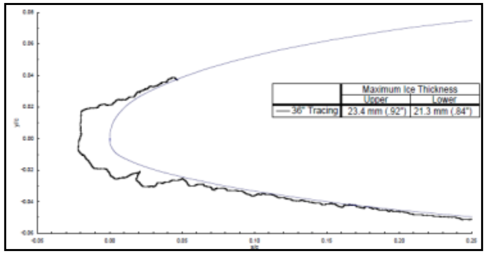
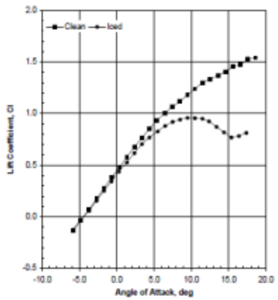
Business from technology





Simple methodology to map and forecast icing for wind power

Winterwind 2014

Sundsvall 11-12.2.2014

Ville Lehtomäki, Simo Rissanen
VTT Technical Research Centre of Finland

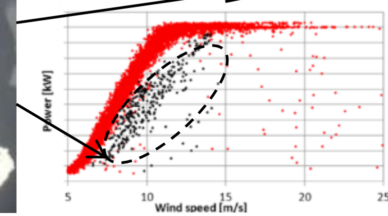
Outline

- Motivation, market potential & customer interviews
- Approach of State-of-the-Art (SotA) study
  - Summary of 1960-2005 icing measurements "in nature"
  - Summary of 2000-2010 icing wind tunnel measurements
  - Icing sensitivity analyses: what is important for wind energy?
- WIceAtlas – robust mapping of icing
- Conclusions

Motivation for work

The Challenge of ice assessment

What is the connection???



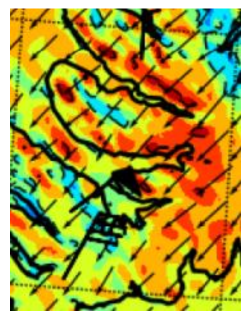
OR

1. AEP losses from icing are often very difficult to estimate before turbine installation

Table. Measurements from met mast and turbine AEP losses [10]

Site	Winter	Met Ice	P-loss	IEA class
	2010	3.1%	**2.5%**	3
	2011	1.8%	**0.5%**	2
	2012	3.0%	**2.1%**	3
	2013->		**???**	
	11-12	2.2%	**1.5%**	2
	12-13	4.7%	**5.0%**	3
	2013->		**???**	

2. Typical shortcomings of on-site measurements (1yr is too short) and mesoscale weather models
   - ➢Both demanding & expensive



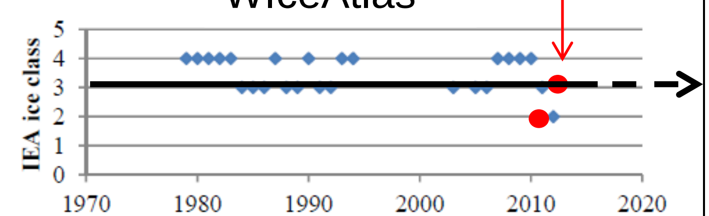
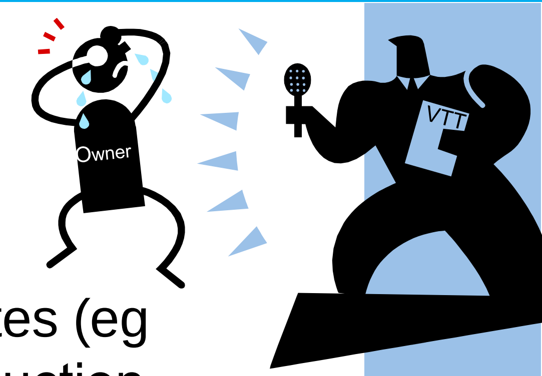


Figure 6: IEA ice class per year for RaR based on local airport cloud base height and temperature. [2]

➢**Need: assess future iced AEP losses from long-term historical data <u>simply</u> yet <u>robustly</u>**

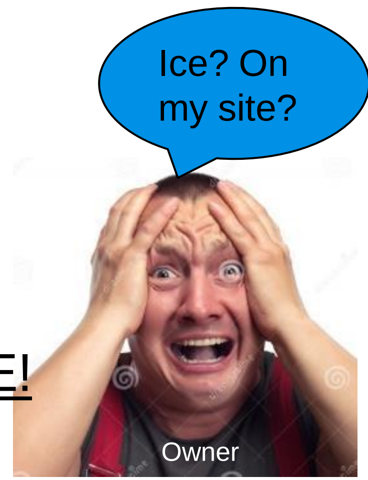
[10]: Recommended Practices for Wind Energy in Cold Climates, IWAIS 2013



CC Market Observations

- We have interviewed many wind farm owners in icing climates (eg Canada, Sweden, Czech…) suffering from ice induced production losses -> financial consequences

- Root cause:
  - insufficent ice assessment (wrong or no ice instruments, too optimistic “gestimation” of AEP losses in finance phase etc.)
  - ➢ <u>MOST RISKS COULD HAVE BEEN ASSESSED IN ADVANCE!</u>



- Icing severity varies significantly from one year to another (mean icing ±200% vs mean wind ±15%)

➢ **Market demads for <u>simple</u> & <u>robust</u> tool for ice assessment!**

Cold Climate Market size [9]

Cumulative installed capacity by end of 2012 [MW]			Forecasted capacity 2013-17 [MW]		
Low temperature	Light icing: safety risk, some economic risk	Moderate to heavy icing: economic and safety risk	Low temperature	Light icing: safety risk, some economic risk	Moderate to heavy icing: economic and safety risk
18,945	41,079	11,478	20,025	22,083	8,003
Total 69,000 (*)			**Total 45,000 – 50,000**		

(*) The total capacity is less than the sum of individual capacities because some of the sites have both low temperatures and icing conditions.

