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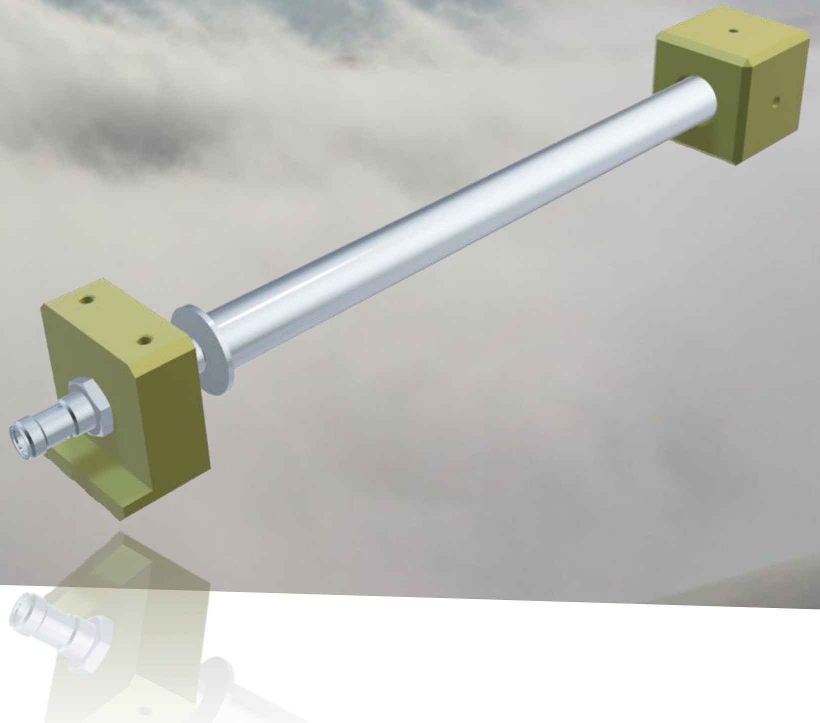
[Serbian+minister+ice+BBC]

Validation of cantilever sensors for ice detection on rotor blades”

Holger Fritsch, Michael Schulz and Thomas Iwert, Bachmann Monitoring GmbH



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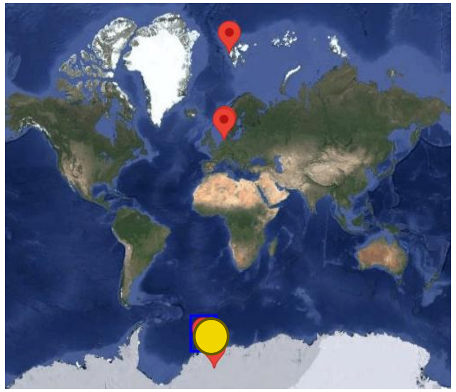
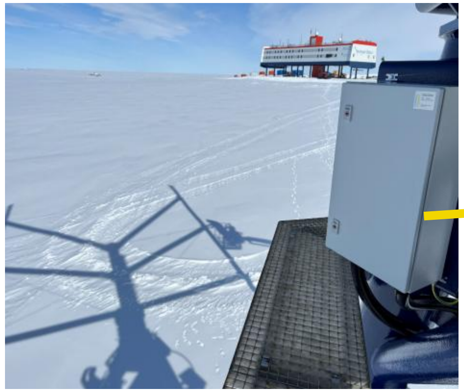
From Load Sensor to Advanced Ice Detection

Agenda

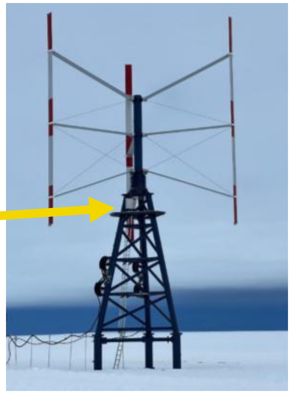
Introduction and Motivation	Bachmann Group in the wind business A big step: CLS from load measurement to ice detection.
Technology overview/measuring principle	Functionality of the CLS - Robustness and long-term stability
Validation	Examples of the use of the CLS from the Ore Mountains in the Czech Republic and Canada (Nergica)
Conclusion and Outlook	Beyond ice detection. What can the use of CLS mean in the wind industry?



Antarctica: Neumayer-Station III



Ekström Ice Shelf, Atka Bay, northeastern Weddell Sea



SHM-System

Bachmann hardware under the harsh conditions of Antarctica

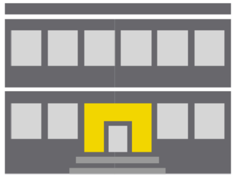
Bachmann Group: Facts & Figures

Bachmann Holding

Bachmann electronic

Bachmann Monitoring | Bachmann Visutec

Corporate structure



Bachmann electronic

547 Employees

102 Mn Euro Turnover

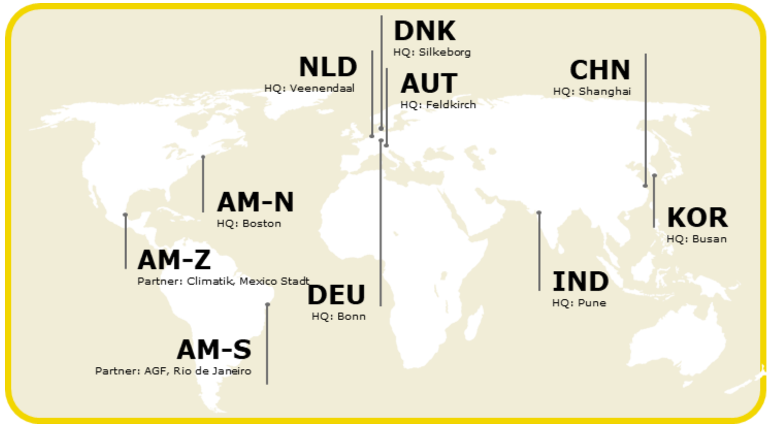
9,8 % Ø Growth p.a.

25 Locations

4 Competence Areas

4 Industries

b.control b.grid b.operate b.guard



Bachmann Monitoring GmbH

63 Employees

11,0 Mn Euro Turnover

12,0 % Ø Growth p.a.

4 Locations

b.guard

CMS-Portfolio

- Hardware
- Sensoren
- Software
- Monitoring
- Services
- Consulting
- Training

Bachmann has automated more than 140,000 WTG worldwide.

