WHEN TRUST MATTERS

Evaluating Icing Losses outside the Nordics with the WICE Model

Case Studies in France, North America, & Spain, and Germany

Luis Baquero,
DNV - Energy Systems Northern Europe

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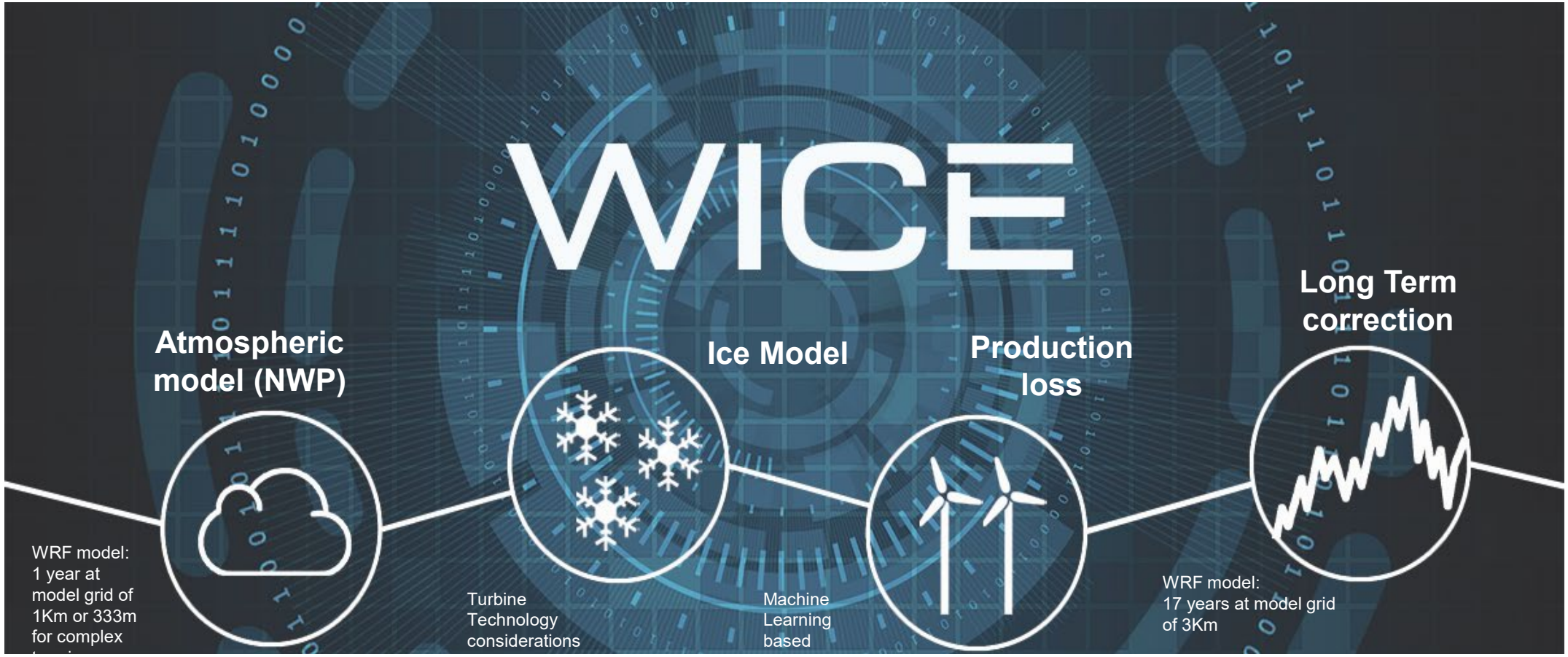
Agenda

1. The WICE Model
2. Case Studies Beyond the Roots:
   - France
   - Spain
   - North America
   - Germany
3. Next Steps
4. Conclution

The WICE Model

The WICE Model

- It computes the long-term annual energy losses due to icing underperformance.



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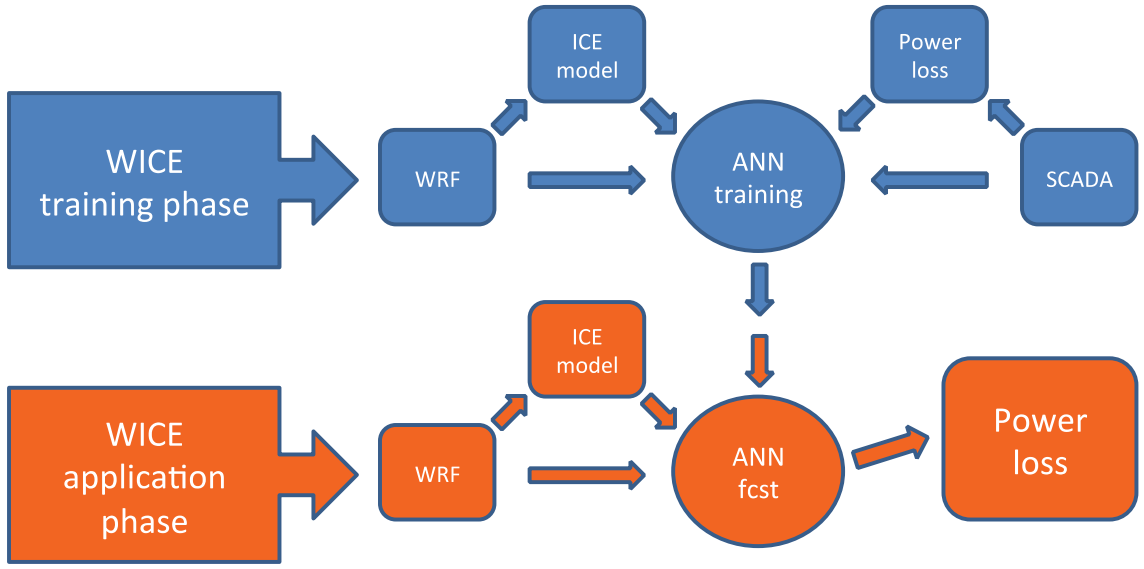
    - Validated in Sweden
  - **WICE 2.0 (2020)**
    - Trained using data from 10 additional wind farms in Sweden, Norway, and Finland, with a data coverage ranging from 2012 to 2017.
    - Validated in Sweden, Finland and Norway + a blind test validation over 6 wind farms in Sweden.
    - Ice Sublimation, and Turbine type considerations.
    - Improved feature engineering for the ML model.
    - IPS modelling capabilities