30GW of new installations to icing conditions by 2017

➢ Compare: new offshore 29GW by 2017!

[9]: BTM World market Update 2012

Approach of SotA study

The approach

To get a simple & robust ice mapping method:

1. Start from turbine perspective; What is really important?
2. Understand typical “in nature” icing condition and variations
3. Connect above two and propose a simplified ice mapping method

The approach

- State-of-the-art literature review with one key question:

  - **What is the SINGLE most important Makkonen icing rate formula parameter that has the largest impact on wind energy?**

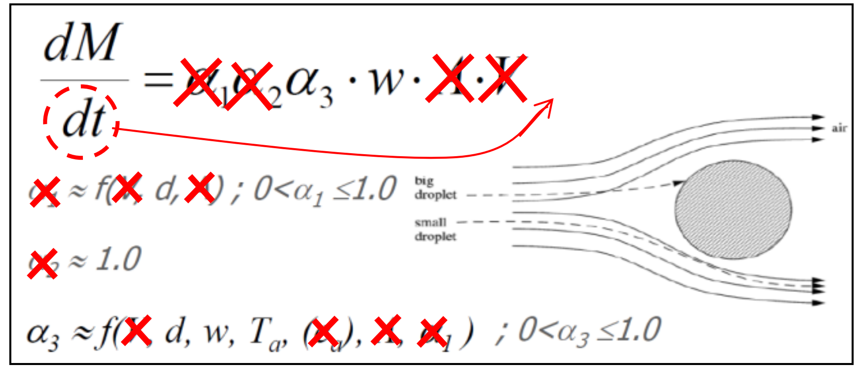
$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 \cdot w \cdot A \cdot V$$

$\alpha_1 = collision\ eff.$
$\alpha_2 = sticking\ eff.$
$\alpha_3 = accretion\ eff.$
$w = water\ content$
$A = object\ size$
$V = flow\ speed$

The approach

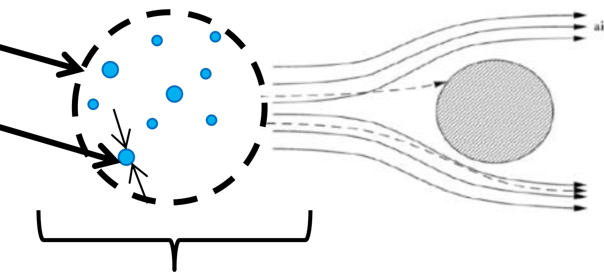
- Assumptions for turbine blade ice "model":

1. Disregard *V* and *A* as blades have tip speeds ≈ 40-75 m/s → wind turbine blade extreme efficient ice collector! Rime ice only $\alpha_{1,2} = 1.0$
2. More ice mass, more aero $penalty = \frac{iced}{clean}$
3. Simplify icing formula to 4 parameters: $dM(LWC, MVD, dt)$ and T



$\alpha_1 = collision\ eff.$
$\alpha_2 = sticking\ eff.$
$\alpha_3 = accretion\ eff.$
$w = water\ content$
$A = object\ size$
$V = flow\ speed$

#	Brief	Long name	Description
1	Ta ->T	Temperature	
2	w -> LWC	Liquid water content	How much water in volume?
3	d -> MVD	Median volumetric diameter	What is droplet size?
4	*t*	Icing duration	How long?



Icing cloud droplets

➢ **Goal: Find influence to rotor aerodynamics (lift CL and drag CD)**

Results

Attention!
Observe very short durations!

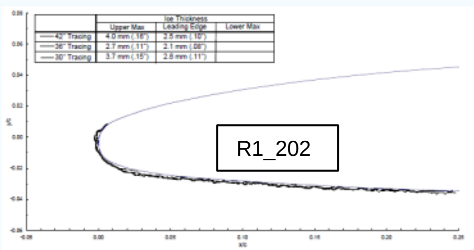
8 scientific references (R1-R8)

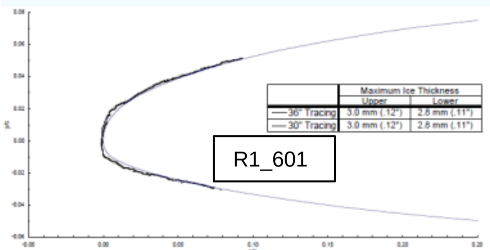
Total of +80 iced airfoil results

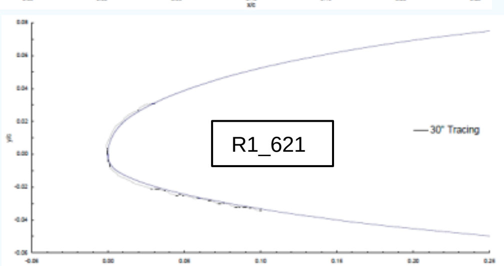
- +50 lift (CL) curves
- +30 drag (CD) curves

Results
-1) Icing wind tunnel measurements-

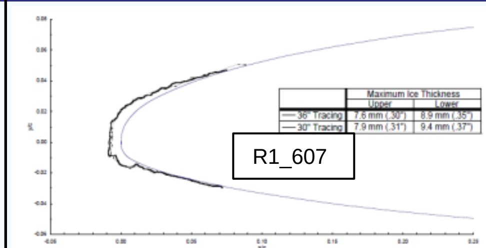
Start of icing	Light icing	Moderate icing	Extreme icing

