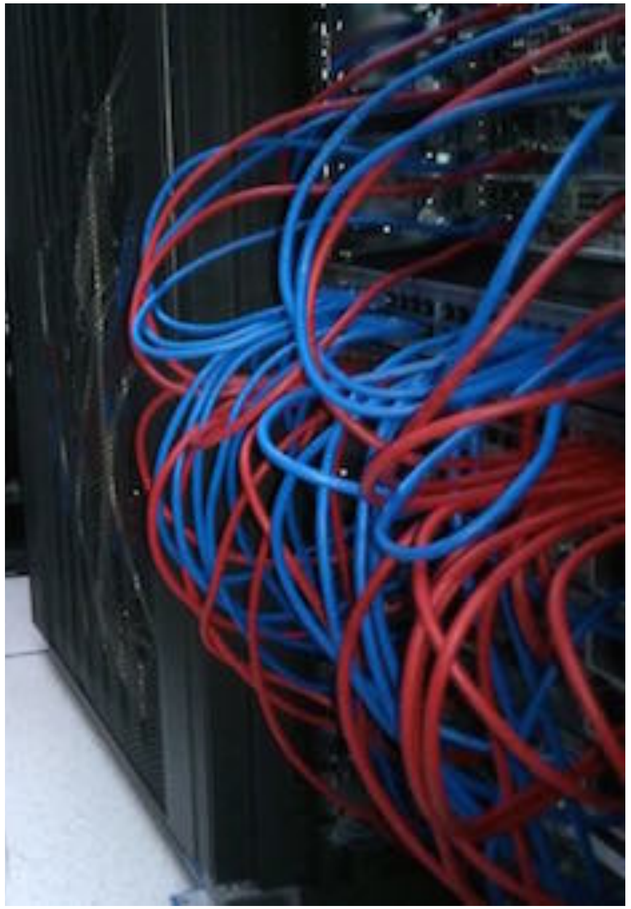
Improve Wind Project Life Cycle Cost of Energy in Cold Climates

Albert Bosch (Vortex)

WinterWind . Åre, February 2020.

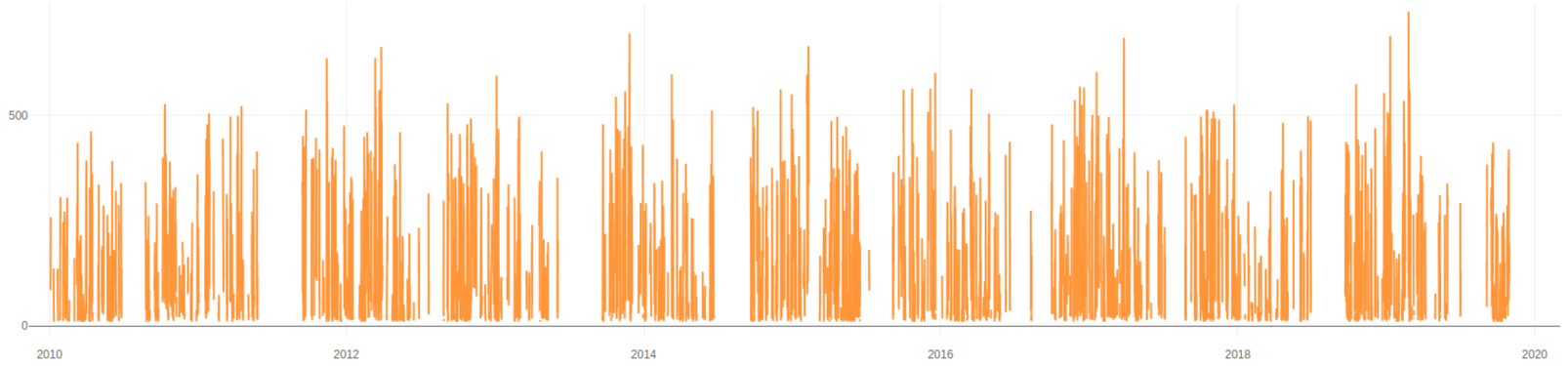
New Tools

Available **new technologies** as well as **computational power** increase, make possible the creation of cold climate related variables **time series** and thus, a **deeper analysis** can be executed regarding the performance of wind farms on such cold regions.