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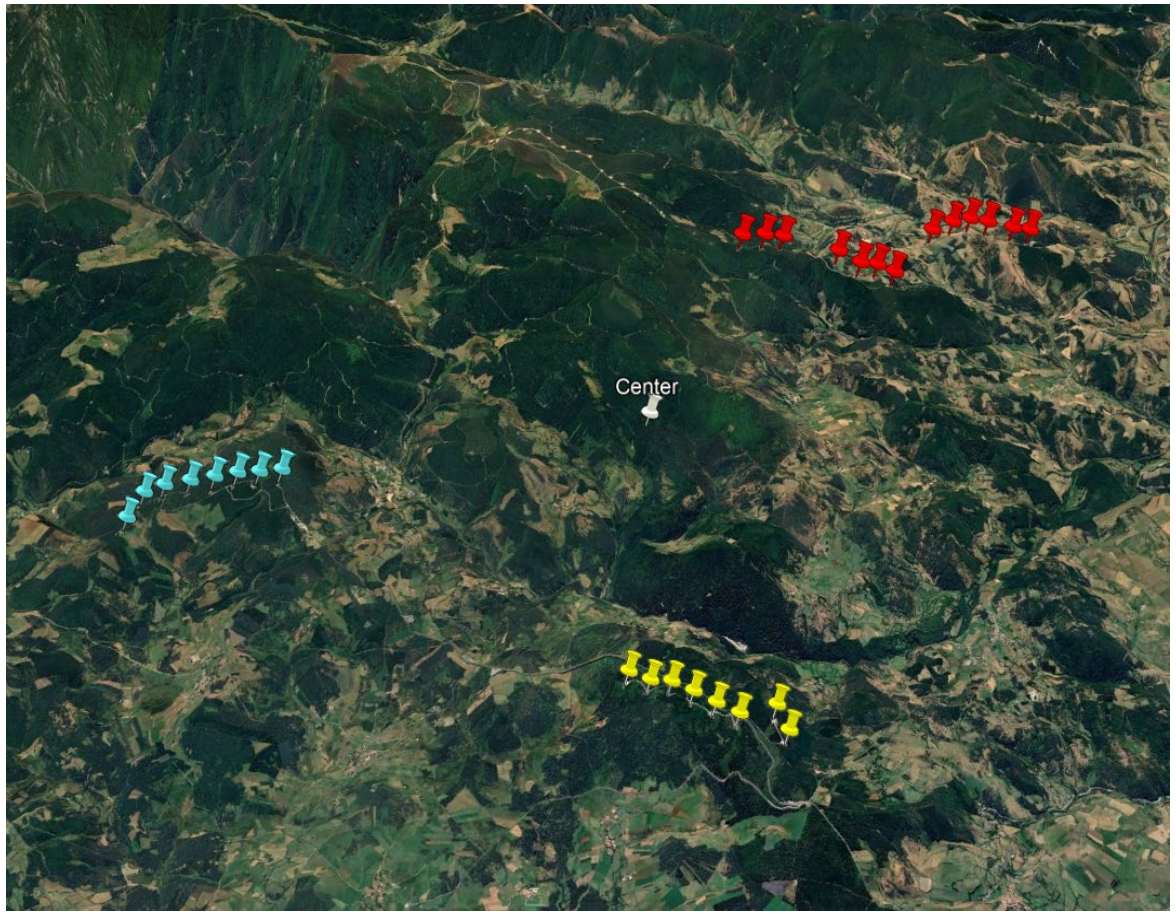
Track Record	
Region	**Countries/Areas**
Nordic Countries	Finland, Norway, Sweden
Eastern Europe & Central Asia	Kazakhstan, Uzbekistan, Russia,
Southeastern Europe (Balkans)	Greece, Kosovo, Serbia, Romania, Bosnia, Croatia
Central & Western Europe	Poland, Italy, Spain, France, Netherlands, UK
North America	West Coast Canada, and Northeastern United States

Case Studies Beyond the Roots

Case Studies Beyond the Roots: France

France - Case Study



Mountainous terrain, All turbines at similar heigh elevations: 1300 – 1350 m ASL

Three sub-farms: Yellow (3 MW E82 @85m), Blue & Red (2.35 MW E82 @78m)

Nearby reservoir (~10 km), and features small rivers flowing through the channels of the mountain formations → higher local humidity and water particle transport

Icing losses: Yellow: 5.0 % (IAV 1.5%) | Blue 4.3 % (IAV 1.4%) | Red 2.3% (IAV 0.7%) |

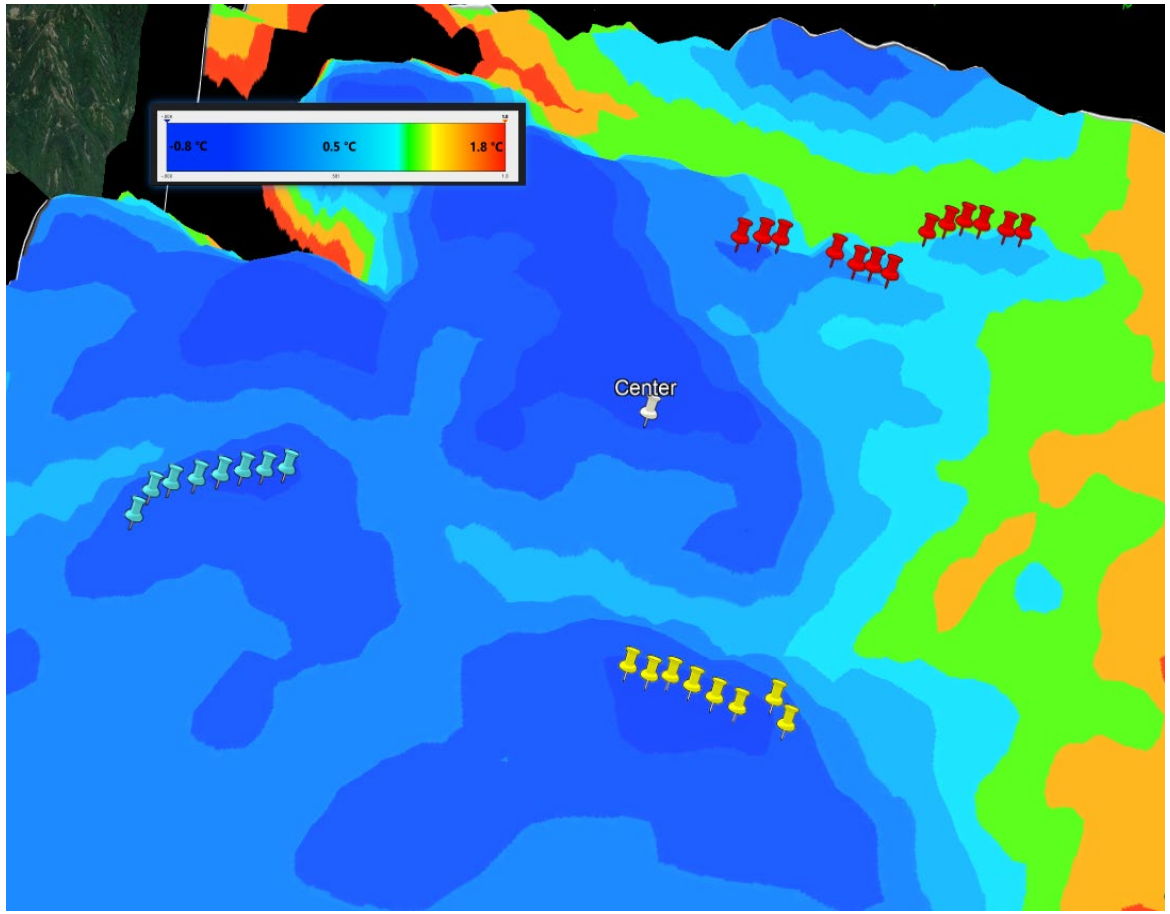
Annual days of icing: 25 days for Yellow WF | 21.5 days for Blue WF | 10 days for Red WF.