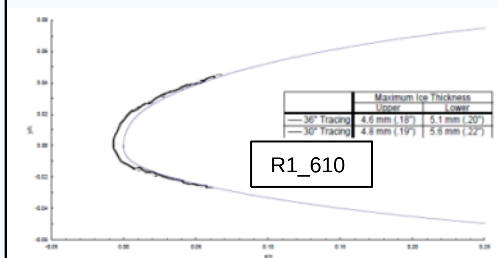


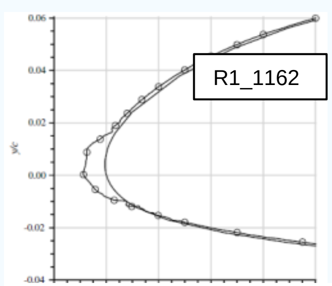




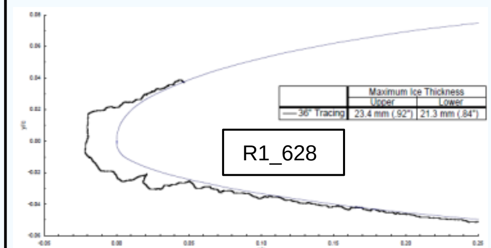
2 min
0-0.2kg/m

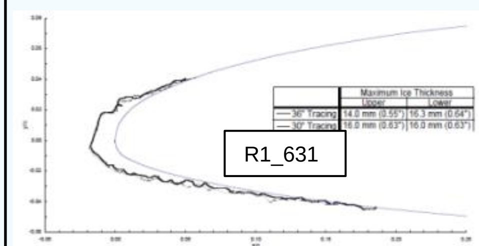


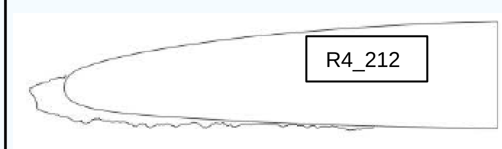




6 min
0.2-1kg/m

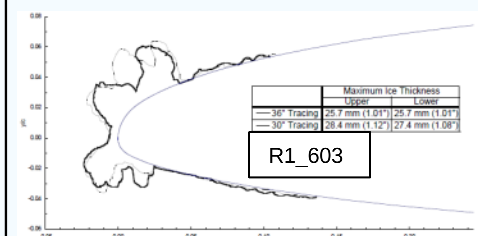


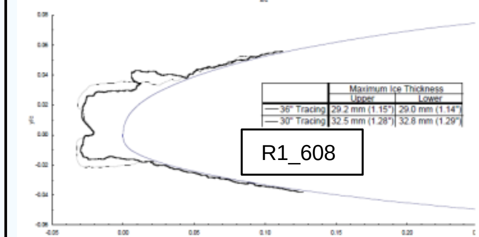


