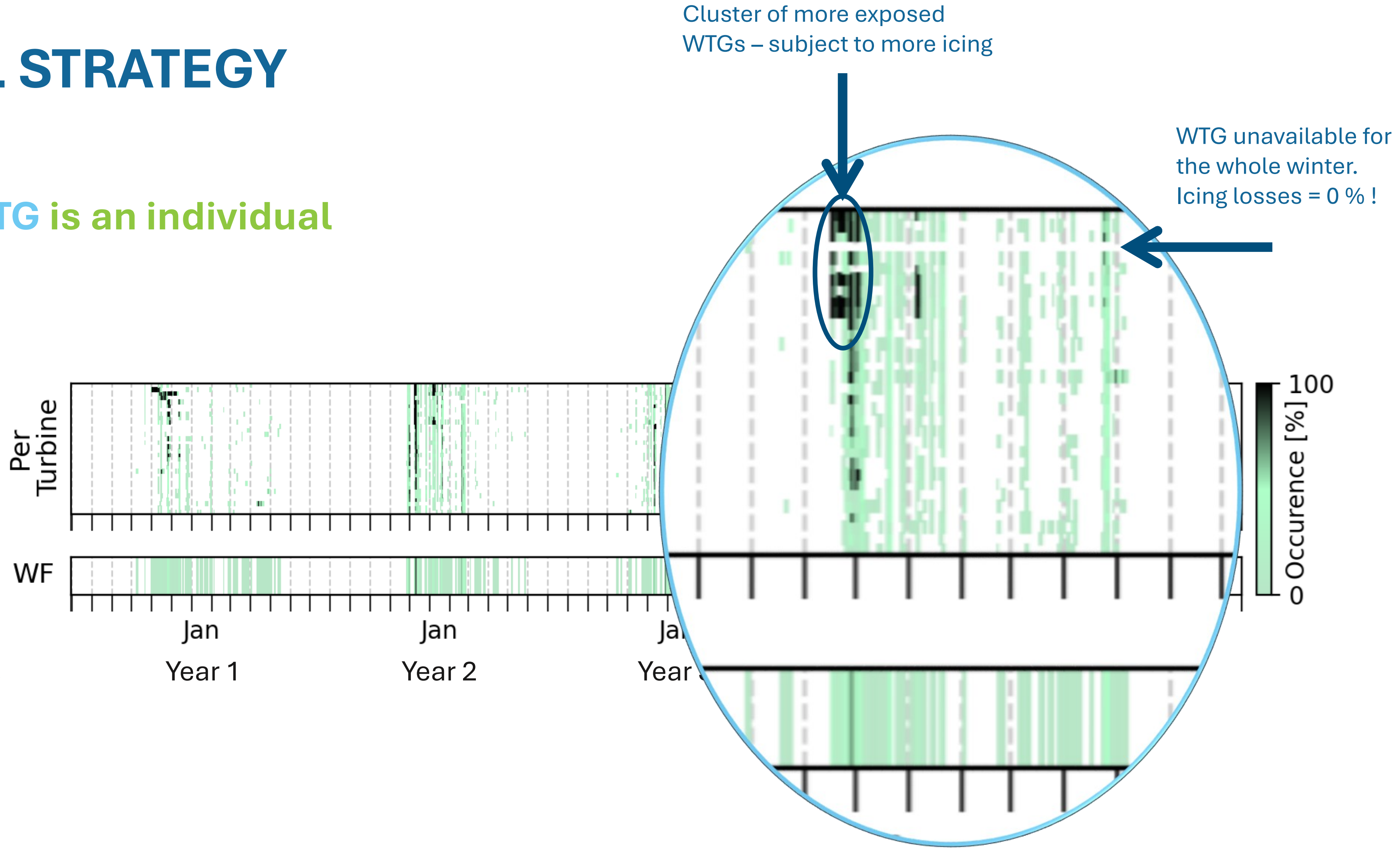
Significant inter-annual variability



② OPERATIONAL STRATEGY

Each wind farm and WTG is an individual

- Environmental
  - Temperature
  - Humidity
  - ...
- Turbine placement
  - Elevation
  - Exposure
  - Wakes
  - ...
- **Turbine O&M**
  - Icing shutdown strategy
  - Availability
  - ...
- Wind resource