Modular control system

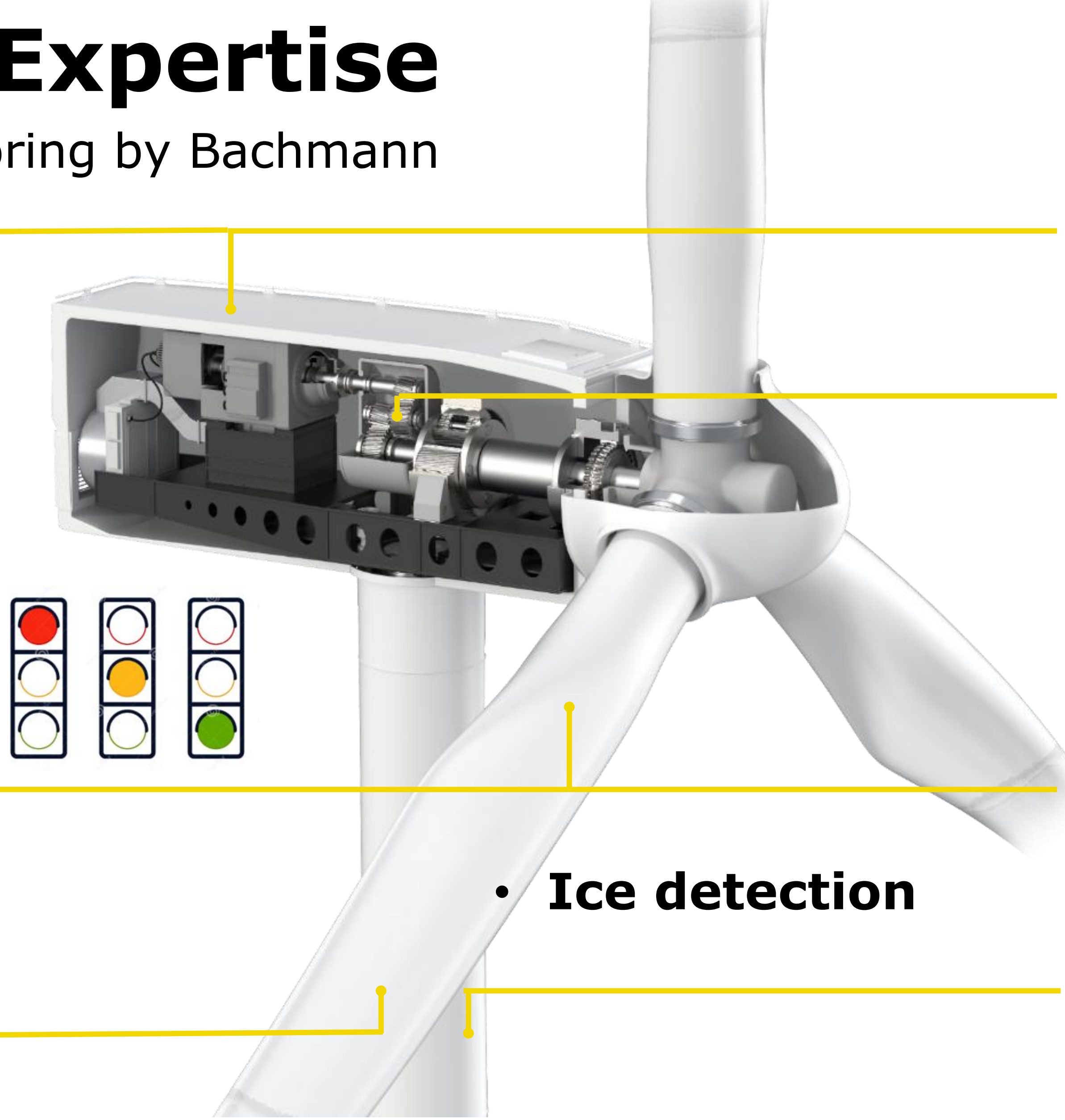
Holistic Expertise

Condition Monitoring by Bachmann


Nacelle monitoring


Blade structural monitoring


Ice detection



Turbine Health Monitoring
- Unbalance detection and monitoring
- SCADA data integration and visualization
- ***Nacelle monitoring***

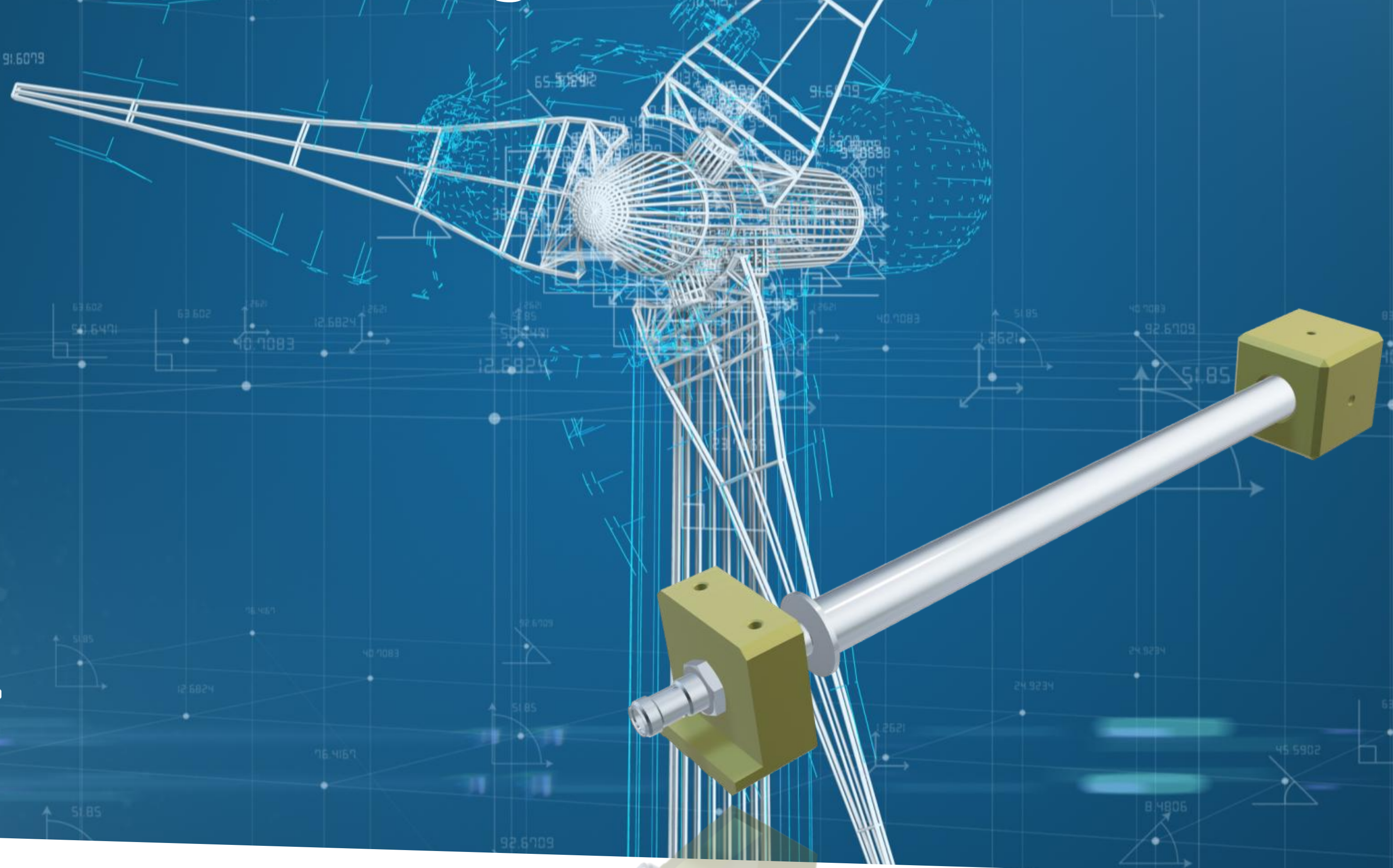
Drivetrain Health Monitoring
- ***Condition Monitoring for replacement and retrofitting***
- Installation und remote monitoring service
- Condition Monitoring with 3rd-party CMS

Rotor Blade Health Monitoring
- Blade load measurement
- ***Blade structural monitoring***
- **Ice detection**

Tower Health Monitoring
- SHM (Structural Health Monitoring)
- LTE (Life-Time-Extension)

Cantilever-Sensor (CLS)

Blade Load Monitoring



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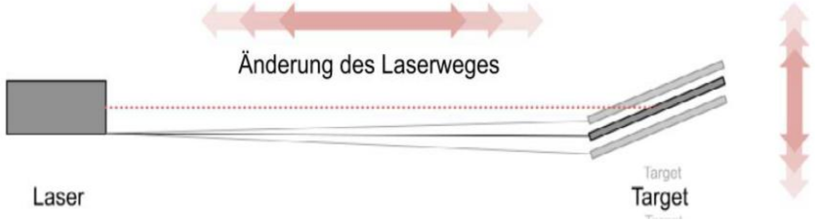
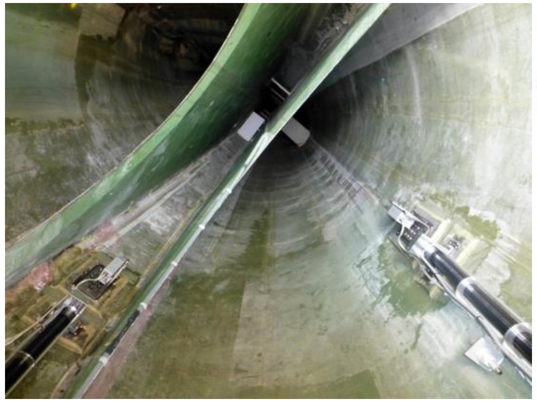
The History of the Cantilever Sensor CLS

Sensor for Load Measurements

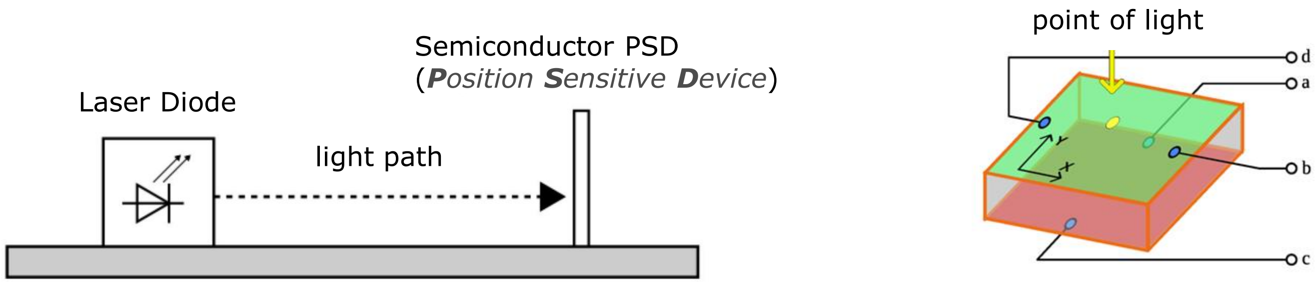
The Goals

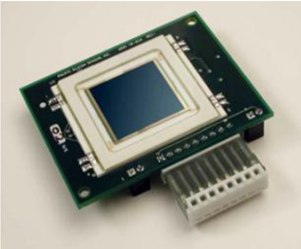
- ✓ **Simple:**
  Industry-proven, easy to install no complicated optical to electrical signal transformation
- ✓ **Robust:**
  Long service and operational life with little maintenance necessary
- ✓ **Reliable:**
  Extremely accurate and reliable data





First generation (2010-2014): Open system using a distance laser and target installed deep inside the rotor blade."