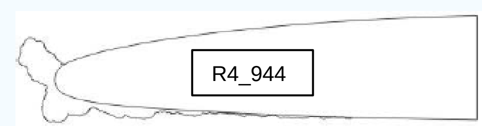


16.7-Minute Rime Ice Shape 212

15-20 min
1-3kg/m





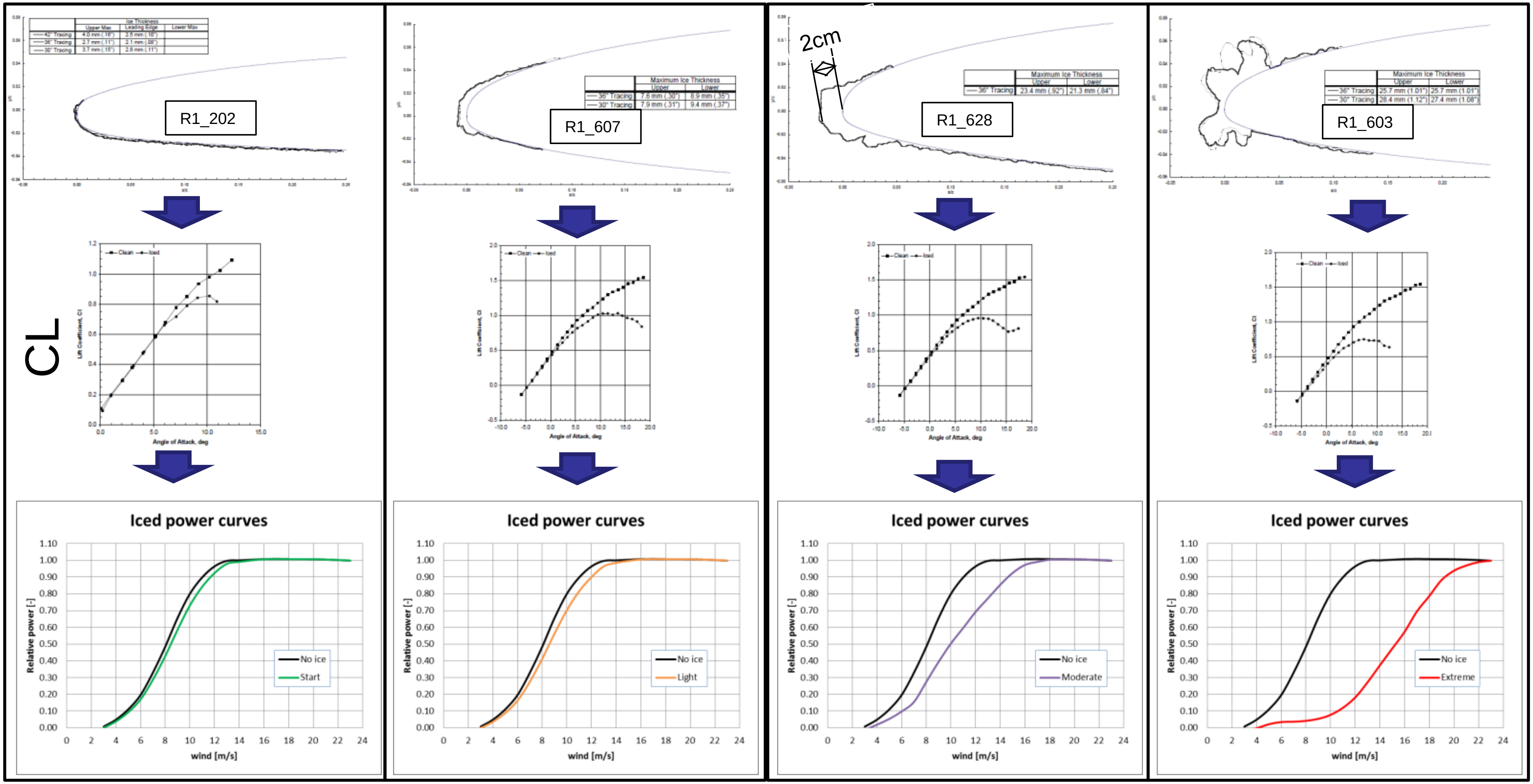


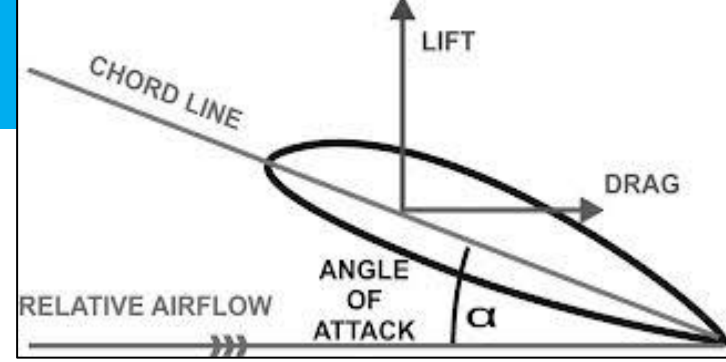
22.5-Minute Glaze Ice Shape 944

20-25 min
3-5kg/m

Results from SoTa
-1) Icing wind tunnel measurements-

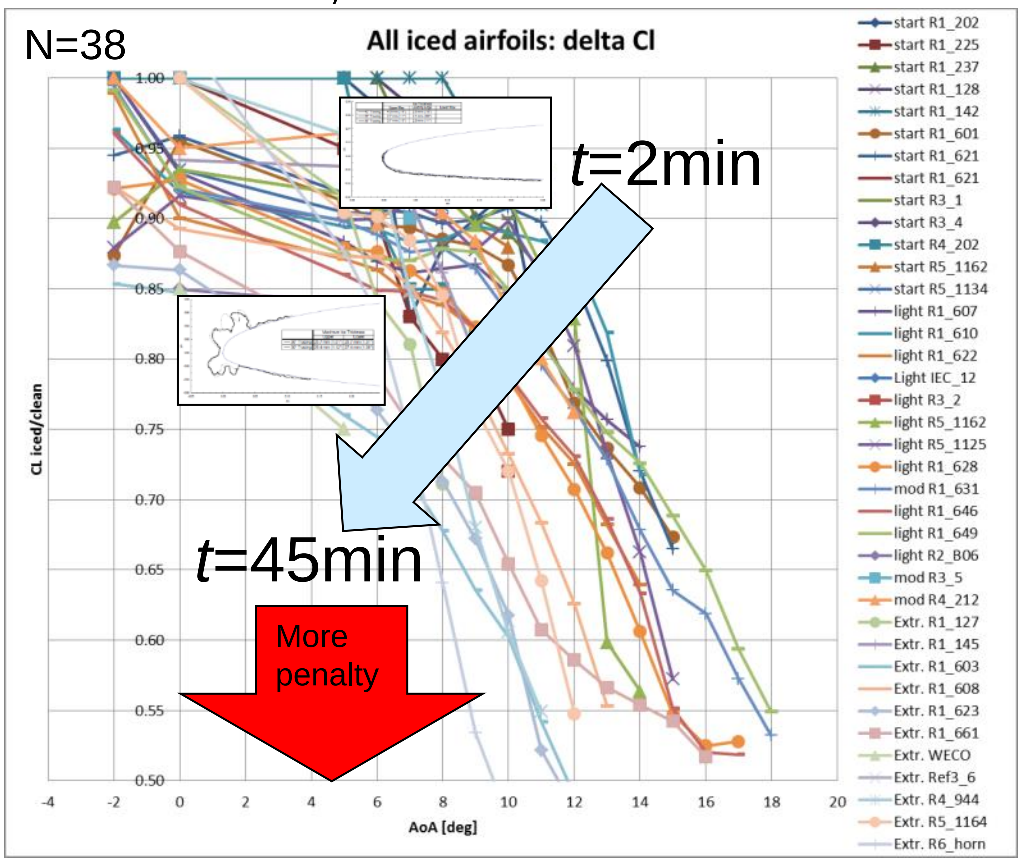
Over 2cm of blade ice -> very low power output!