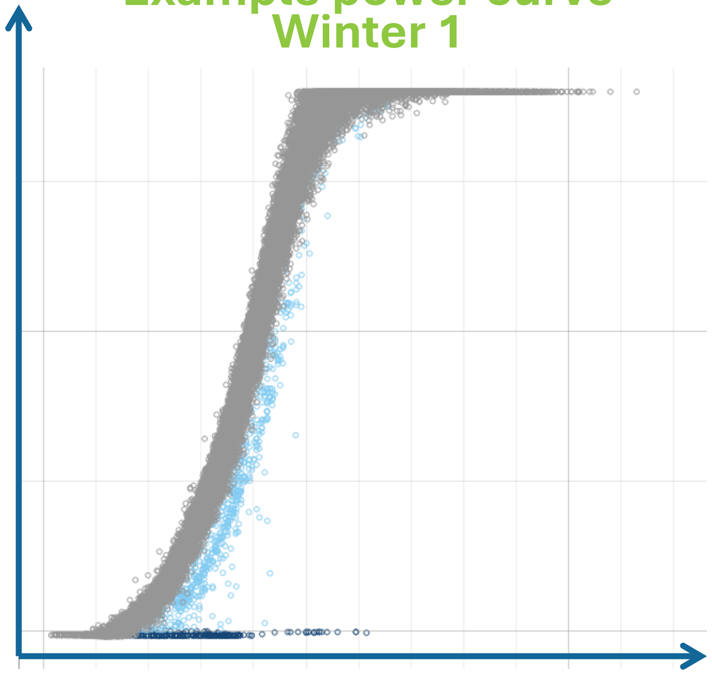


③ IMPACT ON PRODUCTION

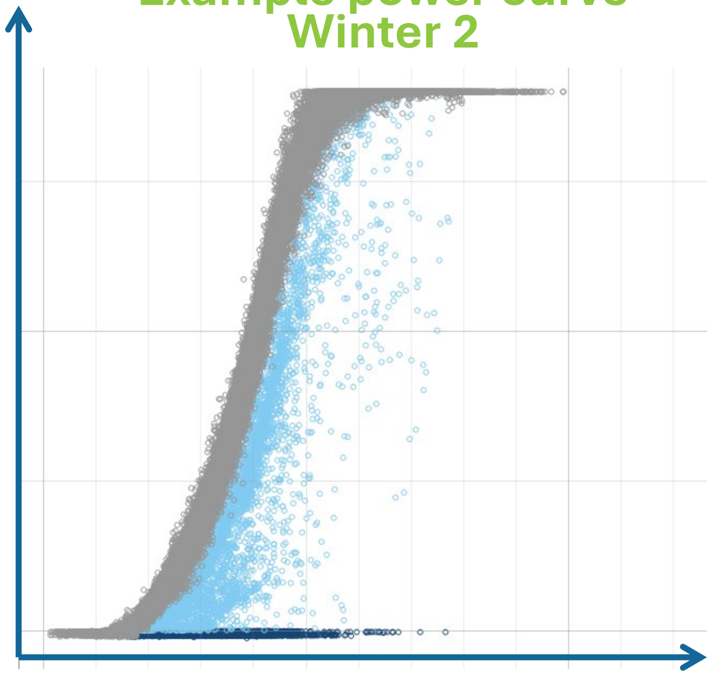
Significant inter-annual variability

- Environmental
  - Temperature
  - Humidity
  - …
- Turbine placement
  - Elevation
  - Exposure
  - Wakes
  - …
- Turbine O&M
  - Icing shutdown strategy
  - Availability
  - …
- **Wind resource**