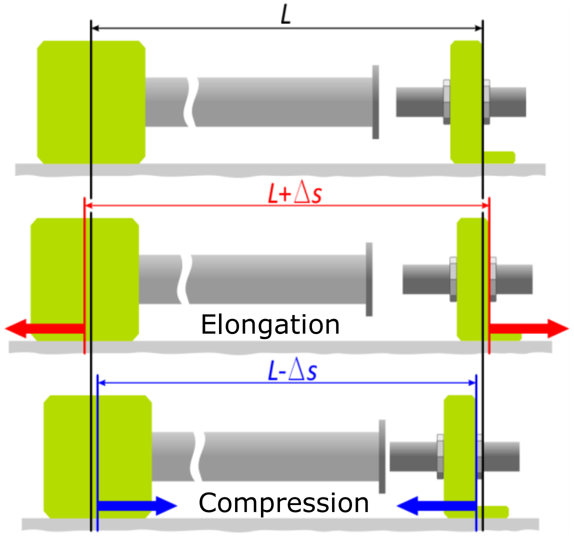


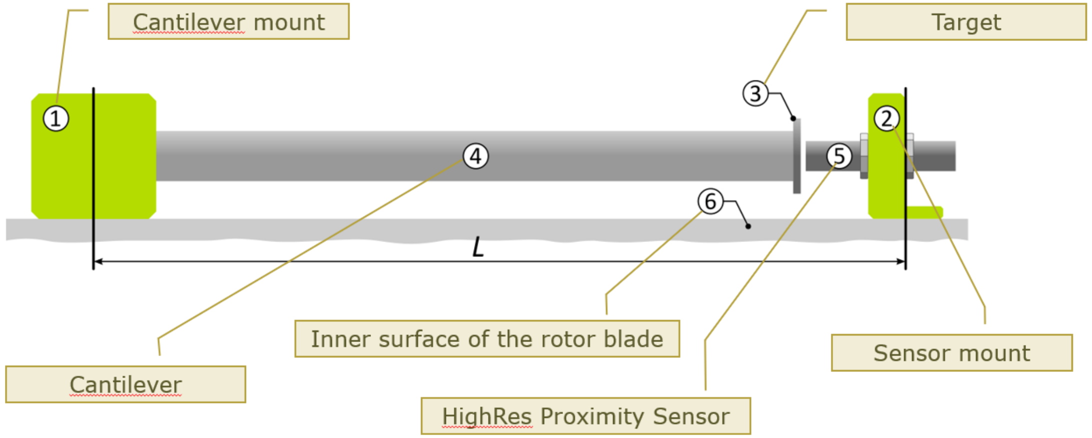


Second Generation (2015-2018): *Integrated system with improved sensor placement for more precise measurements and enhanced durability.*

The History of the CLS

The third generation (2019-present): For Load Measurements





$$\varepsilon = \frac{\Delta s}{L} \quad \Delta\varepsilon_{Res} = \frac{\Delta s_{Res}}{L}$$

$$\varepsilon_{min/max} = \pm\frac{1}{2}\frac{s_{max}}{L}$$

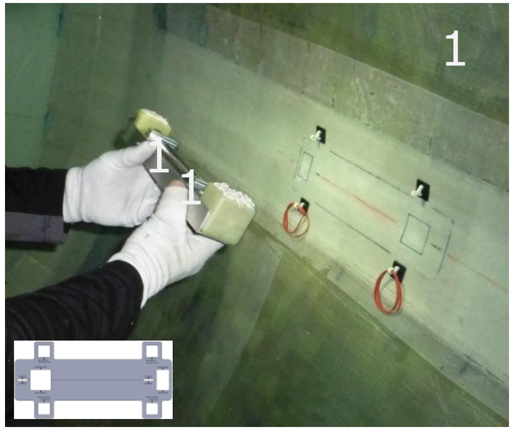
> Third generation (2019-present): Fully embedded system with direct measurement capabilities, optimized for ice detection and structure monitoring.

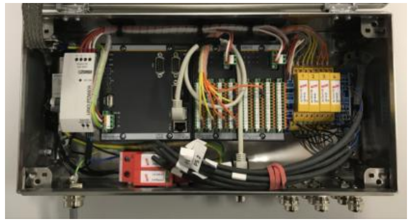
Advantages

- output signal comparable with an electric strain gauge or fiber-optic strain sensor
- Not subject to any mechanical and chemical aging
- guarantees long-term measurement stability
- minimizes influence of local inconsistencies

CLS in the Rotor Blade

Since 2017, various prototype installations in the field





1. The contours of the CLS template are marked on the installation area on the inside of the rotor blade.

2. Alignment of the CL sensor using the CLS template

3. DAQ with lightning protection

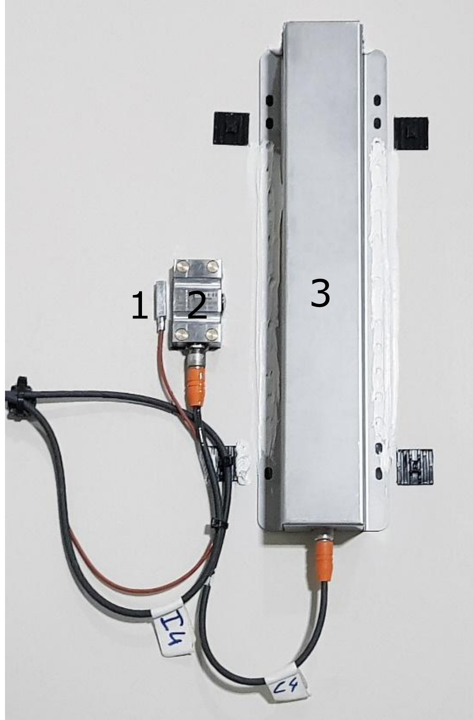
4. The short animation shows an example of an installation for the series equipment. Of course, a retrofit is also possible.