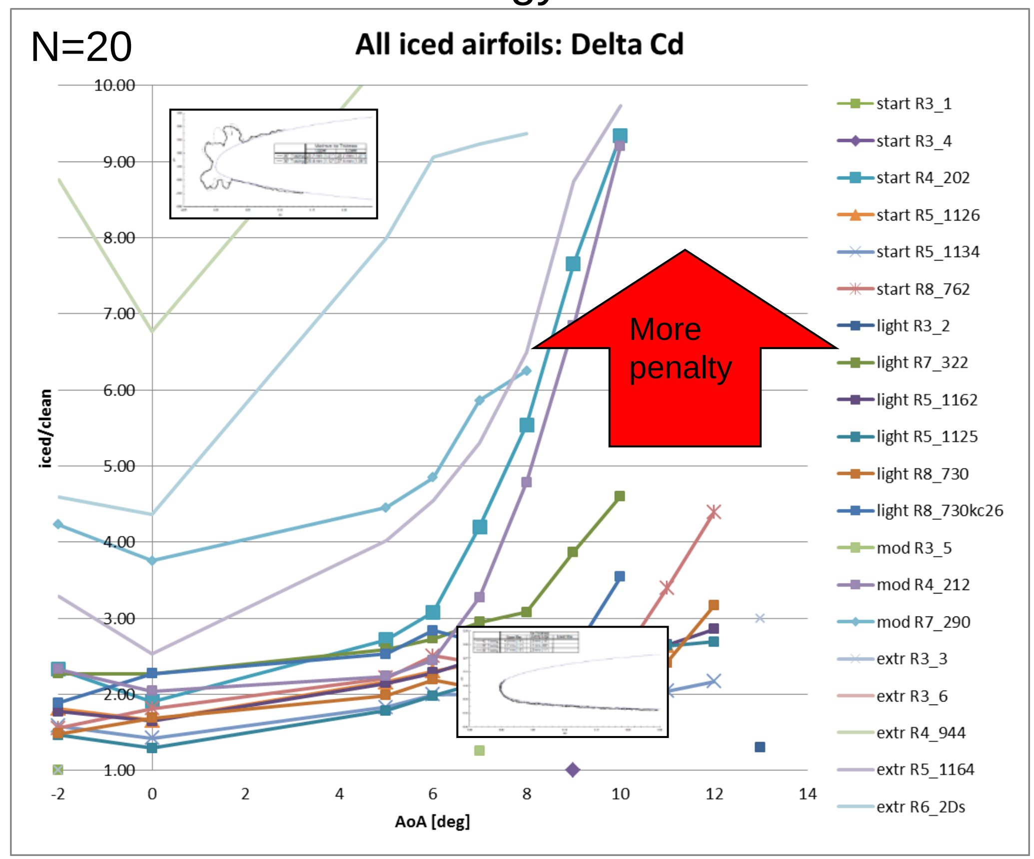




Results
-1) Icing wind tunnel measurements-

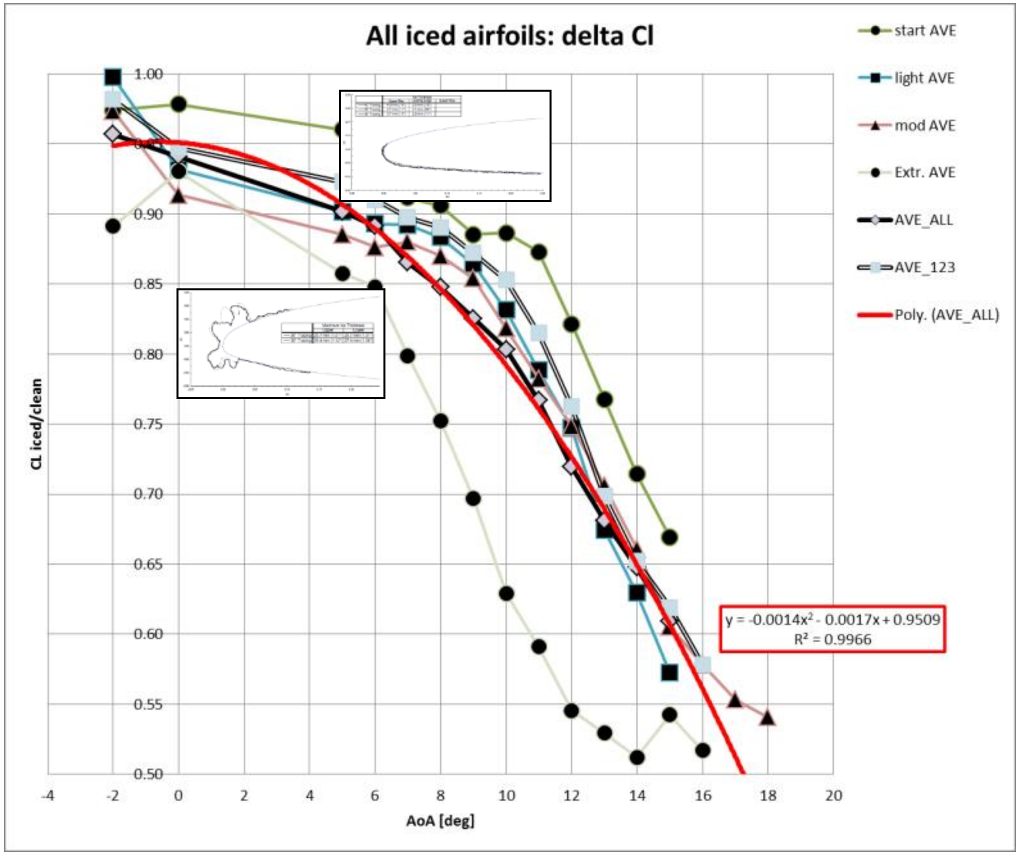
- Icing effect on CL & CD penalty factors $f(AoA) = \frac{iced}{clean}$
  - ➢Goal: Use for iced turbine simulations for AEP & load evaluation
- Clear pattern; 1) Higher AoA, more penalty! <u>2) **Longer *t*, more penalty!**</u>
- ΔCL-5..-50%, ΔCD+100..800% => BAD COMBINATION for wind energy!