Strong need for precise microclimate modeling

IPS Implementation

Ice throw and Ice strike Assessment required

France - Case Study



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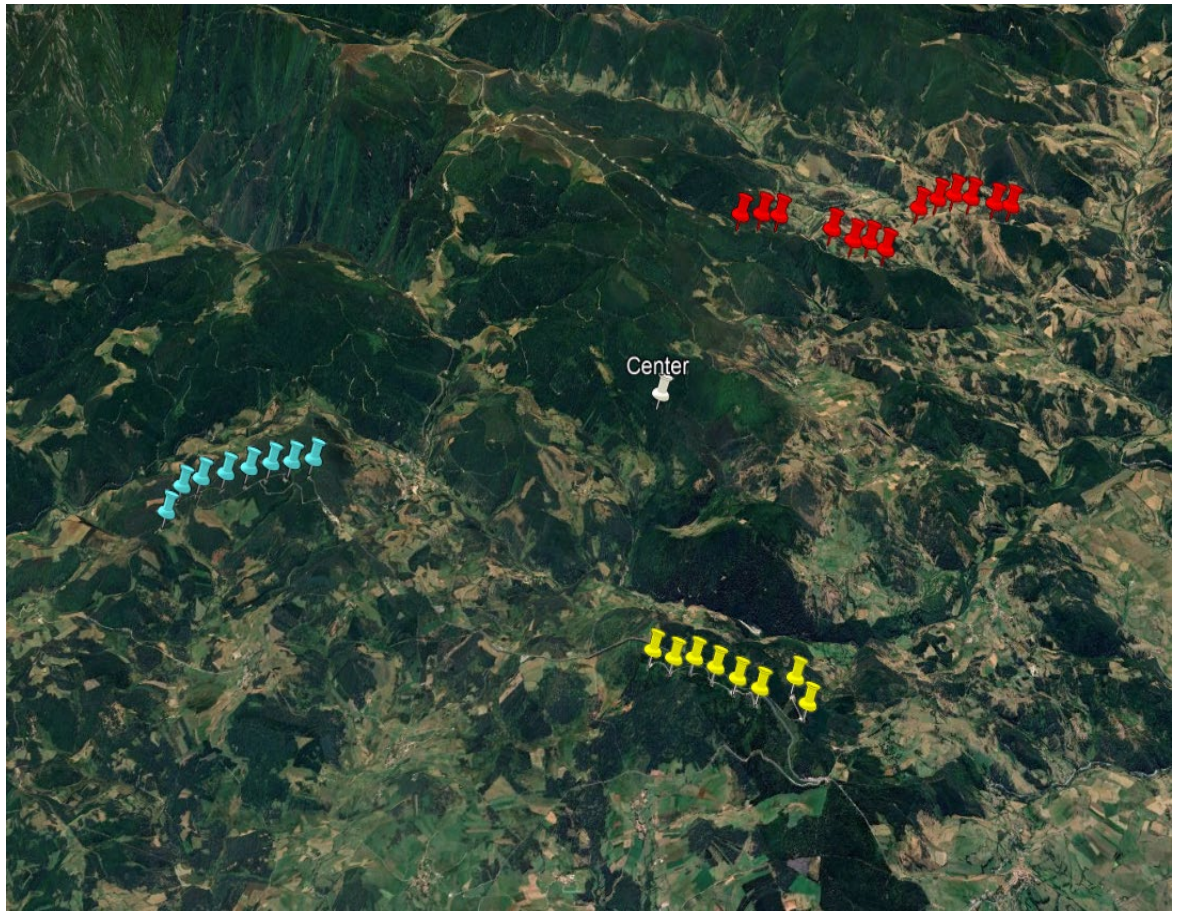

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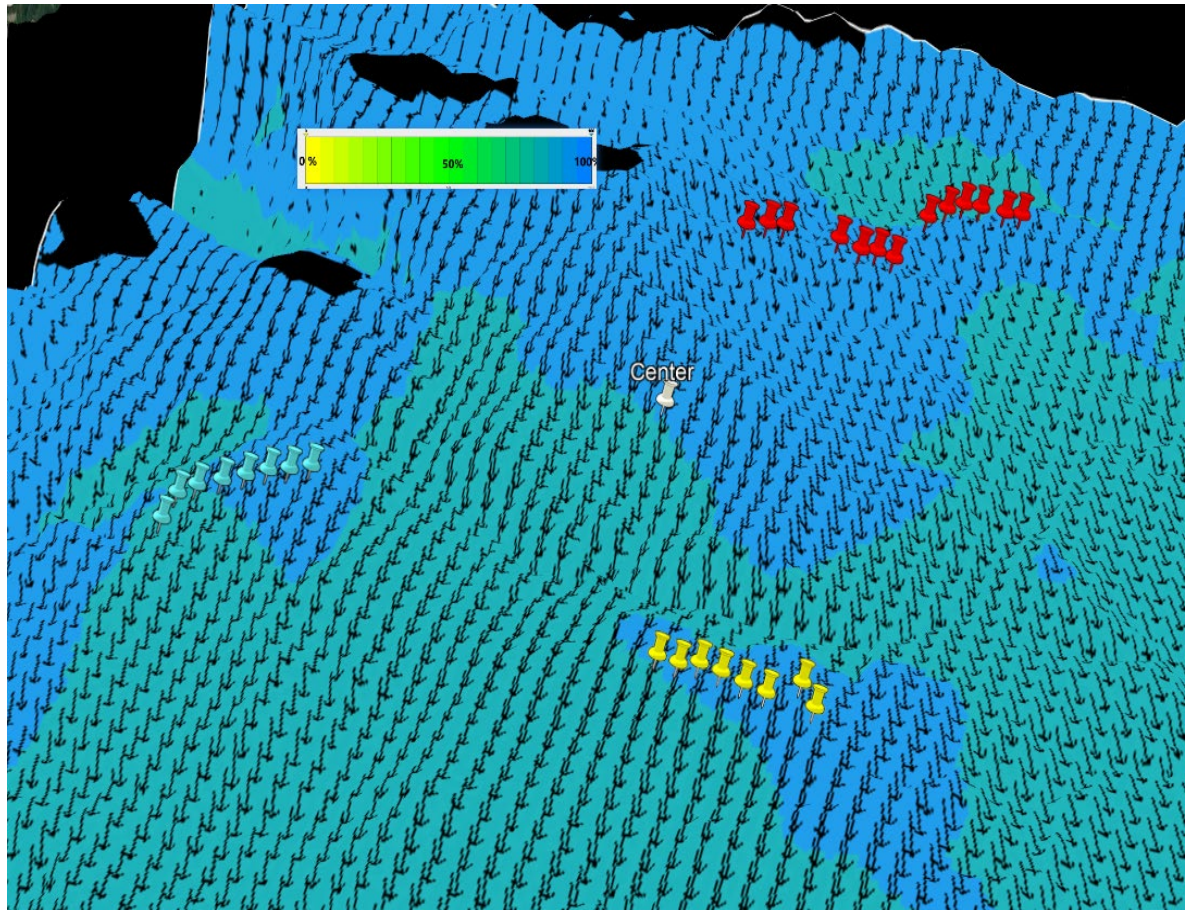