5. cable routing through the blade bulkhead,

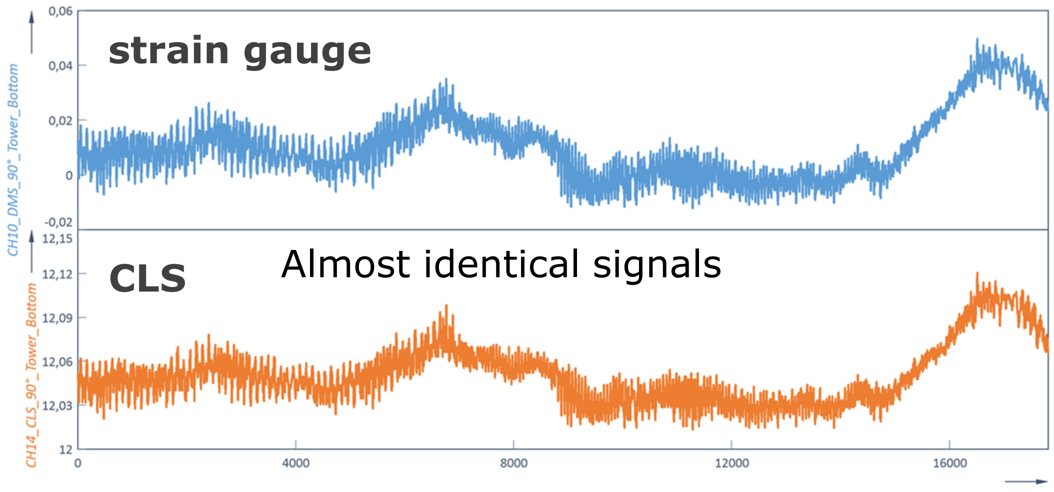
6. The compact DAQ inside the hub

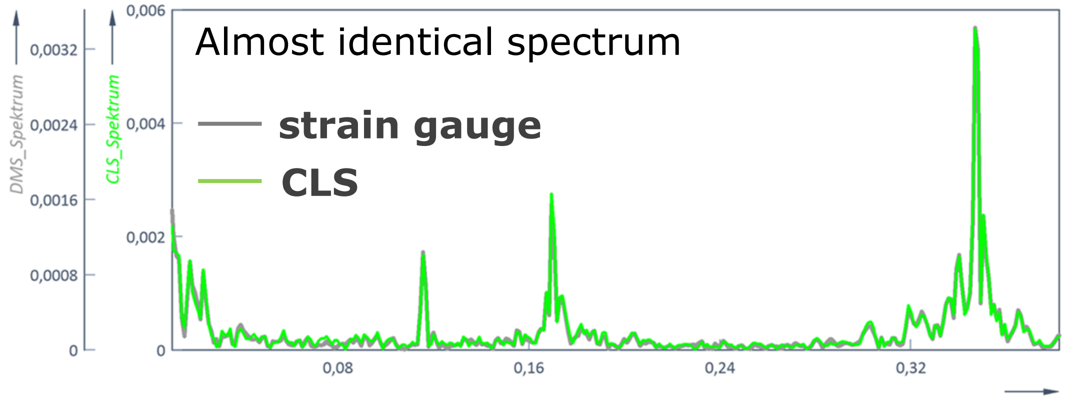
Another use case for the CLS

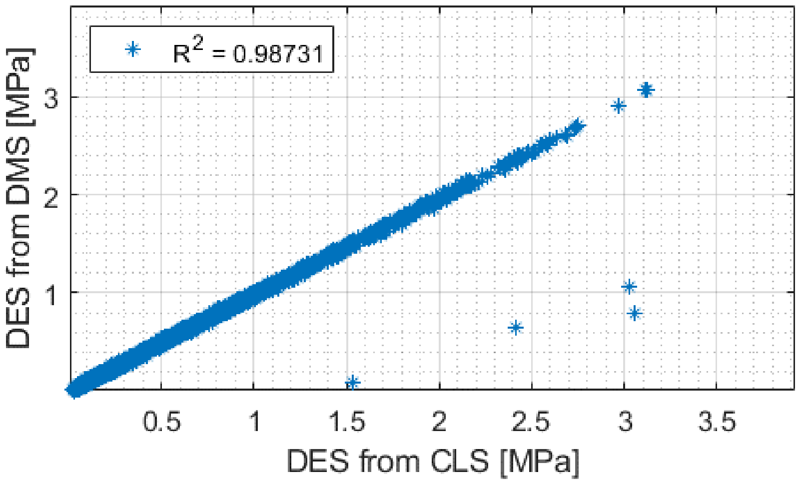
Structural monitoring of steel towers



Installation on the inner surface of a steel tower:
1. temperature sensor,
2. strain gauge, 3. CLS







*DES = Damage Equivalent Stress (Fatigue Load)

There is an excellent correlation between the measured values.

CLS: The comparison with strain gages showed a very good match between the sensor signals.

CLS – Advanced Monitoring for WTG’s

From Load Monitoring to Structural Health – The Versatility of CL Sensors

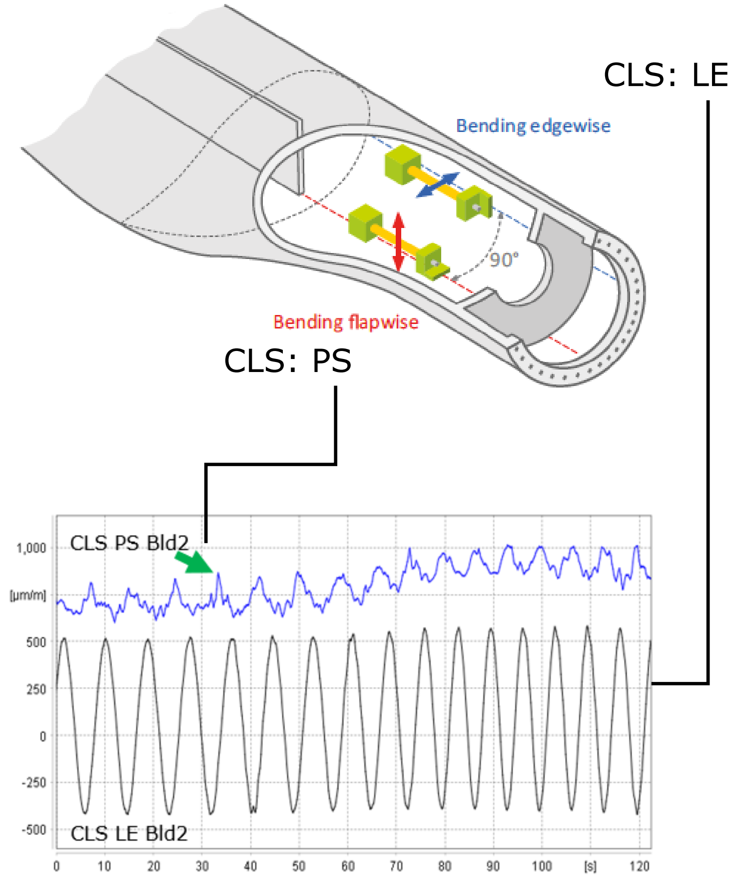
CL-Sensors are designed for applications in rotor blades of WTG’s:

Initial Applications:

- ✓ **Detection of critical operating conditions** through real-time load measurements
- ✓ **Recording of load history** (e.g., via "Rainflow Counting")

Current Applications:

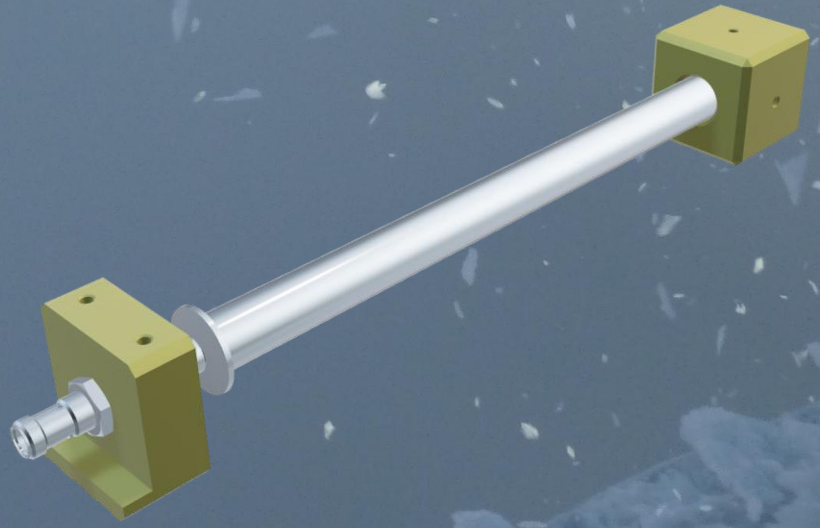
- ✓ **Use as a control input**, e.g., for individual pitch control (IPC)
- ✓ **Deviation analysis between blades** to identify faults or malfunctions
- ✓ **Structural monitoring** of steel and hybrid towers (latest applications)



Additional approach:

“Can CLS also be used for ice detection on rotor blades?”

Can CLS also be used for ice detection on rotor blades?



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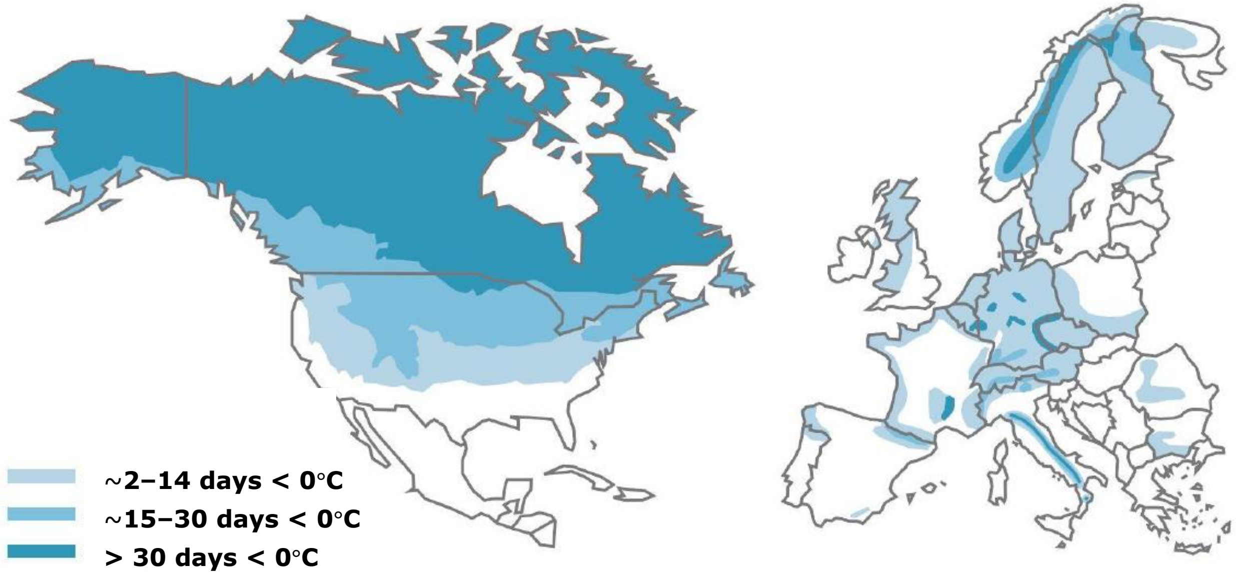
Two examples of financial losses caused by icing of rotor blades