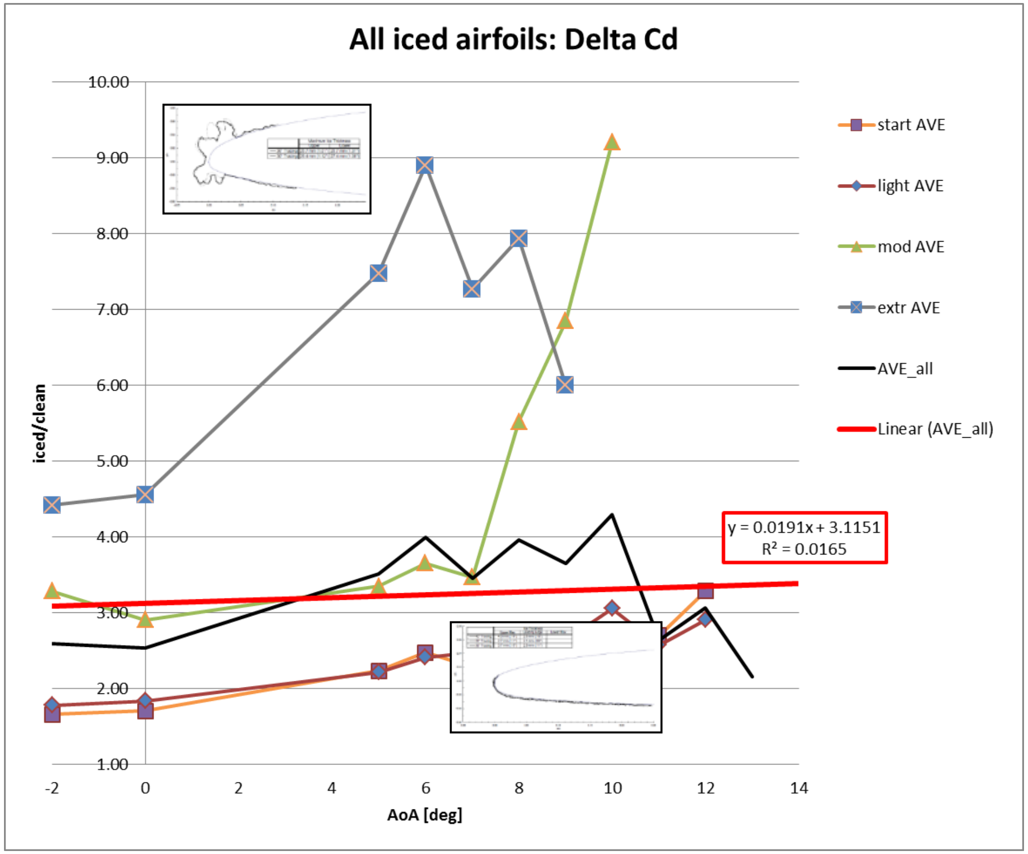




Results
-1) Icing wind tunnel measurements-

- **Statistical penalties used in new IEC 61400-1 ed4 cold climate DLCs for iced turbine simulation! [23]**





Results from SotA
-2) Meteorological measurements-

Time	Location	T [C°]	LWC [g/m³]			MVD [µm]			Icing duration *t* [h]			Ref
		max…min	Min	Mean	Max	Min	Mean	Max	Min	Median	Max	
1960-	US	0…-30	0.05	0.3	0.8	10	15	100				[11]
1987-1990	Ylläs, FI	-1…-13	0.07	0.19	0.43	8	12	20				[12]
1985	Mount x, FR	-1…-16		0.34		11	12	72				[13]
1990-1996	Ylläs, FI	-3…-6	0.09	0.31	0.43	12	15	20				[14]
1995-1999	US	-10		0.28		1	15	30				[18]
2001-2004	Luosto, FI	0…-22								6	61	[15]
2002-2003	Obers., AU	0…-14							1	7	45	[15]
2001-2004	Tauer., AU									4	34	[15]
1996-2004	Canada, US		0.1	0.14	1.0			<50				[16]
2006-2008	Puijo, FI	-		0.039		3	7	17				[17]
	TYPICAL=	**-5**	**0.1**	**0.25**	**0.7**	**8**	**15**	**45**		**6**	**45**	

➢Typical values present long-term (20-30yr) averages

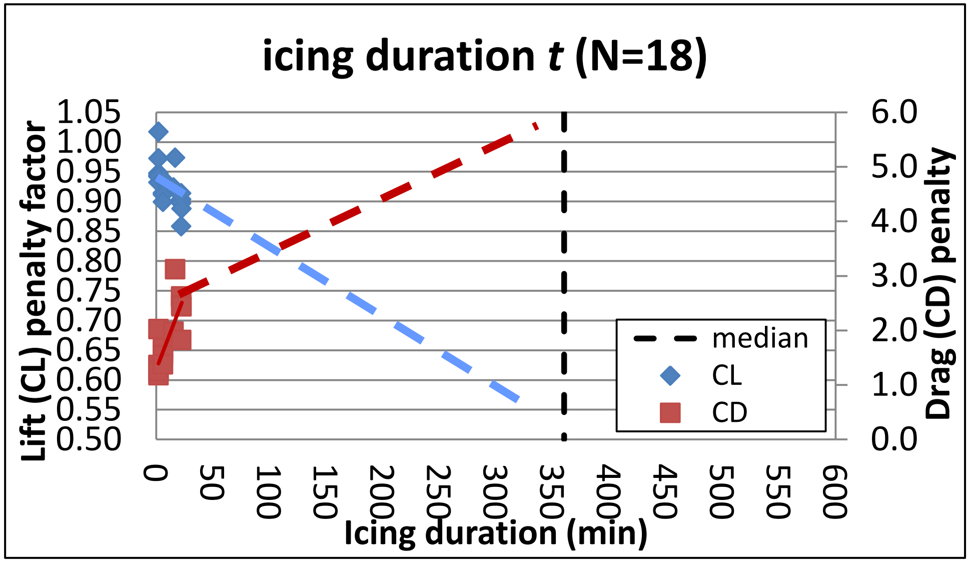
Icing sensitivity analyses: what is important for wind energy?