Example power curve
Winter 1



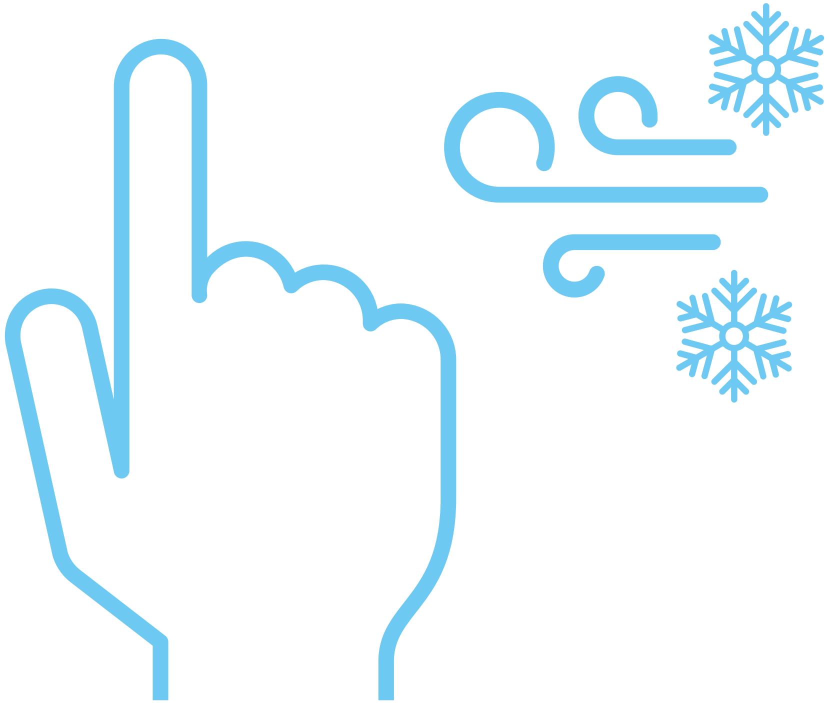
Example power curve
Winter 2



WHAT APPROACHES ARE THERE?

Accounting for inter-annual variation

- **Do nothing**
  - Just use observations from the analysis period and assume it'll be the same
- **Make a time-based adjustment**
  - Based on likelihood of icing
- **Fall back on pre-construction models**
  - Accurate weather models, but...
  - ... don't account for turbine control
  - ... don't account for detailed topography

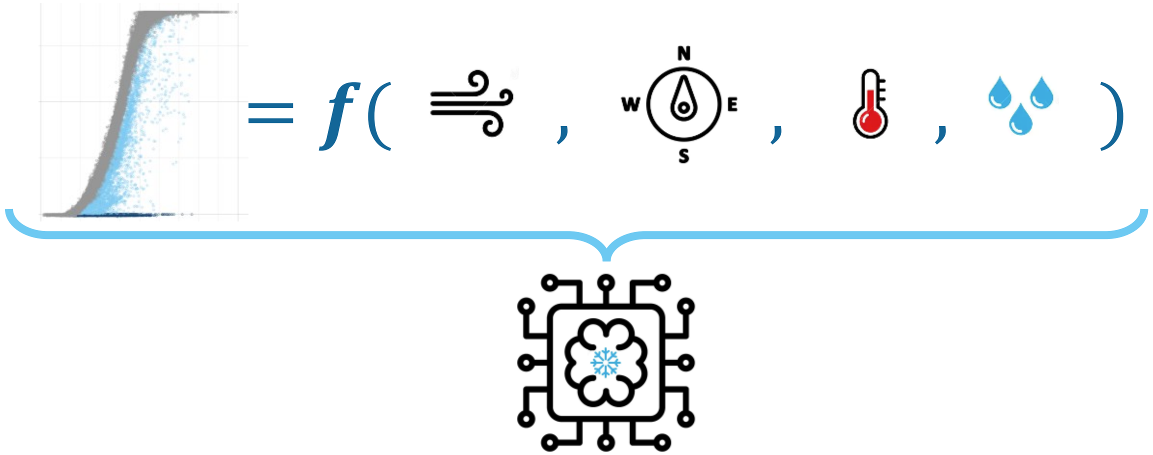


A DIFFERENT APPROACH

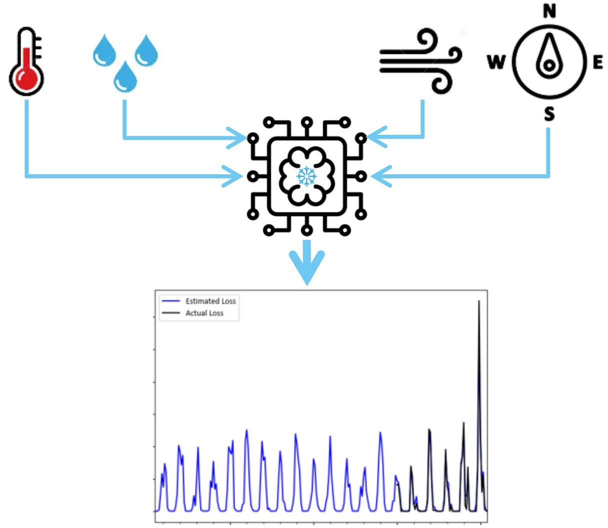
Machine learning model

- Inputs:
  - Timeseries icing energy losses
    - Identified in 10-minute SCADA data using WTG events data and proprietary in-house methods
    - Calculated using machine learning power curves
  - Reanalysis data
- Periods affected by non-icing losses removed to prevent bias
- Model trained + proprietary modifications
- Evaluated using long-term reanalysis data