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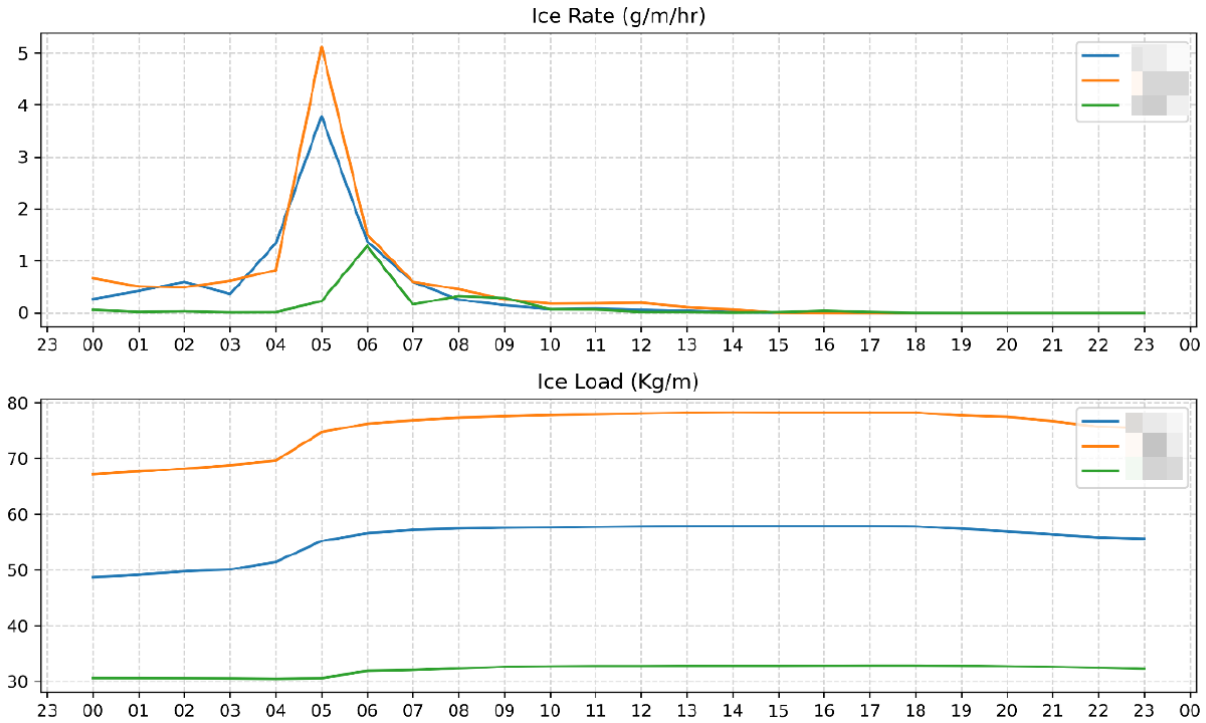

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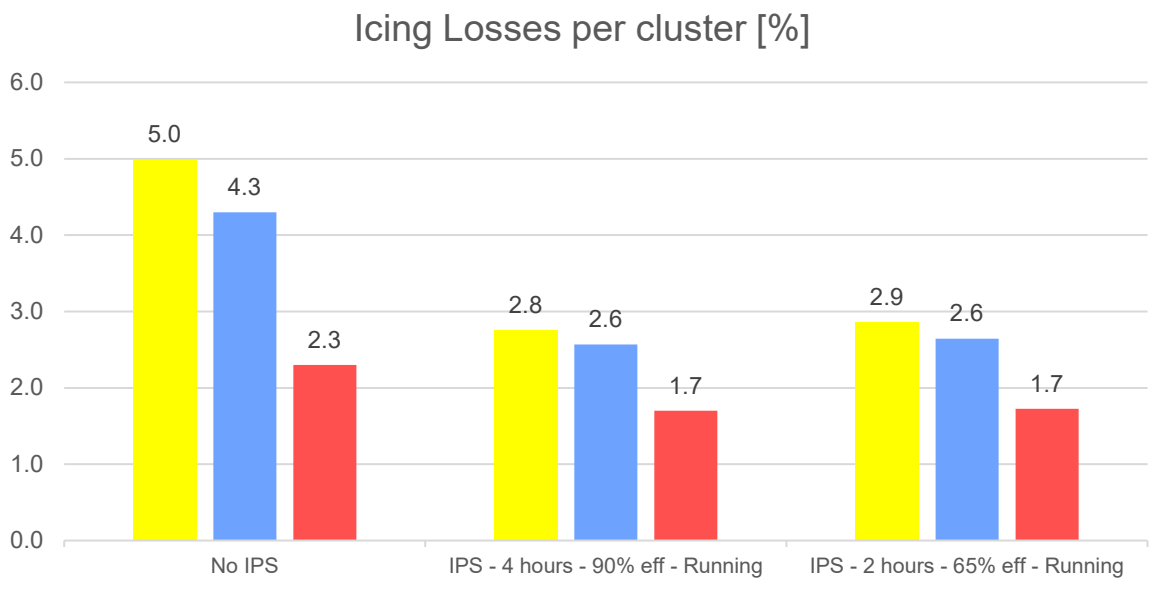
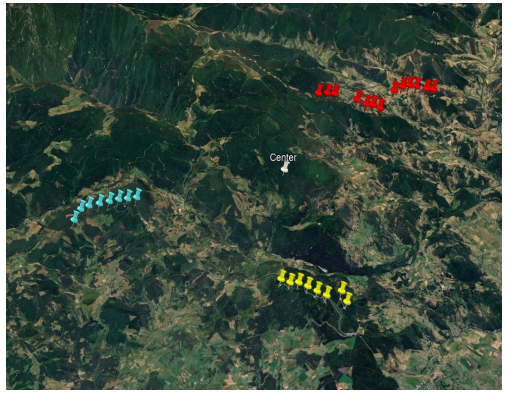
France - Case Study

No.	P1314 Blade heating automatic	P1315 Permit Blade Heating during operation	P1317 Min. Duratio of Blade Heating	DNV Scenrario
1	Yes	Yes	4:00h	4h restart
2	Yes	Yes	2:00h	2h restart

- Losses varied from ~5% to ~2% in the same portfolio
- Local elevation, terrain complexity, & microclimate differences
- **De-icing system** mostly used in standstill mode → partial benefit. **Control setting need to be adjusted.**
- Model high-resolution (333 m) helps to describe better the intra wind farm icing situation





France - Case Study – Key Findings

- France sites can have notable icing in some regions
- Terrain-driven differences cause variations in icing losses
- Important to confirm real turbine ops (shutdown or keep running) and analyze configuration of the IPS
- High regulations regarding ice throw and ice strike risks
- WICE is adaptable but must check site-specific assumptions. Local validation is needed, or a model trained over local conditions

Case Studies Beyond the Roots: North America

North America - Case Studies

- 4 Sites in the Northeastern United States, primarily in New Hampshire, New York, and Pennsylvania.
- 1 Site in Canada, located in Atlantic Canada, for PPA purposes.

The icing losses due to degradation for the four USA sites ranged from 2 to 3.5%, with relatively low interannual variability.

The icing loss due to degradation for the Canada site was computed at 1.4 %, with a low interannual variability.