Energiewerkstatt (V90 and V112 WF Sternwald, Austria):
Without blade heating (V90): 908 icing hours/year, 526 MWh loss (**€26,300/MW/winter**).
With blade heating (V112): 387 icing hours/year (-57%), 427 MWh loss (**€21,350/MW/winter**).
Source: A. Stökl and A. Krenn, *Evaluation of the Vestas Rotor Blade Heating System,* Energiewerkstatt, 2019. [Online]. Available: https://www.energiewerkstatt.org

Technikakademie Weilburg:
Over 4 winters, six 3 MW turbines recorded **5,773 hours of downtime**, 56% due to missing automatic restart functions.
Source: Technikakademie Weilburg, *Study on the operation of ice detection systems on 3-MW-class wind turbines,* [Online]. Available: https://archiv.windenergietage.de/

Ice-prone regions in Europe and North America



B. Wölfel and C. Ebert, "Ice Detection on Rotor Blades: Automatic Restart Function," Wind Energy Days, Nov. 11, 2015. [Online]. Available: https://www.woelfel.de

Validation of CL sensors for ice detection

Project Description: Validation of an Ice Detection Algorithm based on CLS

Joint ice detection project on rotor blades with Nergica

April 2021: Installation of cantilever sensors (CLS) in a Senvion MM92 (2.1 MW) by Nergica experts, with remote support from Bachmann.

Measurement campaign: 3 months (winter 2021-2022), recording of sensor data & SCADA data.

Reference systems: Comparison with detection results from six other ice detection systems (anonymized) that were already installed on the same turbine during the study period.

Results: Validation & further development of Bachmann's **I**ce **D**etection **A**lgorithm ***(IDA)*** based on camera recordings & various icing events.

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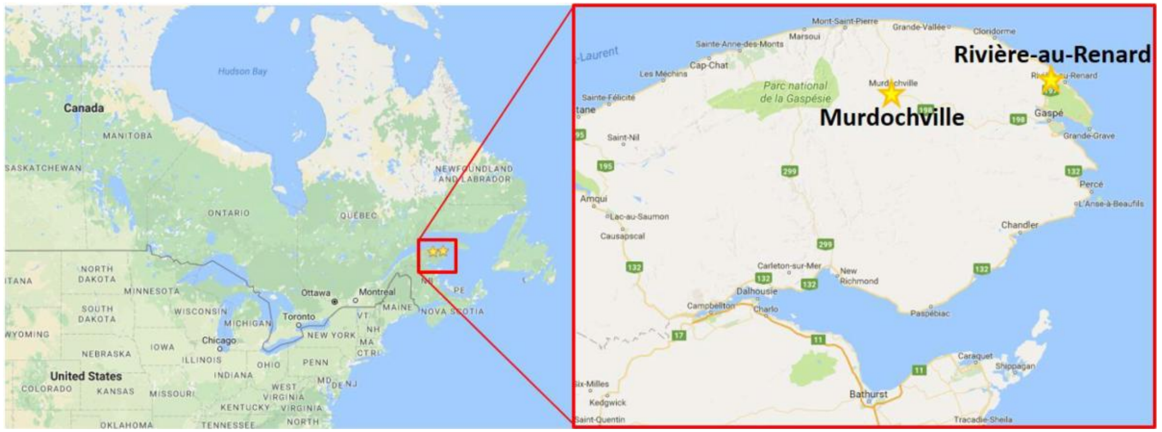
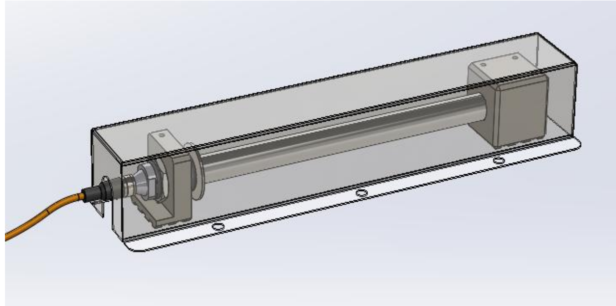
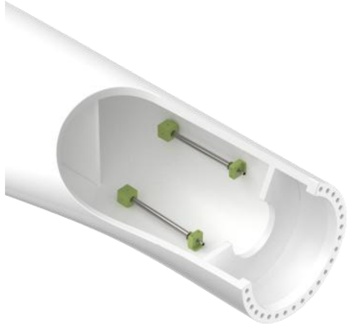


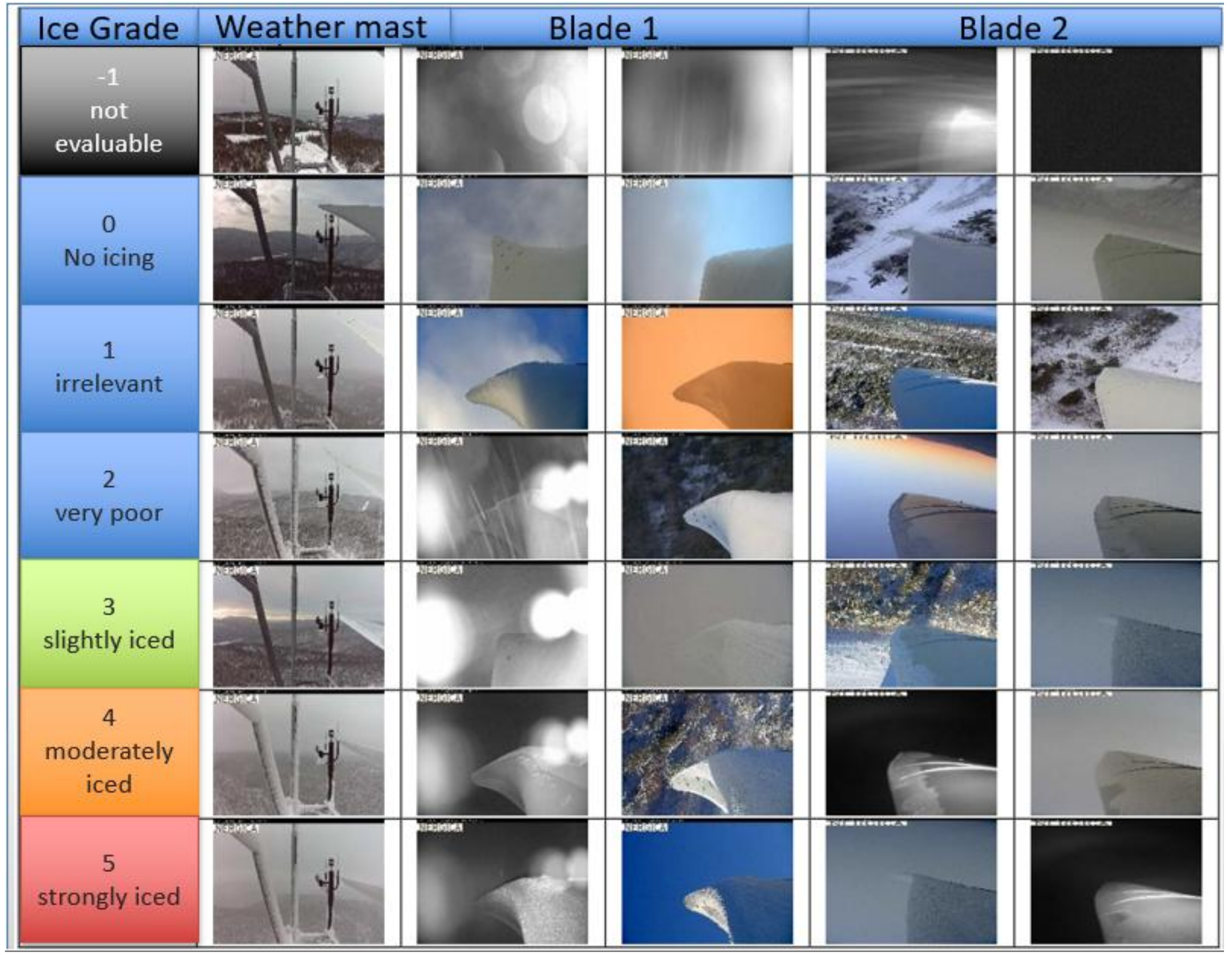
WF: Gaspé peninsula, Québec, Canada Site nordique experimental en éolien CORUS (SNEEC)





Challenges in Optical Icing Evaluation

Error Sources and Limitations of Camera-Based Assessment"



The icing levels (0 to 5) were determined through a weighted evaluation of image sources.