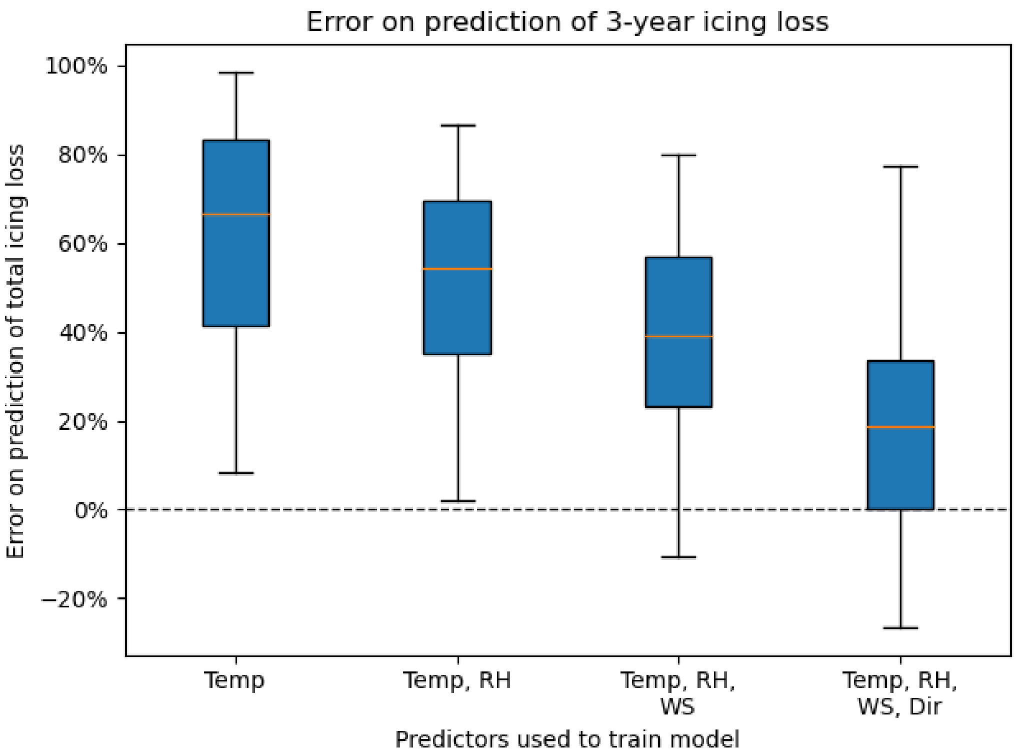
Training



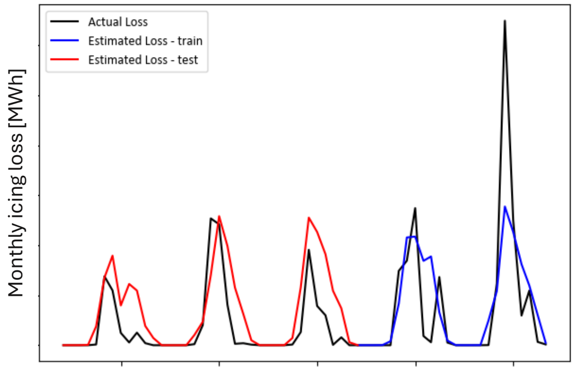
Evaluation



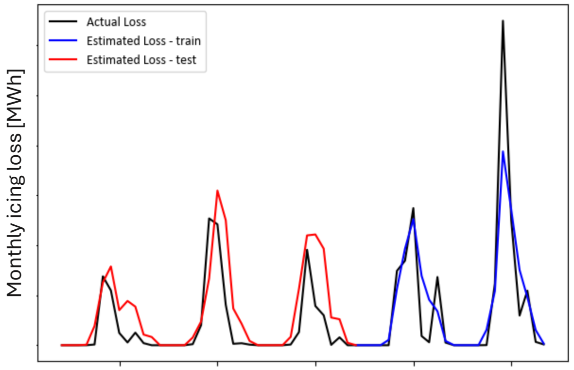
CHOOSE PREDICTORS WISELY



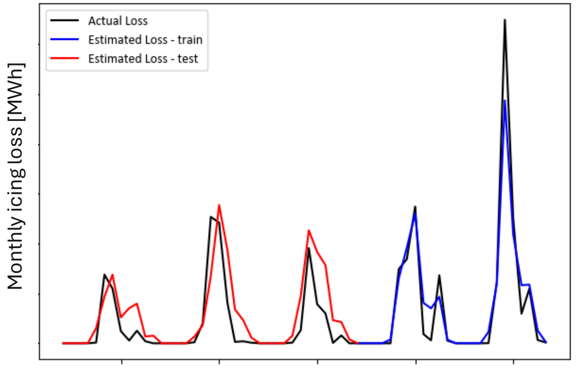
Temperature



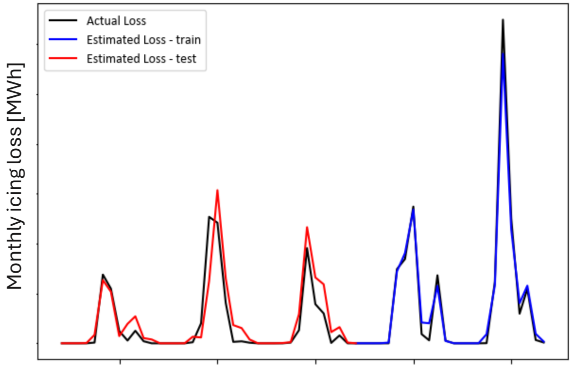
Temp & Relative Humidity



Temp, RH & Wind Speed



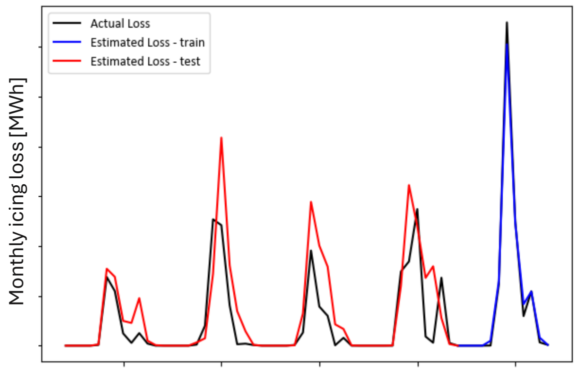