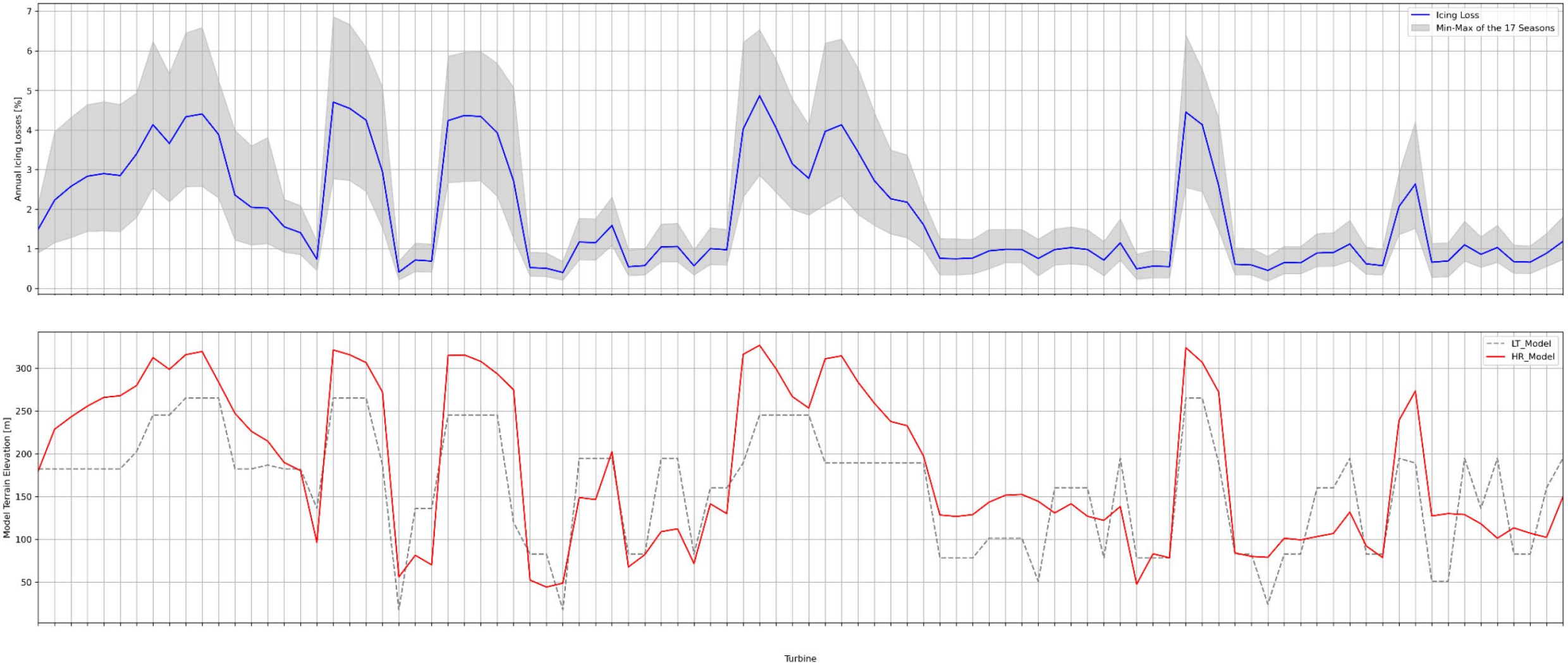
- For the USA sites, an active IPS was not evaluated. When compared against local measurements, the model capture well the icing events seen by the observations.

- The Wind farm in Canada has a PPA aim to secure a 24x7 energy supply, therefore producing energy in winter months was a relevant discussion, to size the back up systems required to meet the demand. IPS modeled.

Due to the nature of the project a wind farm icing loss value was not than relevant. The Customer required more insights on turbine level basis, and icing yearly profiles.

The WICE model time series per turbine were analyzed to discover more insights. Only informative results. Not uncertainty quantification.

Canada – Case Studies



Canada – Key Findings

The mean wind farm icing loss does not represents the real conditions inside of the wind farm

As per difference in the terrain elevation, icing losses at turbine level are much higher than the average.

Considering targeted IPS installations on high-loss turbines

The Model is not fully trained to target high-accuracy single-turbine losses.

The model is not validated at the turbine level; therefore, there is no quantification of the uncertainty for turbine icing losses.

The yearly icing loss profile helps plan backup systems and mitigation strategies for wind farm operations in specific months.

Highlights the need to expand WICE for fine-grain (turbine-level) icing forecasts and yearly icing profiles

The Project could benefit from a high resolution yearly icing profile to better operation planning.

Case Studies Beyond the Roots: Spain

Spain - Case Study

Photo Credit: Iberdrola España. 2024.

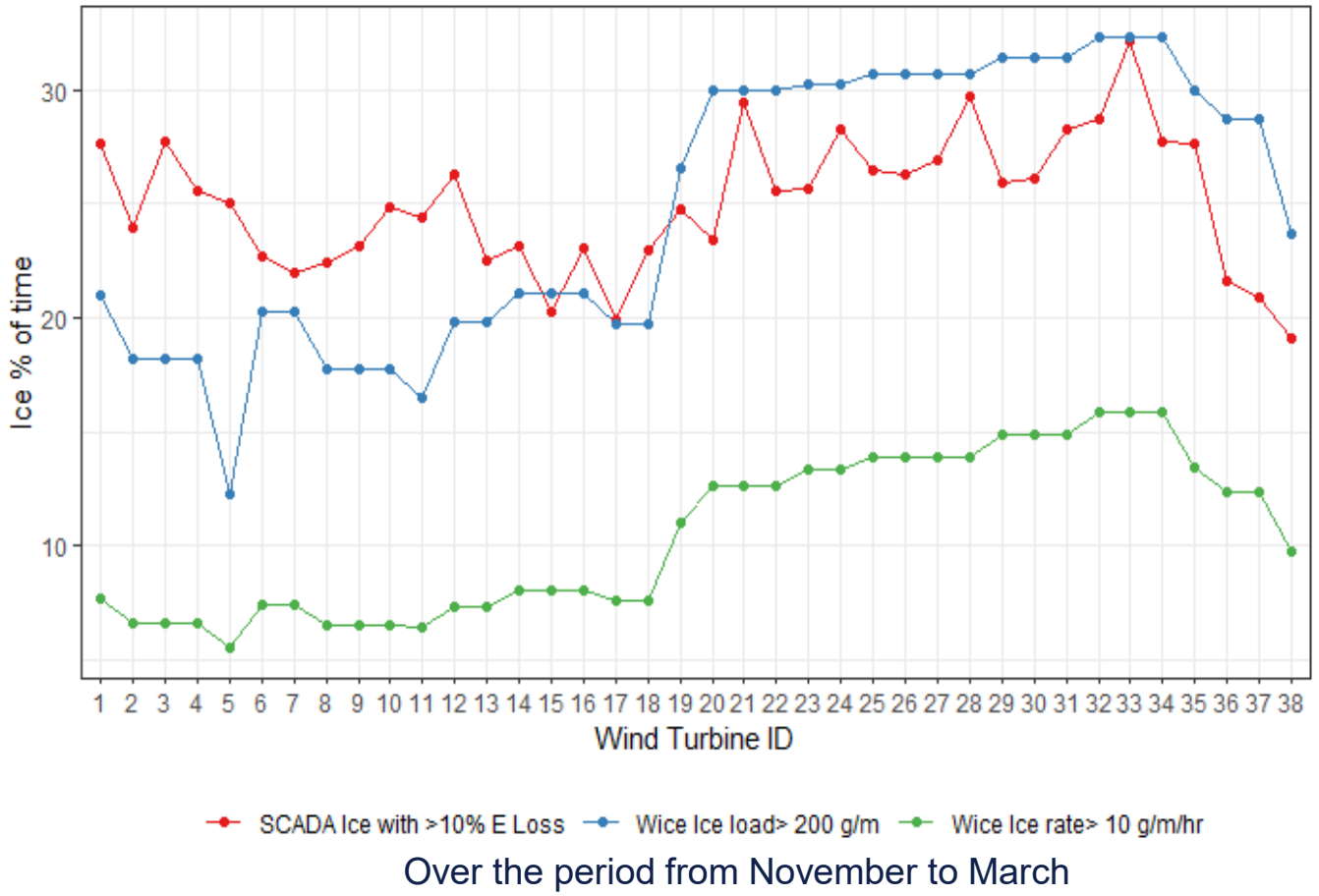
- Validation of modeled ice events against real data (SCADA and met mast)
- Existing wind farm in southern Europe (North of Spain), mountainous terrain ~1000–1200 m
- Older ~0.85 MW turbines, no built-in ice protection system
- Operating strategy: shut down turbines for safety at any sign of ice
- **Observed Reality**: SCADA shows **higher icing losses** (up to ~30%) because the site regularly shuts down in icing