Potential Error Sources:
Objective:

- Partially obscured blade surface
- Camera angle causes optical distortions (ice growth and melting not always visible)

Subjective:

- Varying light conditions (day, night, weather)
- Differences in ice roughness and reflectivity
- Different icing geometries (visible break-off edges vs. a closed ice layer, where thickness changes are hard to detect)

Selecting the Best Reference

How Camera-Based Evaluation Enables Reliable Benchmarking

Premise:
No Perfect Ice Benchmark Exists:

- A flawless ice benchmark does not exist.
- All empirical references, including the camera rating, are subject to errors.
- Therefore, no reference is preferred a priori; all are considered equal.

First Step

How to determine the most reliable reference from the existing ones

"Pairwise testing of reference relationships using association metrics (e.g., Yule's Q after G. U. Yule) enables ranking by confidence or quality."

The camera rating is the best available reference for ice detection.

Second step

Evaluation of our own algorithm (IDA)
- position in the ranking -

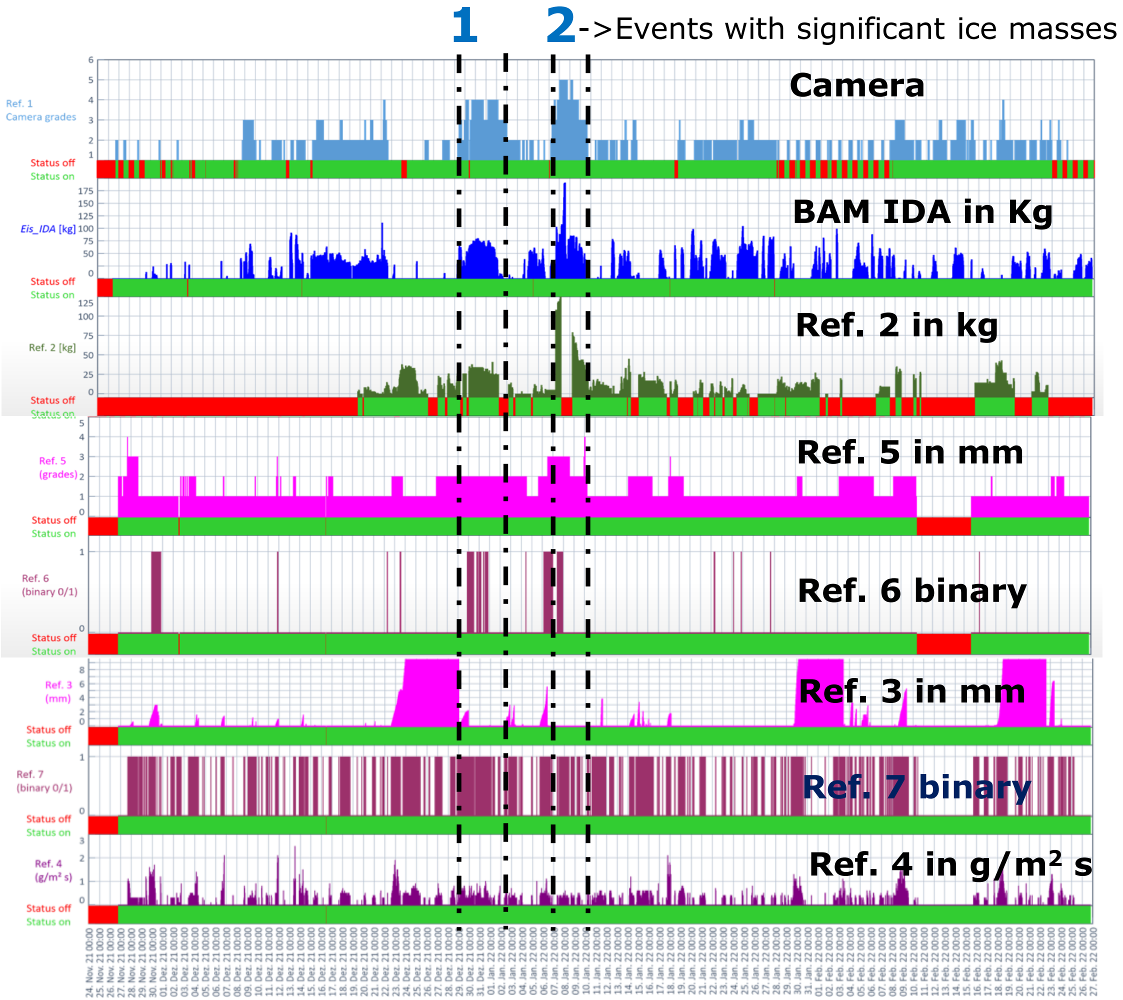
"All against IDA": Comparing IDA with all references, including the camera rating.

"All against camera": Comparison of all references + IDA with the most trustworthy reference (the camera rating)

IDA achieved the best results in qualitative and quantitative test categories.

Time series comparisons

The comparisons are based on the time series of all references,

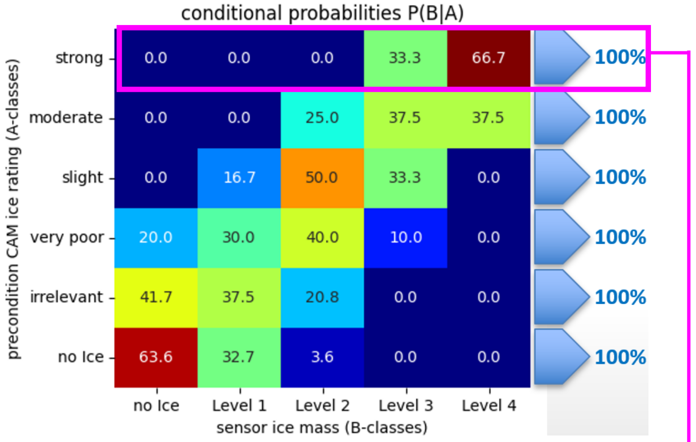


The comparisons are based on the time series of all references

CAM (A)	Sensor Level (B)					Row sum
	no Ice	1	2	3	4	
strong	0.0	0.0	0.0	0.8	1.6	2,4
moderate	0.0	0.0	1.6	2.5	2.5	6,6
slight	0.0	1.6	4.9	3.3	0.0	9,8
very poor	3.3	4.9	6.6	1.6	0.0	16,4
irrelevant	8.2	7.4	4.1	0.0	0.0	19,7
no Ice	28.7	14.8	1.6	0.0	0.0	45,1
Column sum	40,2	28,7	18,8	8,2	4,1	=100%

*The **joint probability P(A∩B)** describes the probability that 2 events (of A and B) occur simultaneously*

When using **joint probabilities**, interesting subsets with a small number of events (e.g., heavy ice events) can easily be overlooked.



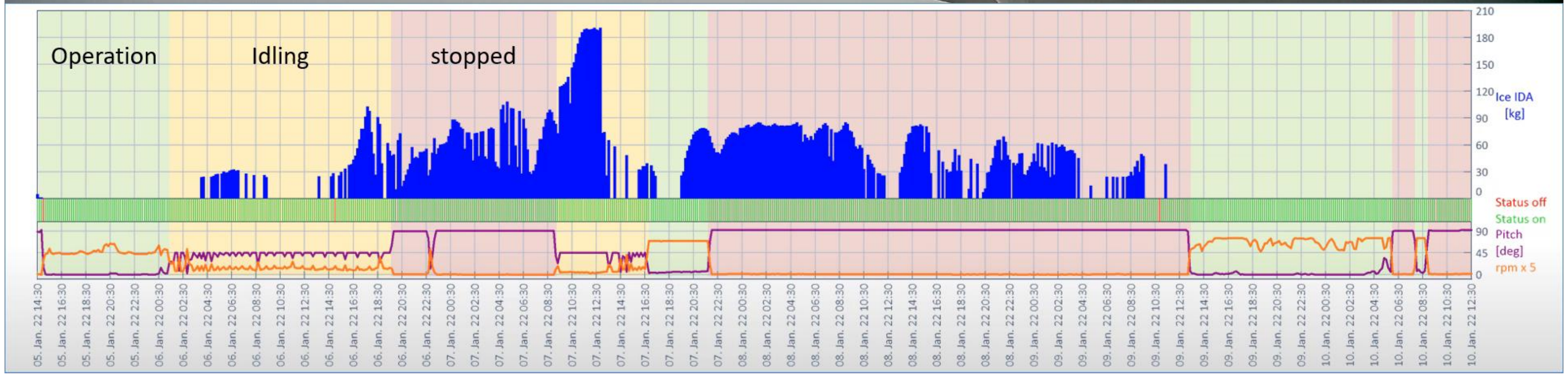
→Distribution of the subset of B
→Row normalization
→CAM rating is given

e.g.: How is the IDA rating distributed if the camera level "strong" is considered given?

With **conditional probabilities**, correlative dependencies of small subsets can be better identified and illustrated.