Temp, RH, WS & Direction

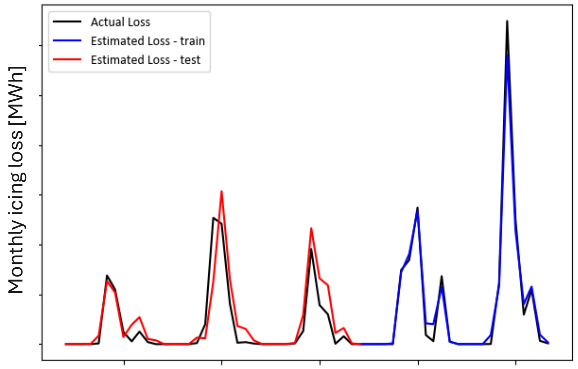


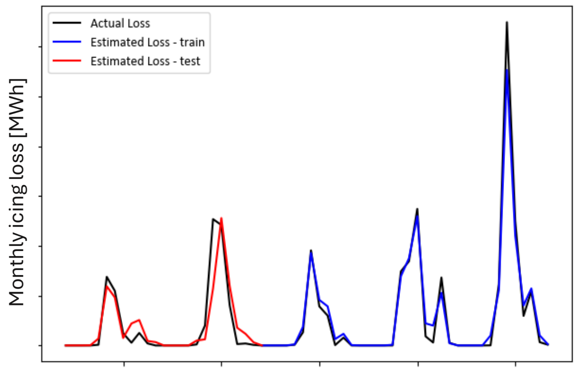
MAXIMISE AVAILABLE DATA

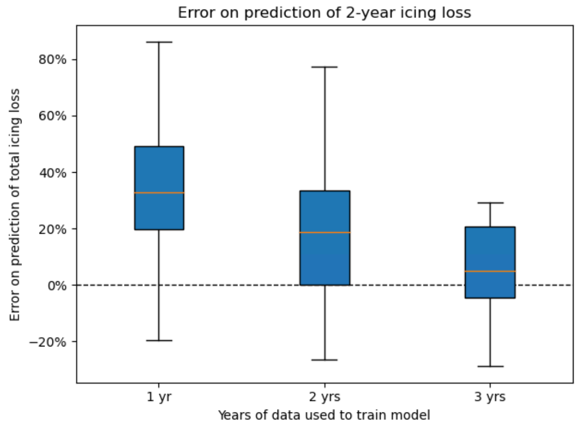
- Model progressively improves with the addition of more data

- With 3 years of training data, the median error is around 5 % of observed loss
    - 5 % icing loss → 0.25 % yield error