Spain - Case Study – Key Findings

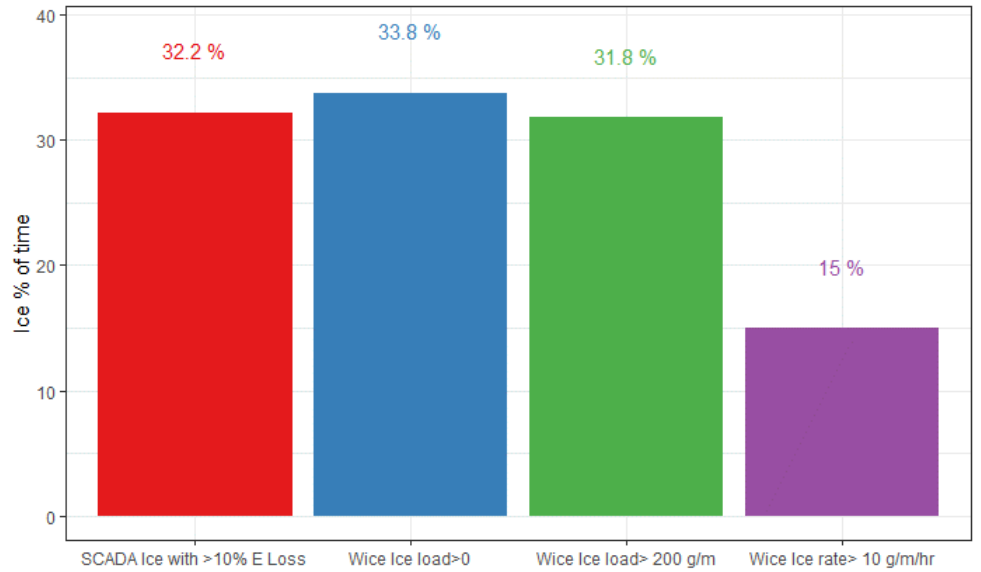
- WICE captures almost all events with significant ice energy loss

Spain - Case Study – Key Findings

- The WICE model can follow the icing shutdown operational strategy. It does this by using the modelled ice load, analyzed both per turbine and on a wind farm level.



Over the period from November to March



Spain – Key Findings

When assessing icing losses, it is essential to understand the wind farm turbine operation strategy

Almost all ice losses (from 70 to 95% depending on the wind turbine) correspond to wind turbine shutdown due to security reasons.

The WICE model was trained on turbines that remain operational under icing conditions -> icing losses due to degradation and not shutdown.

Model & real data do align on “when” icing occurs, but not how the site reacts

WICE Need explicit **shutdown rules** in the model for accurate results

Ice load can follow the trends for the icing shutdowns behaviors.

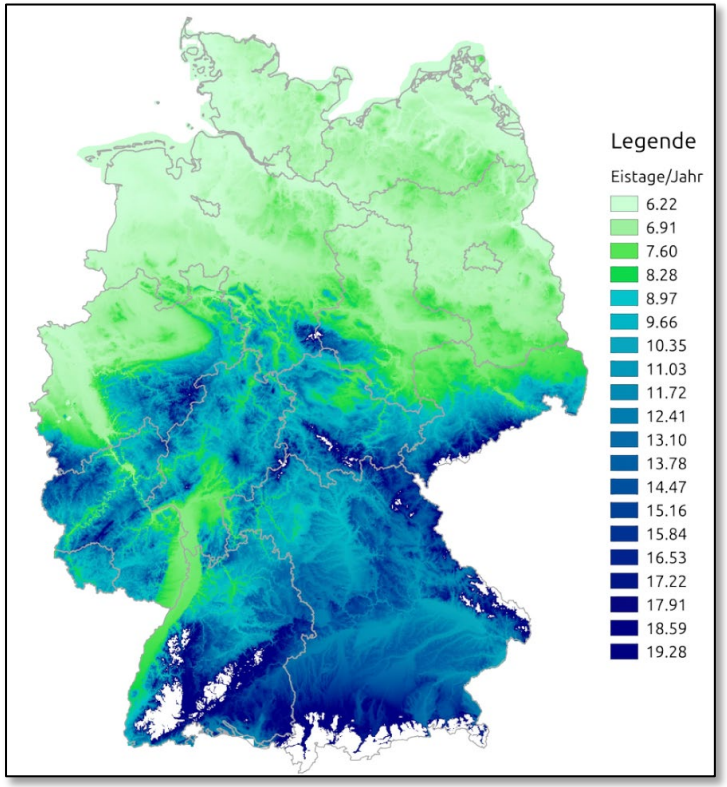
Possible Next Step: Include a shutdown limitation matrix (ice load vs ice rate) to better reflect real standstill decisions.

Case Studies Beyond the Roots: Germany

Germany – Current situation

The general approach is to use a representative value for the region based on site data or the FGW icing map as representative icing loss for the project lifetime (~20 years)