Results
-Icing sensitivity to aerodynamics-

- Vary 1 of 4 parameters at a time (others constant), look at CL & CD penalties
- Extrapolate CL & CD penalties to "in nature" mean icing condition

Table. Typical "in nature" ice parameters vs aero penalties

	Mean Ice tunnel	Mean Nature	Penalty sensitivity	
			CL	CD
T	-10°C	-5°C	0.92	2.3
LWC	0.4	0.25	0.90	1.6
MVD	20µm	15µm	0.93	1.7
t	20min	360min	0.5	>6



t largest impact!

See extra slides for more info

Main findings

1. Measured mean and distribution "in nature" for T, LWC and MVD have small effect to lift & drag = power curve, **NOT CRITICALLY IMPORTANT! -> OK to use long-term averages**

2. Icing kills the aerodynamics very quickly, < 15 minutes
   - Icing can be simplified in being on/off (start-stop) criteria!

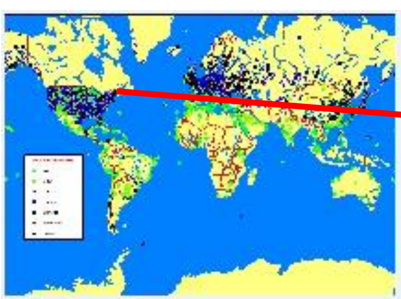
3. Icing duration *t* has by far the largest impact of lift and drag = power curve, **VERY IMPORTANT!**

- **Simply put: Long-term icing for wind energy can be assessed by icing duration only**
  - **And this can be done with…**

Wind Power Icing Atlas

- Is an icing database based on long-term +20yrs of measurements and observations from meteorological stations globally
  - ➢ ***To answer: How large are yearly variations of icing?***
- +4000 stations globally and increasing
  - ➢ ***To answer: Where are the icing risks likely to happen?***
- Method: Low level clouds + low temperatures = icing <-> IEA Ice Class
  - ➢ ***Simple & robust method: Ice detected as on/off criteria***

➢ *Estimate next 20yrs iced production losses!*



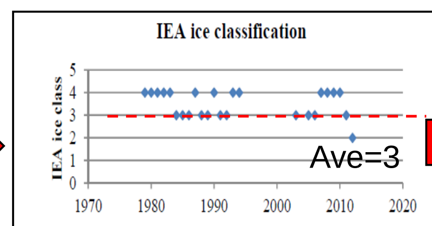


Figure 6: IEA ice class per year for RaR based on local airport cloud base height and temperature.

*: not stop turbine with iced blades
**: stop turbine with iced blades

IEA ice class	Duration of Meteorological icing [% of year]	Duration of Instrumental icing [% of year]	Production loss [% of AEP]
5	>10	>20	>20
4	5-10	10-30	10-25
3	3-5	6-15	3*-12**
2	0.5-3	1-9	0.5-5
1	0-0.5	<1.5	0-0.5

Wind Power Icing Atlas -Main Benefits-

IEA ice class	Duration of Meteorological icing [% of year]	Duration of Instrumental icing [% of year]	Production loss [% of AEP]
5	>10	>20	>20
4	5-10	10-30	10-25
3	3-5	6-15	3*-12**
2	0.5-3	1-9	0.5-5
1	0-0.5	<1.5	0-0.5

*: not stop turbine with iced blades
**: stop turbine with iced blades

- Main benefits before and during site assessment:
  1. Unique, EARLY site IEA ice classification to
     a) design proper measurement campaign to increase data availability and quality and
     b) quantify financial risks based on +20 years of historical observation data
  2. Inexpensive and fast delivery of results
     - Now results as quickly as in 1-2 weeks
     - Future goal: online, immediate answer eg mobile app

- Currently sold as ice assessment service
- More detailed WiceAtlas validation and example case, see [23]

Conclusions

- For turbine aerodynamics: icing duration most effect to CL & CD penalties -> output power
- Key for ice mapping: Large yearly icing variations need to be assessed!
- Typical 1-2yr site resource (ice) assessment NOT able to see large yearly variations for next 20yrs -> BIG AEP ESTIMATE UNCERTAINTY!
- Simple & robust ice mapping: VTT's Wind Power Icing Atlas (WIceAtlas)

Key takeaway

Keep in mind LWC and MVD as additional icing information

BUT

Focus on icing duration!