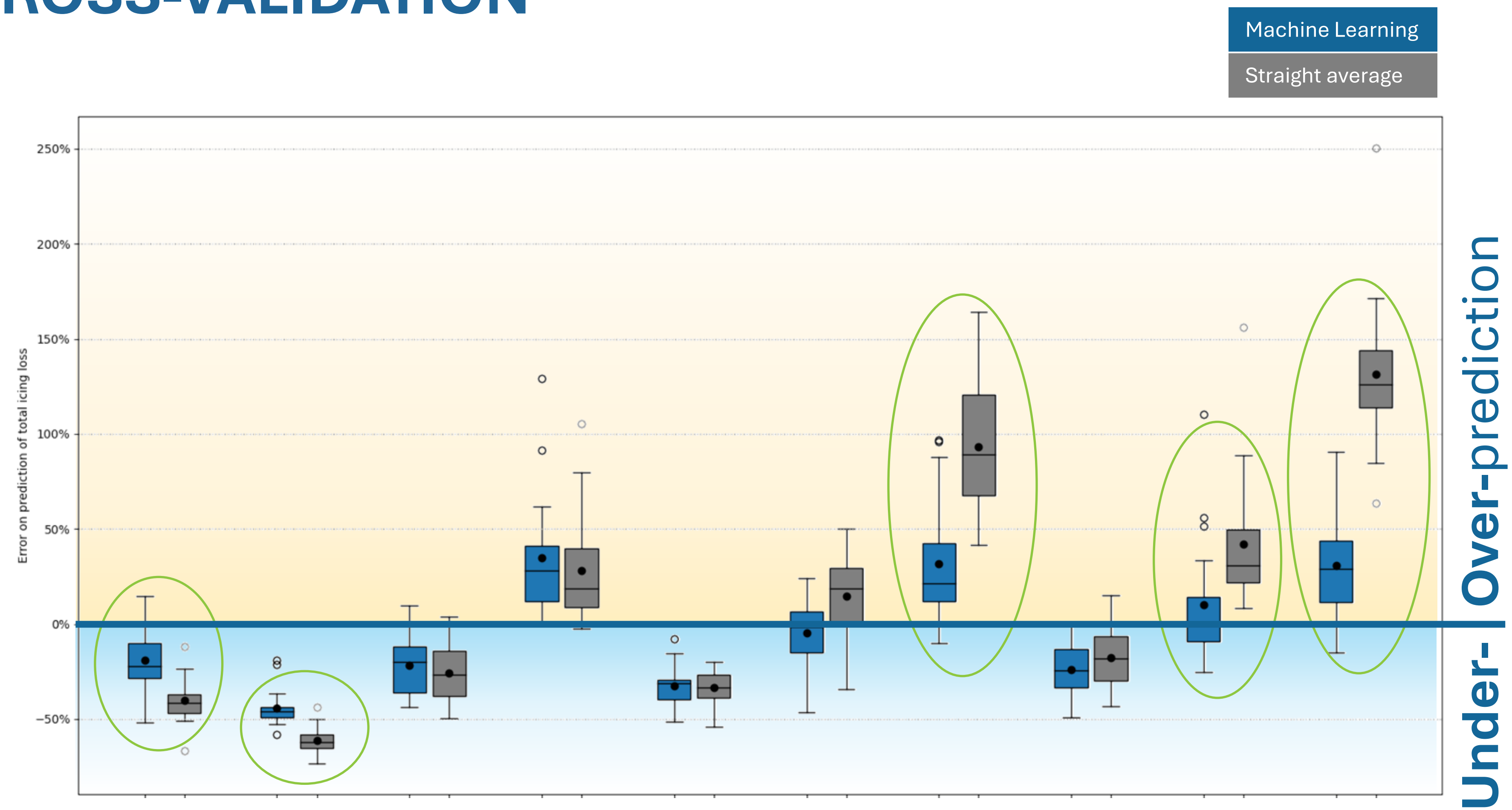


LEAVE-P-OUT CROSS-VALIDATION

Total 5 years available

Model trained using 2 winters to predict remaining 3

Significant reduction in error when observed period has outlier winters

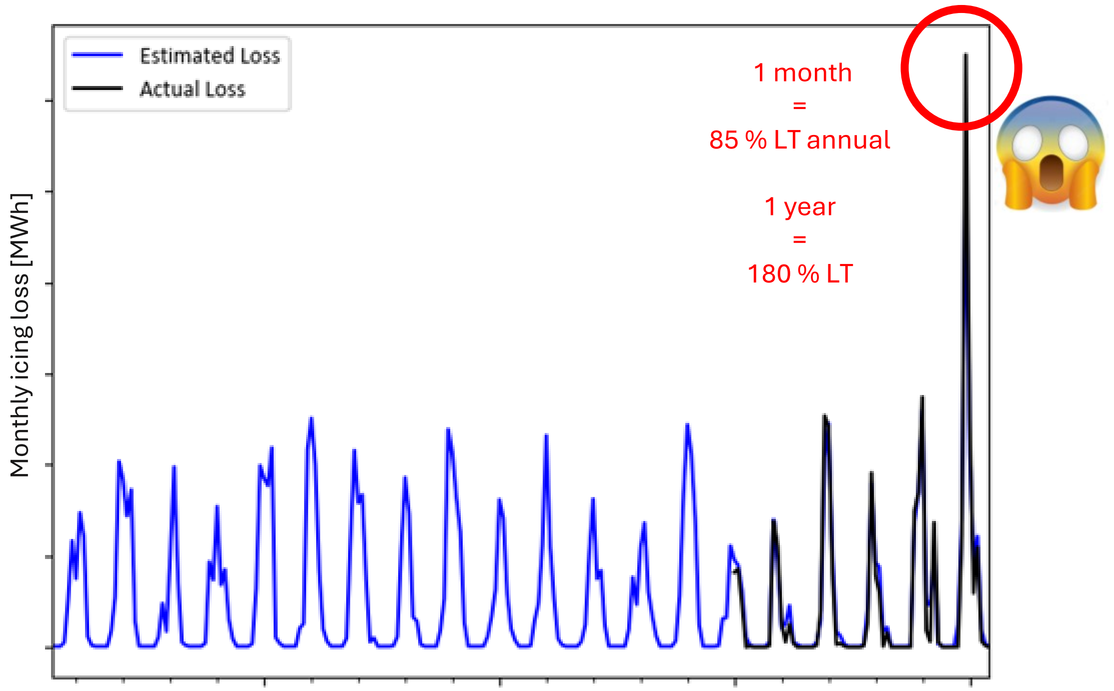


USE CASES – LONG-TERM ICING