Time Series

Detailed **hourly information** will become an essential tool for the wind industry in cold climate regions causing time-collapsed averaged data to become obsolete.



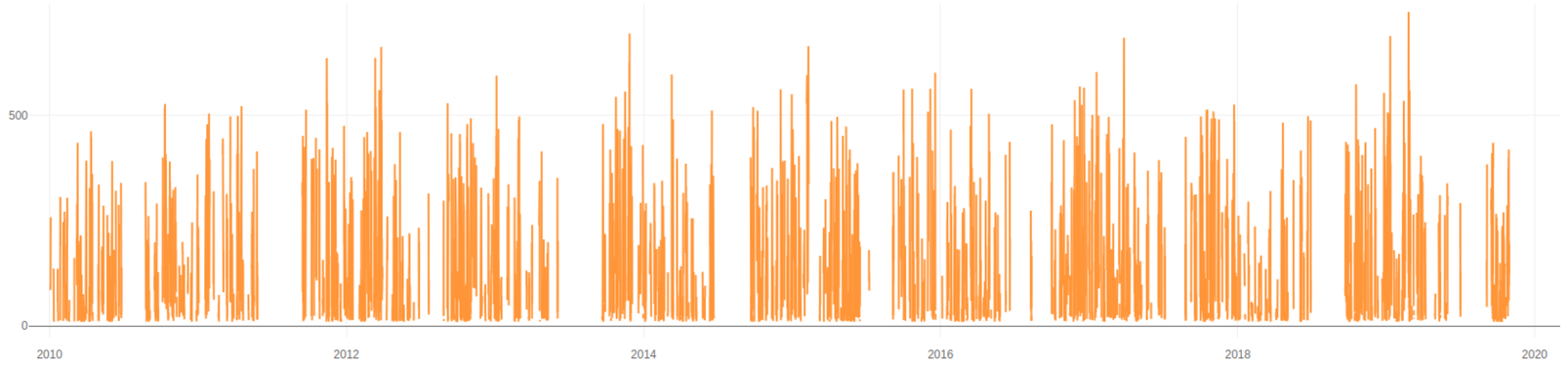
Lat=63.450364 Lon=13.065289 Height=100 Timezone=0

T100: Temperature at 100m horizontal resolution
ref: Vortex-SERIES variables at 3km horizontal resolution as climate reference

YYYYMMDD HHMM	dmdt(g/h)	T100(C)	Tref(C)	Mref(m/s)	Dref(deg)	RHref(%)
20191028 0000	86.1	-7.2	-4.8	10.6	314	100.0
20191028 0100	95.8	-7.3	-5.0	10.8	311	100.0
20191028 0200	107.3	-7.3	-5.0	10.8	309	100.0
20191028 0300	131.2	-7.2	-5.0	10.7	308	100.0
20191028 0400	165.6	-7.2	-5.2	10.7	305	100.0
20191028 0500	190.3	-7.3	-5.2	11.0	303	100.0
20191028 0600	220.0	-7.3	-5.2	11.3	300	100.0
20191028 0700	266.0	-7.5	-5.2	11.8	297	100.0
20191028 0800	298.9	-7.6	-5.2	12.7	294	100.0
20191028 0900	294.3	-7.6	-5.3	12.8	291	100.0
20191028 1000	268.7	-7.4	-5.2	12.6	291	100.0
20191028 1100	241.0	-6.8	-4.7	12.1	293	100.0
20191028 1200	280.7	-6.5	-4.2	12.1	295	100.0
20191028 1300	309.0	-6.5	-3.9	12.3	297	100.0
20191028 1400	317.8	-6.6	-3.9	12.4	298	100.0
20191028 1500	316.0	-6.6	-4.0	12.5	299	100.0
20191028 1600	297.5	-6.6	-4.2	12.8	304	100.0
20191028 1700	287.5	-6.5	-4.2	13.0	309	100.0
20191028 1800	289.1	-6.6	-4.2	13.0	313	100.0
20191028 1900	263.1	-6.7	-4.2	12.9	318	100.0
20191028 2000	185.9	-6.8	-4.5	12.6	322	100.0
20191028 2100	170.8	-7.0	-4.7	12.4	322	100.0
20191028 2200	207.4	-7.2	-4.8	12.4	324	100.0
20191028 2300	226.5	-7.2	-4.8	12.7	321	100.0
20191029 0000	207.5	-7.2	-4.7	12.8	312	100.0
20191029 0100	200.5	-7.2	-4.5	13.9	309	100.0
20191029 0200	226.4	-7.1	-4.5	14.5	308	100.0
20191029 0300	244.8	-7.0	-4.5	14.6	308	100.0
20191029 0400	303.8	-7.0	-4.5	14.7	306	100.0
20191029 0500	373.8	-7.2	-4.8	14.8	305	100.0
20191029 0600	378.8	-7.2	-4.8	14.9	305	100.0
20191029 0700	363.7	-7.2	-4.7	14.6	305	100.0
20191029 0800	341.7	-7.3	-4.7	14.2	306	100.0
20191029 0900	281.1	-7.3	-4.7	13.6	307	100.0
20191029 1000	202.7	-7.4	-4.5	13.0	311	100.0
20191029 1100	167.3	-7.3	-4.3	12.3	316	100.0
20191029 1200	142.9	-7.2	-4.2	11.3	317	100.0