Plausibility check of an icing event

Validation of ice detection with Bachmann’s IDA (**I**ce **D**etection **A**lgorithm)



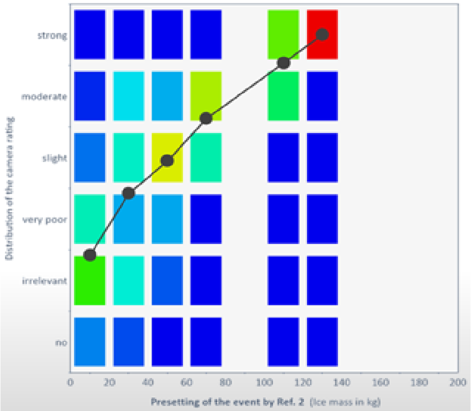
Plausibility check of an icing event by comparing the ice indicator with camera images:

- The images from the different cameras were converted into videos.
- The progress of the ice indicator was synchronized with the video streams.

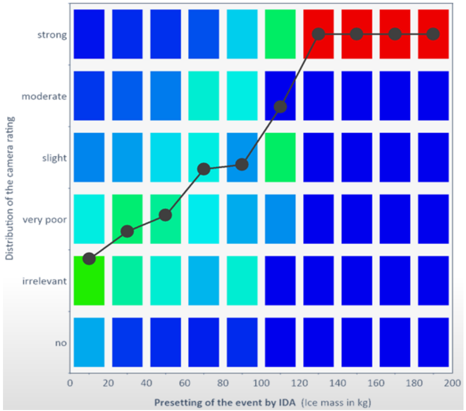
Result: One can see a plausible correspondence between ice events and the camera images, the IDA algorithm from Bachmann, and the process variables of the plant.

Validation of CL sensors for ice detection

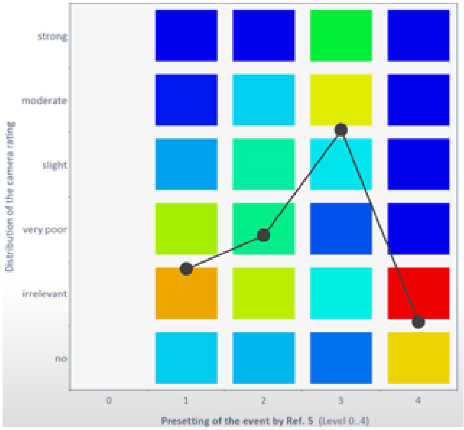
Qualitative correlation analysis, references vs. Camera



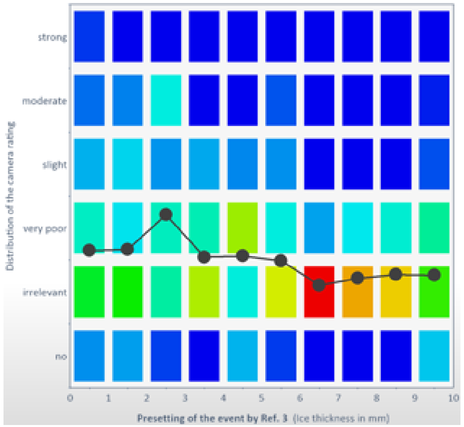
Reference-System 2



CLS and IDA



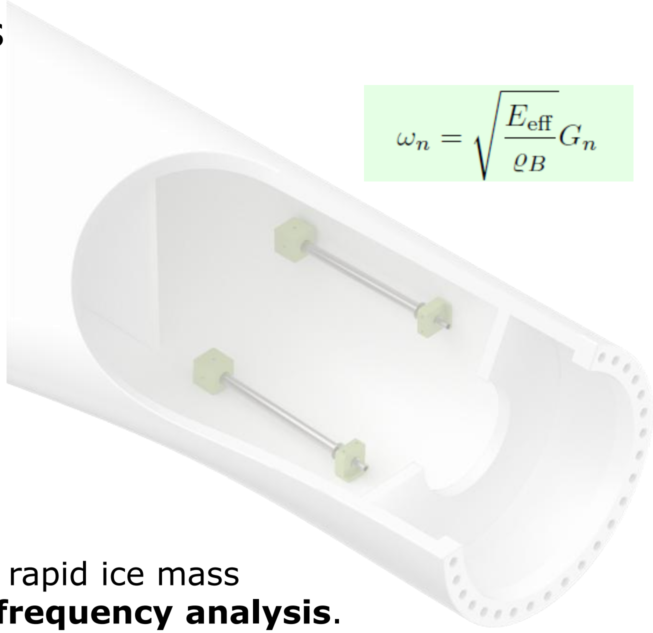
Reference-System 5



Reference-System 3

Results: The "Reference-System 2" and the CLS combined with IDA demonstrated the highest correlation with camera images.

Note: A diagonal distribution center line indicates a strong correlation with camera images



$$\omega_n = \sqrt{\frac{E_{\text{eff}}}{\varrho_B} G_n}$$

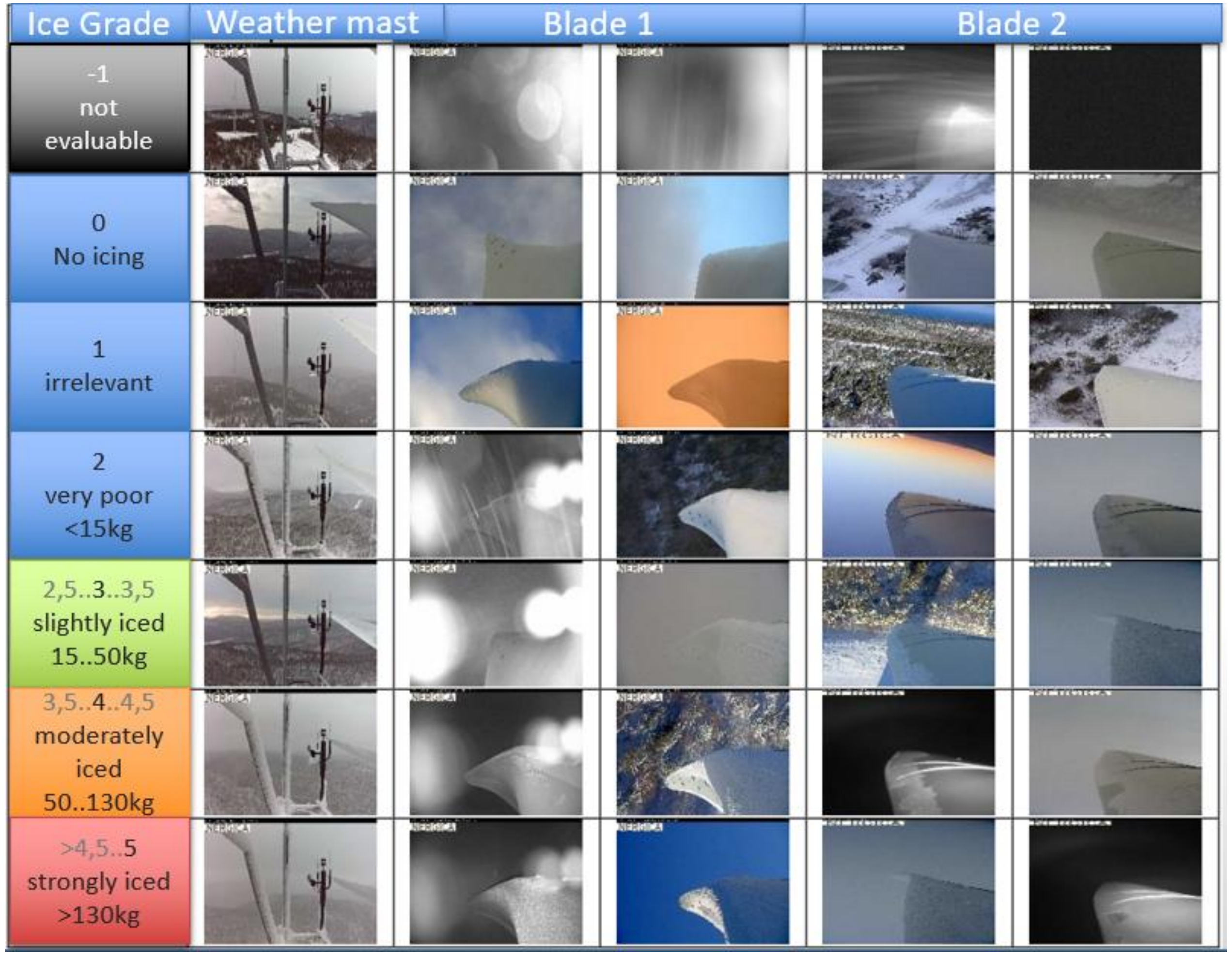
$$\Omega_n = \frac{\omega_n(P') - \omega_n(P)}{\omega_n(P)} = \frac{\Delta\omega_n(P)}{\omega_n(P)} = \frac{1}{\omega_n(P)} \sum_{k=1}^{r} \frac{\partial \omega_n(P)}{\partial P_k} \Delta P_k$$