Expected variability of annual icing loss

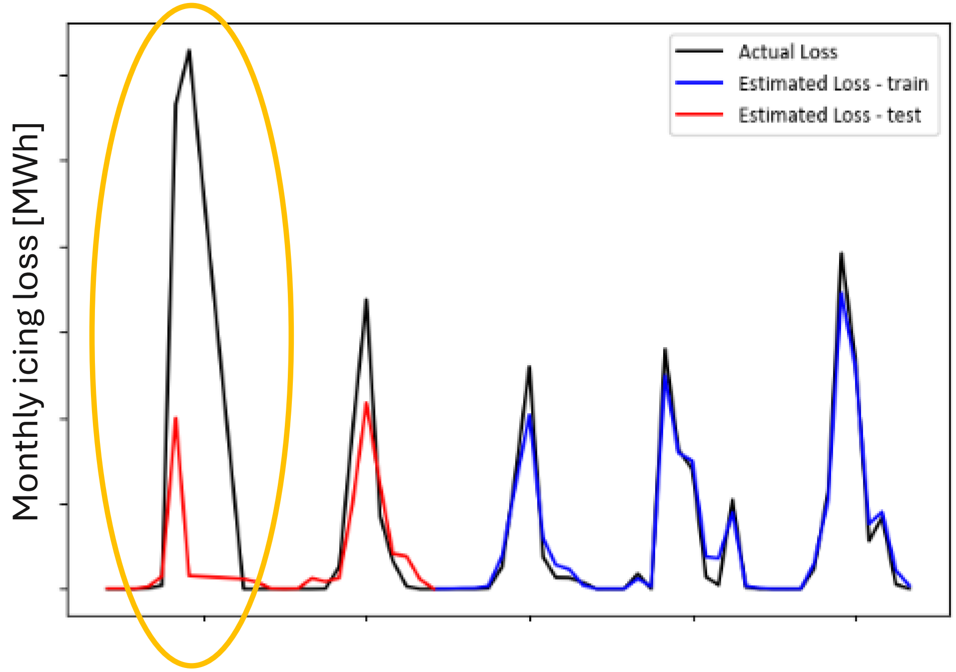
- **Long-term** estimate of icing loss, for **individual** WTGs
- Bias removed from other non-icing losses and downtime during observation period
- Allows likelihood of given icing losses to be estimated for financial modelling