Time Series

Time series has become now a reality which leads to a new approach when analyzing the **project life cycle**, specially regarding the **energy cost estimation**.

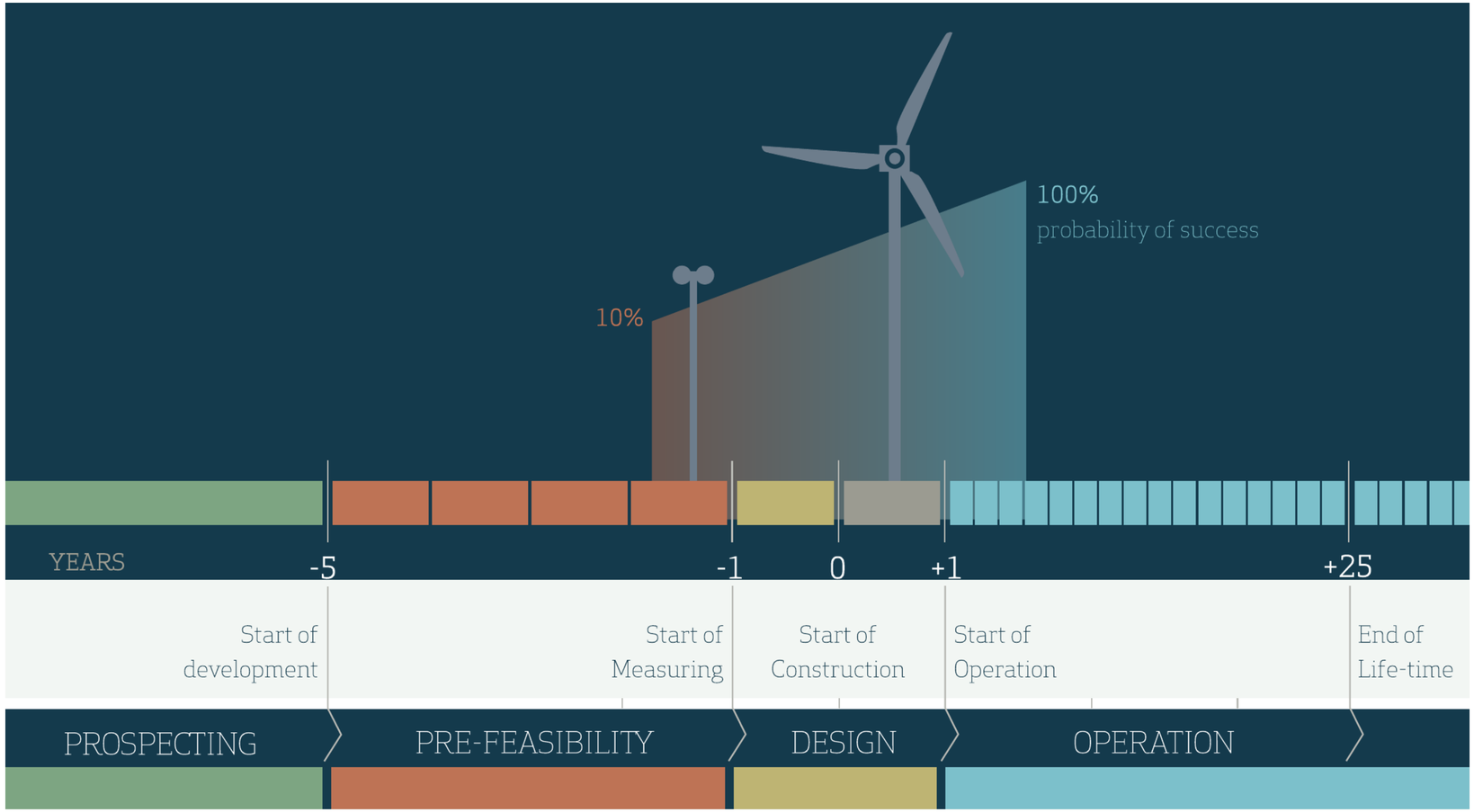