Icing days per year



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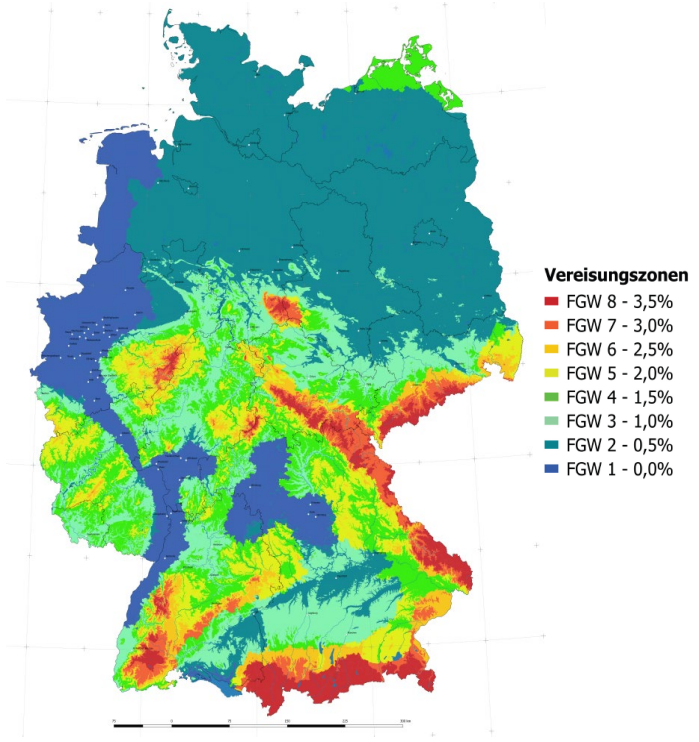
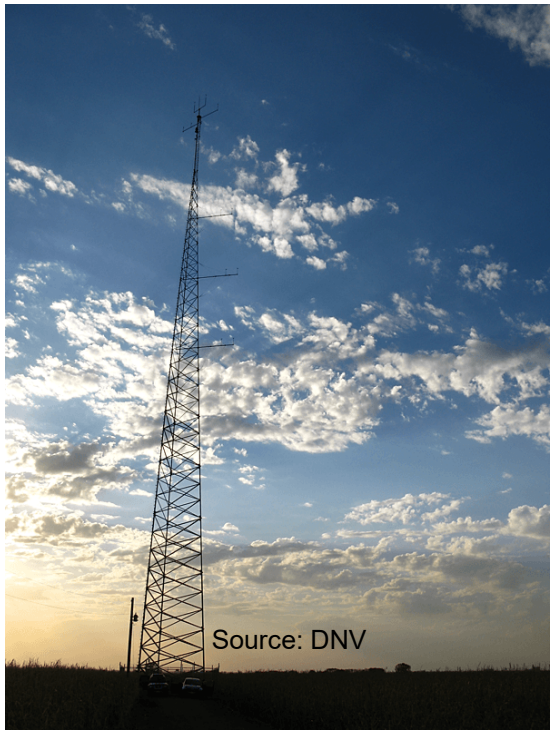
FGW Icing Map



Source: FGW, Icing Map TR6. based on the DIBt snow load zones

Measurement campaign or SCADA data



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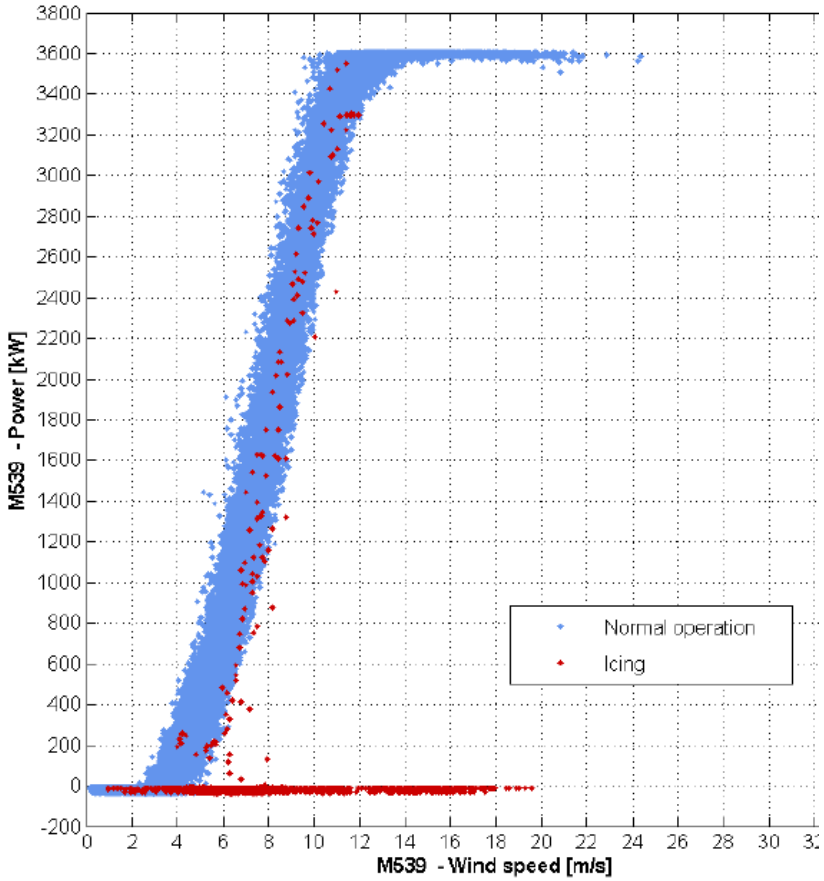


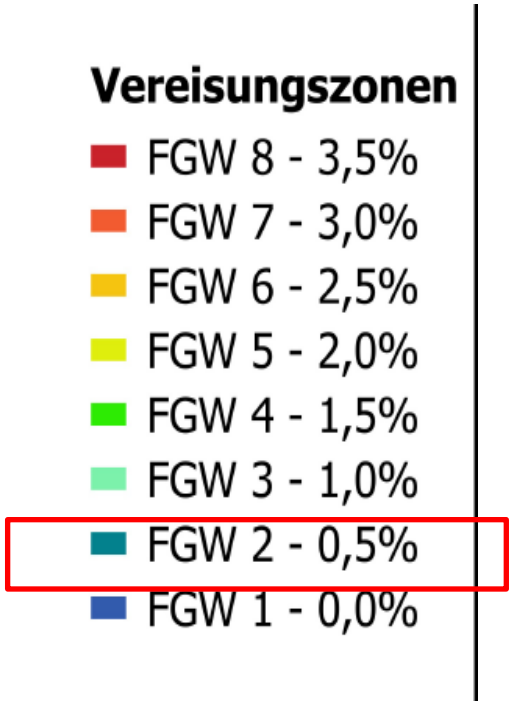
- Regarding icing, energy production is more affected by **icing shutdowns** than **underperformance.**
- **TR6** assumes a relation of 3/4 for icing shutdowns and 1/4 for blade degradation (**75 % vs 25 %)**

Source: DNV

Germany – Assumption vs Reality

- There is evidence that sites are prone to higher icing losses rather than the maximum value assumption of 3.5%
- For example:

  - Wind farm in commercial operation since 2020
  - Located in eastern Germany.
  - Located in a "Vereisungszone" **FGW 2**
  - Expected annual icing losses: **0.5 %**
  - No ice protection system was Installed