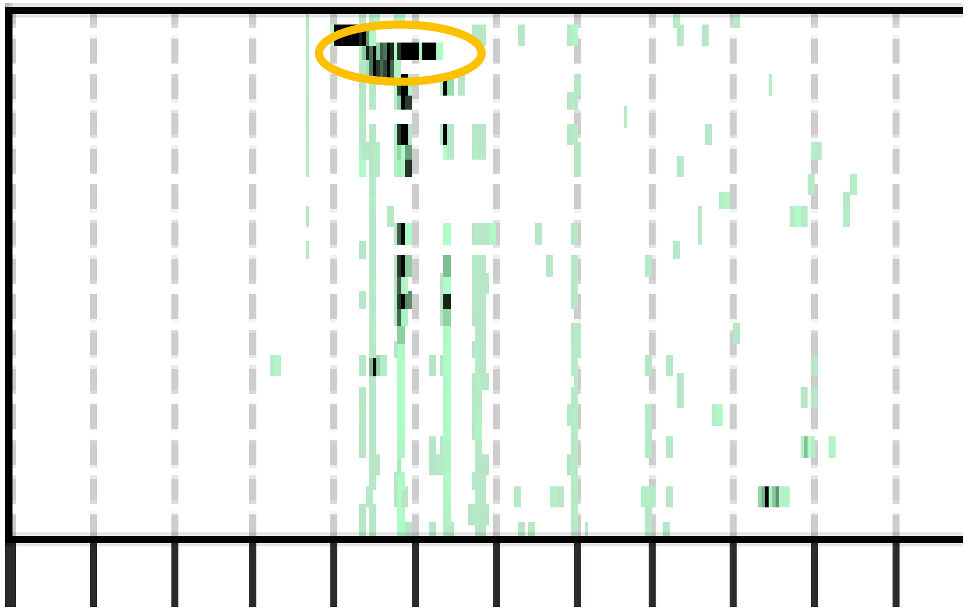
Long-term monthly icing loss at one WTG



USE CASES – IDENTIFICATION OF INCORRECT OPERATION

Outlying peak in first winter → **Over-triggering of icing shutdown**



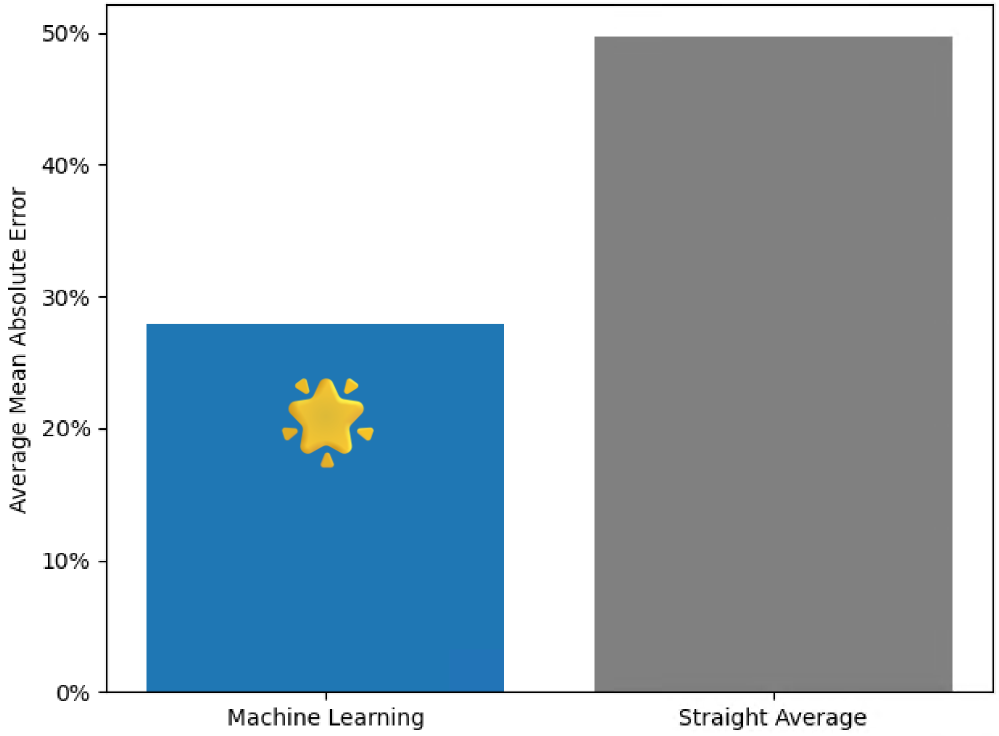


THOUGHTS TO TALK ABOUT AT DINNER LATER...

Take-aways on measuring icing impacts

- Need to correct for **long-term** variability
- Need to account for **how icing interacts** with other losses
    - availability and O&M strategy
    - ... and the wind resource too
- Each wind farm and WTG is **unique**

Overall results



Be smart!

Do nothing

THANK YOU