VTT - 70 years of **technology for business and society**

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ville.lehtomaki@vtt.fi
Phone: +358 40 176 3147

References

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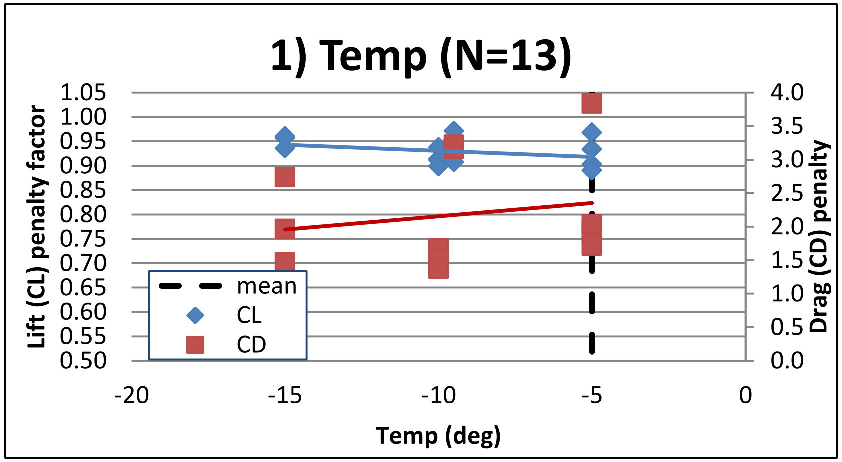
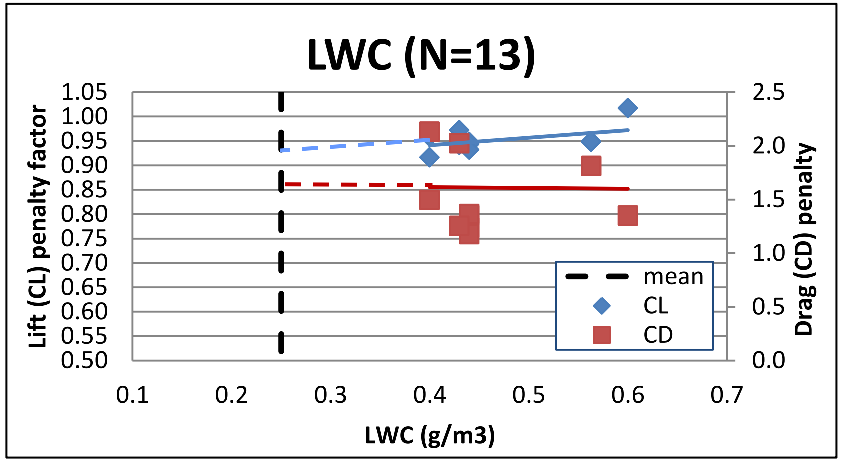
[23]: Lehtomäki et al., Input to new IEC 61400-1 design standards from two case studies of iced turbine load analysis, WinterWind 2014
[24]: Lehtomäki et al., Wind power icing atlas - tool for financial risk assessment, WinterWind 2014

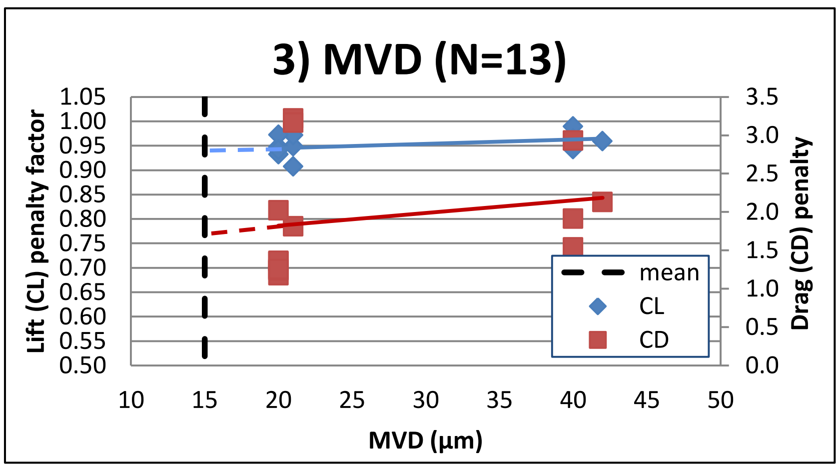
Extra slides

Results
-Icing sensitivity to aerodynamics-

- Vary 1 parameter at a time (others constant), look at CL & CD penalties
- Extrapolate CL & CD penalties to "in nature" mean icing condition







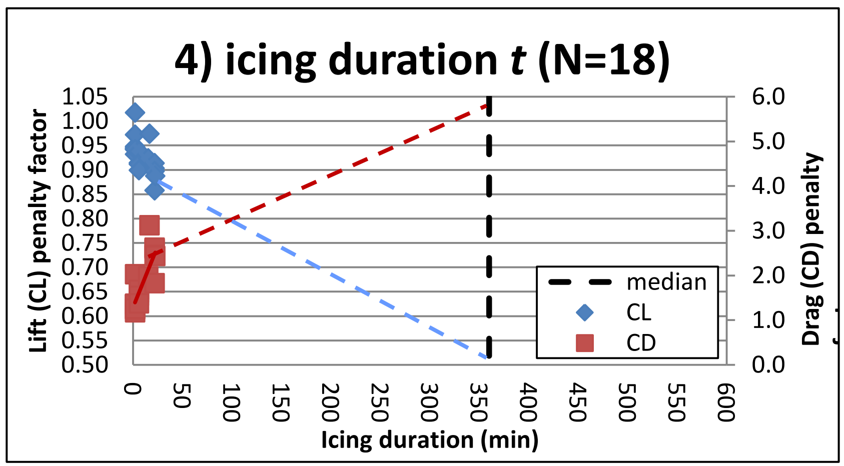


Table. Typical "in nature" aero penalty values

	Airfoil penalties	
	CL	CD
Temp	0.92	2.3
LWC	0.90	1.6
MVD	0.93	1.7
t	0.5	>6

t largest impact!

Wind Power Icing Atlas (WIceAtlas)

WIceAtlas will tell the -€€€ effects for power production! [24]