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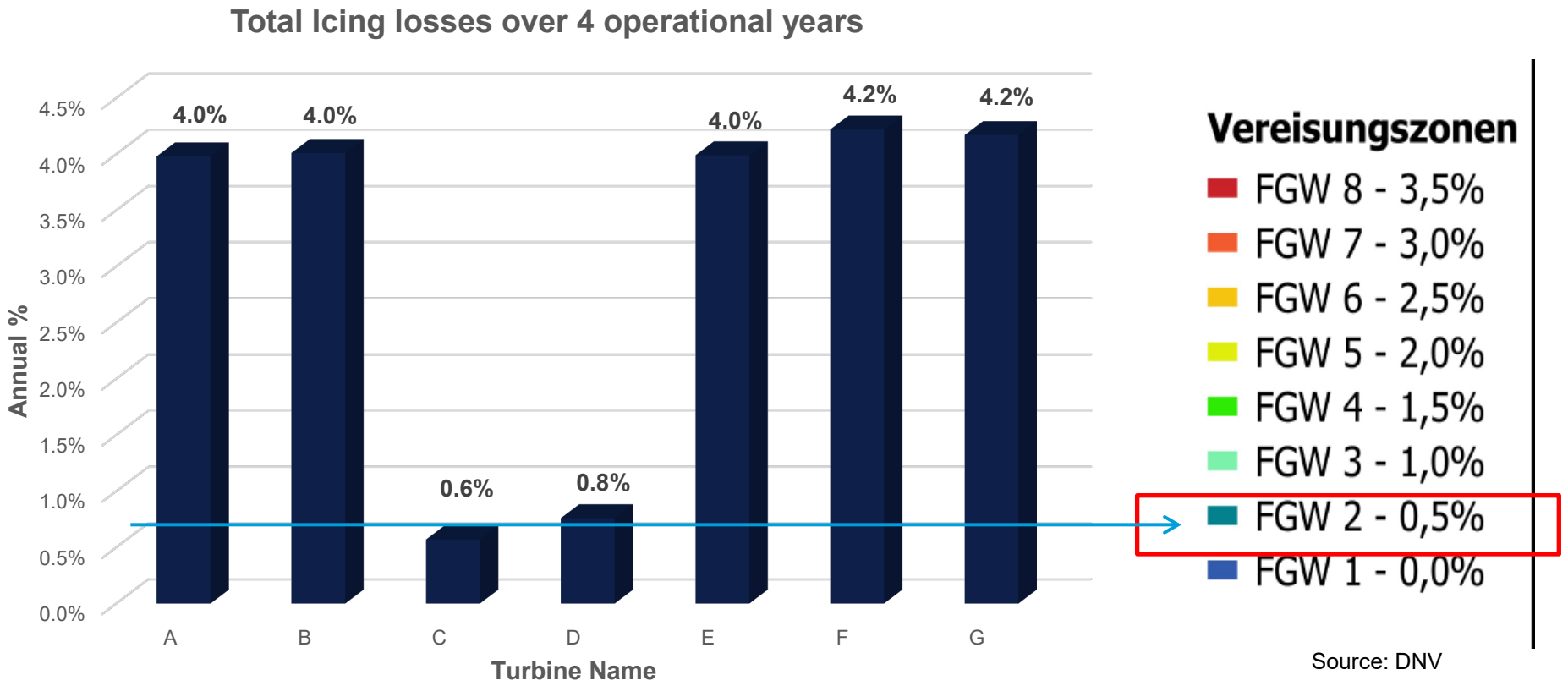

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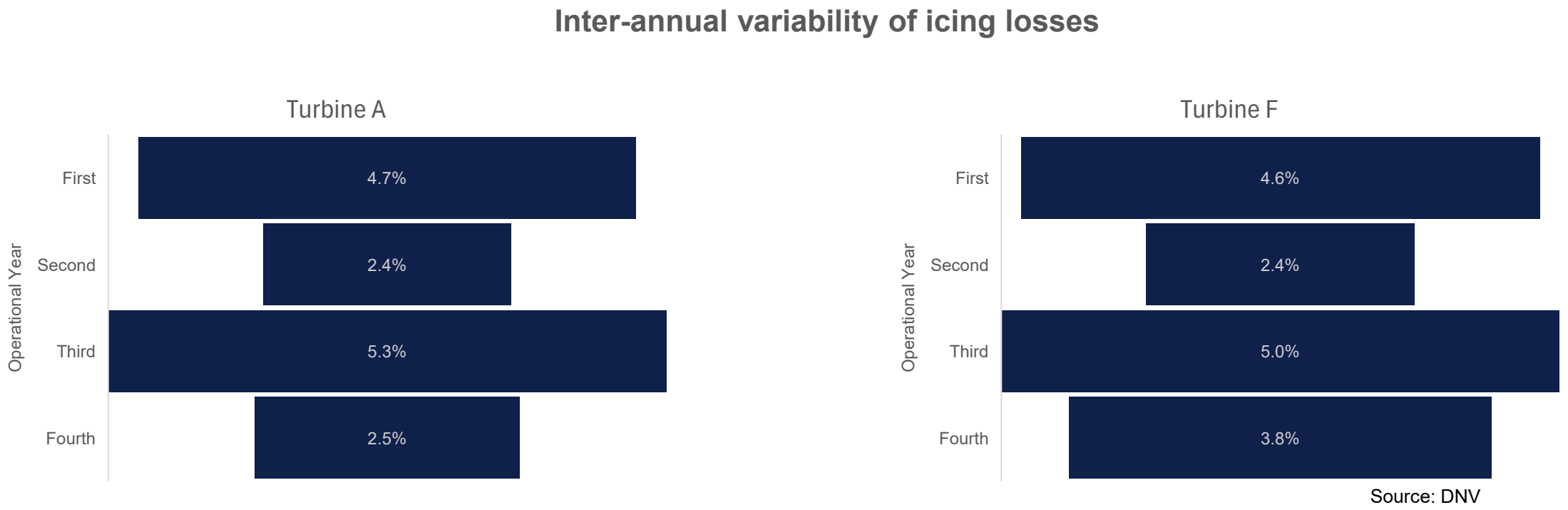

Source: DNV

Germany – Key Findings

Most of the icing losses experienced in Germany are due to control strategies that shut down the turbines as soon as an icing event is detected.

Strong regulations regarding ice throw or ice fall

It is possible that an onshore wind farm in Germany experiences icing losses higher that the maximum suggested FGW value of 3.5%.

It is recommended to contrast icing assumptions with measurements for sites prone to icing conditions.

WICE can be used to quantify icing shutdowns, but a test case is required to measure its performance in Germany

Next Steps

Future Plans – WICE 3.0

Expanded Training & Validation: A worldwide-adapted model with more robust trained datasets.

Improved Machine Learning: Validate several machine learning models for the icing loss prediction task to enhance prediction performance by selecting the best model or combining the top-performing models.

IPS Integration: Extend the current IPS modelling capabilities to cover the latest advancements and technical behaviours of the current IPS models available to better quantify benefits

Turbine technology: Investigate the ice sensitivity of various turbine models and explore methods for integrating this factor into the quantification of icing-related energy losses.

Conclusion

Closing Thoughts

Factors such **as terrain elevation** and **microclimatic conditions** influence variations in icing losses within a wind farm. Analyzing these losses at different spatial scales, whether at the **cluster level**, as demonstrated in the French site, or at the **individual turbine level**, as applied in the Canadian site, offers valuable insights into intra-wind farm icing dynamics.

Operational decisions play a critical role in icing-related losses, particularly when turbines are **shut down due to safety or regulatory constraints**. This effect is notably pronounced in the Spanish study case, and German markets, where shutdown-induced icing losses constitute a significant portion of the total icing-related losses. In the case of French site, the icing shutdowns are linked to risk regarding ice throw.

Icing loss quantification models need **to extend their validations and datasets** to better related the local climate conditions to the local operational behaviours.

Incorporating IPS benefits into icing loss assessments remains a key challenge – Limited SCADA data without IPS influence hinders model training – IPS performance is highly site-specific, requiring better data and collaboration

Future directions: – **Strengthen partnerships with operators and IPS manufacturers** to quantify benefits – Develop frameworks to compare IPS solutions and predict long-term impacts

Ensuring **robust training datasets and incorporating site-specific IPS data** will be pivotal for advancing WICE 3.0

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Luis Baquero M.Sc.
Senior Engineer | Project Development & Project Engineering,
DNV Energy Systems Germany GmbH

luis.baquero@dnv.com
WICE website

www.dnv.com