Lat=63.450364 Lon=13.065289 Height=100 Timezone=0

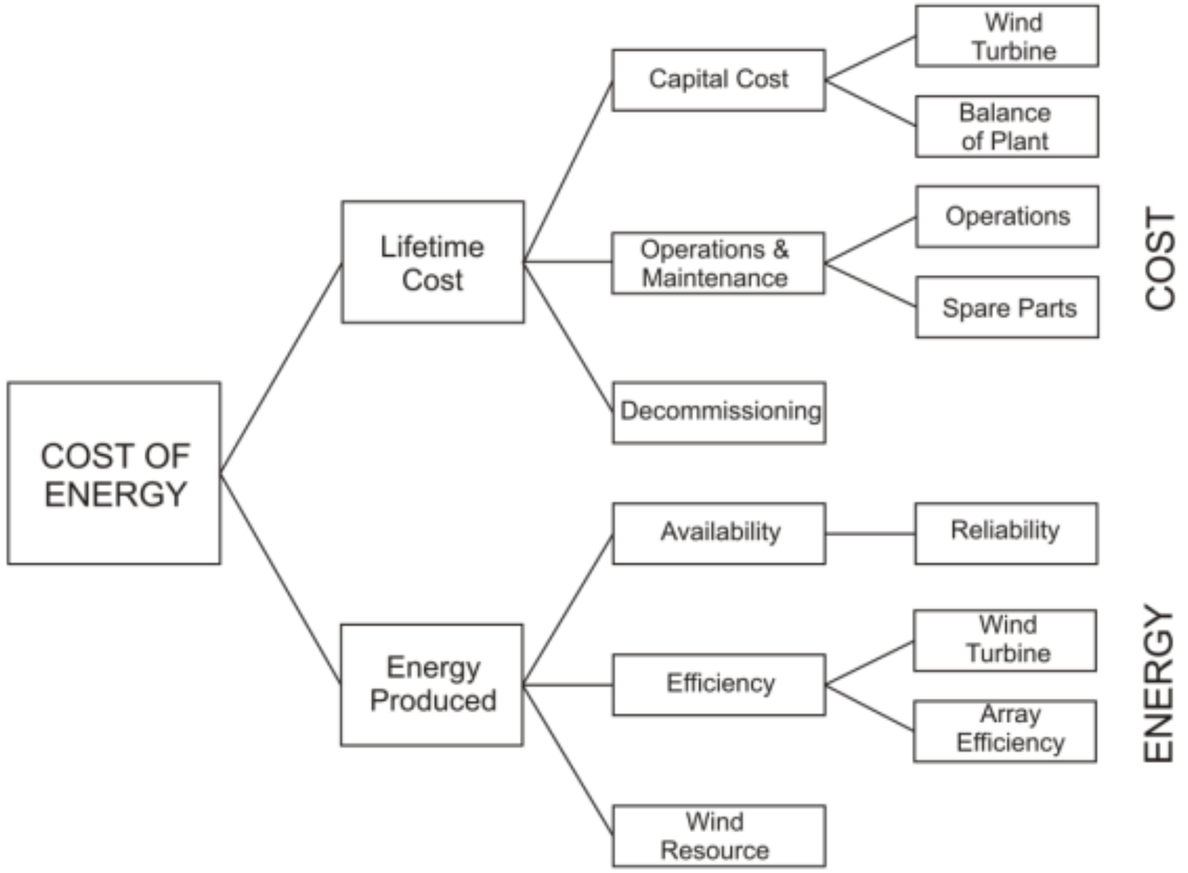
T100: Temperature at 100m horizontal resolution
ref: Vortex-SERIES variables at 3km horizontal resolution as climate reference