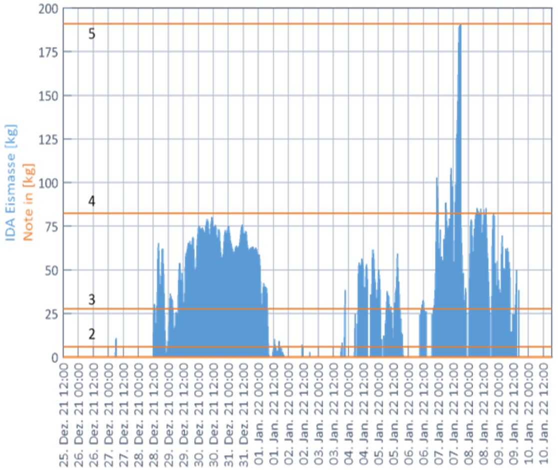
$$\Omega_n = \sum_{k=1}^{r} \left[\frac{1}{2E_{\text{eff}}} \frac{\partial E_{\text{eff}}}{\partial P_k} - \frac{1}{2\varrho_B} \frac{\partial \varrho_B}{\partial P_k} + \frac{1}{G_0} \frac{\partial G_0}{\partial P_k} \right] \Delta P_k$$

Slow structural changes (e.g., aging, erosion) and rapid ice mass accumulation can be differentiated through **eigenfrequency analysis**.
Source: M. Schulz: *Rotordynamik.pdf*, S. 50–54, Bachmann Monitoring 2024.

Validation of CL sensors for ice detection

Quantitative correlation analysis, references vs. Camera

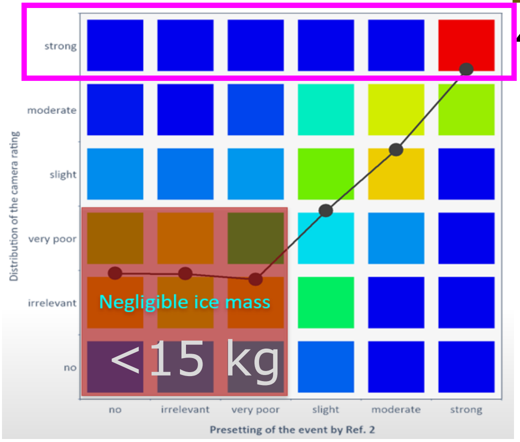




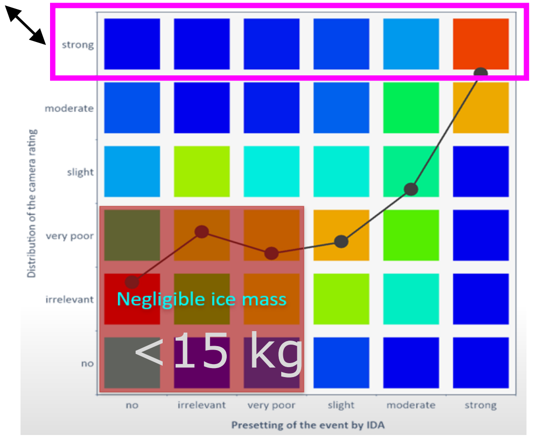
Approach: Best fit with a power function

$$\frac{m_{Eis}}{m_{Eis,Max}} = \left(\frac{Note_{ordinal}}{Note_{ordinal,Max}}\right)^{\gamma}$$

>130kg



Reference-System 2



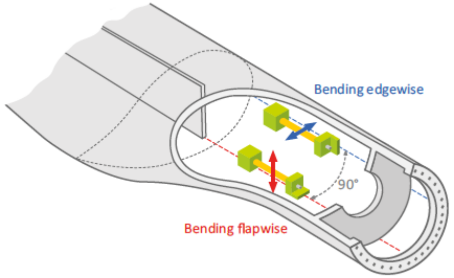
CLS and IDA

Conclusion & Outlook

Advantages of CLS over FBG & Acceleration-Based Blade Monitoring

📌 Successful Pilot Installation & Validation:

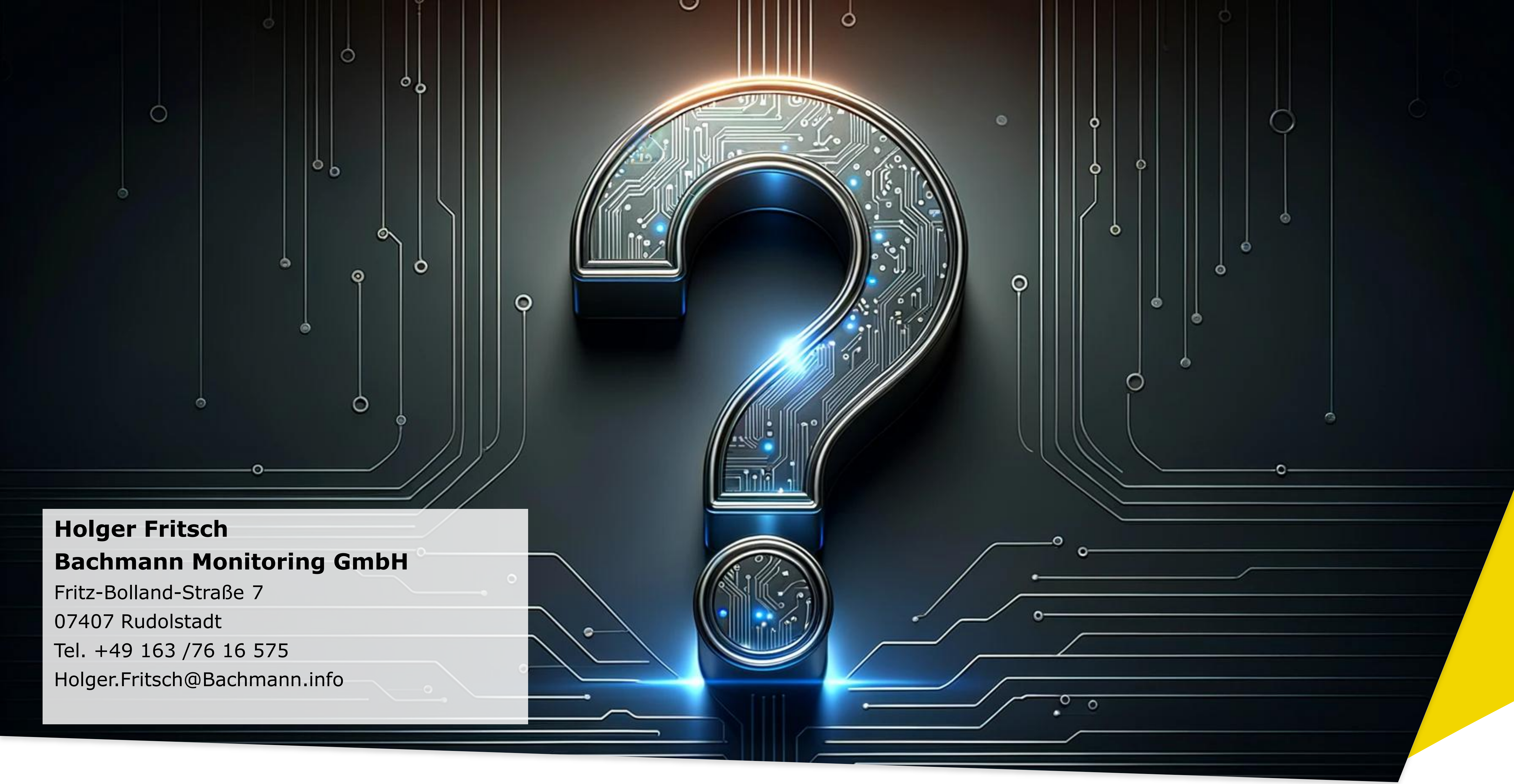
- Collaboration with **Nergica** for the pilot installation
- Bachmann system validated against six reference systems & camera images.
- **Best results**: Reference System 2 + CLS with ice detection algorithm (**IDA**).



CLS sensor placement inside the blade – enabling precise ice detection & structural monitoring.

Advantages of CLS:	Expandable Functions	Economic Benefits:
✓ **Reliable data** – No mounting impact ✓ **Longer lifespan** – No mechanical wear ✓ **Direct signal** – No converter needed ✓ **Plug & Play** – No special tools ✓ **Easy training** – Step-by-step guide	**Individual Pitch Control** (IPC) **Early anomaly detection & real-time load measurements** **Long-term load monitoring (e.g., via "Rainflow Counting")**	**CLS as an all-in-one solution** **Cost savings by reducing sensor complexity & logistics** **Contributing to a significant reduction in Levelized Cost of Energy**

CLS enables cost-effective ice detection, ensuring safe wind turbine operation in cold climates.



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