YYYYMMDD HHMM	dmdt(g/h)	T100(C)	Tref(C)	Mref(m/s)	Dref(deg)	RHref(%)
20191028 0000	86.1	-7.2	-4.8	10.6	314	100.0
20191028 0100	95.8	-7.3	-5.0	10.8	311	100.0
20191028 0200	107.3	-7.3	-5.0	10.8	309	100.0
20191028 0300	131.2	-7.2	-5.0	10.7	308	100.0
20191028 0400	165.6	-7.2	-5.2	10.7	305	100.0
20191028 0500	190.3	-7.3	-5.2	11.0	303	100.0
20191028 0600	220.0	-7.3	-5.2	11.3	300	100.0
20191028 0700	266.0	-7.5	-5.2	11.8	297	100.0
20191028 0800	298.9	-7.6	-5.2	12.7	294	100.0
20191028 0900	294.3	-7.6	-5.3	12.8	291	100.0
20191028 1000	268.7	-7.4	-5.2	12.6	291	100.0
20191028 1100	241.0	-6.8	-4.7	12.1	293	100.0
20191028 1200	280.7	-6.5	-4.2	12.1	295	100.0
20191028 1300	309.0	-6.5	-3.9	12.3	297	100.0
20191028 1400	317.8	-6.6	-3.9	12.4	298	100.0
20191028 1500	316.0	-6.6	-4.0	12.5	299	100.0
20191028 1600	297.5	-6.6	-4.2	12.8	304	100.0
20191028 1700	287.5	-6.5	-4.2	13.0	309	100.0
20191028 1800	289.1	-6.6	-4.2	13.0	313	100.0
20191028 1900	263.1	-6.7	-4.2	12.9	318	100.0
20191028 2000	185.9	-6.8	-4.5	12.6	322	100.0
20191028 2100	170.8	-7.0	-4.7	12.4	322	100.0
20191028 2200	207.4	-7.2	-4.8	12.4	324	100.0
20191028 2300	226.5	-7.2	-4.8	12.7	321	100.0
20191029 0000	207.5	-7.2	-4.7	12.8	312	100.0
20191029 0100	200.5	-7.2	-4.5	13.9	309	100.0
20191029 0200	226.4	-7.1	-4.5	14.5	308	100.0
20191029 0300	244.8	-7.0	-4.5	14.6	308	100.0
20191029 0400	303.8	-7.0	-4.5	14.7	306	100.0
20191029 0500	373.8	-7.2	-4.8	14.8	305	100.0
20191029 0600	378.8	-7.2	-4.8	14.9	305	100.0
20191029 0700	363.7	-7.2	-4.7	14.6	305	100.0
20191029 0800	341.7	-7.3	-4.7	14.2	306	100.0
20191029 0900	281.1	-7.3	-4.7	13.6	307	100.0
20191029 1000	202.7	-7.4	-4.5	13.0	311	100.0
20191029 1100	167.3	-7.3	-4.3	12.3	316	100.0
20191029 1200	142.9	-7.2	-4.2	11.3	317	100.0

Life Cycle of a Wind Farm



Cost of Energy (€/MWh)

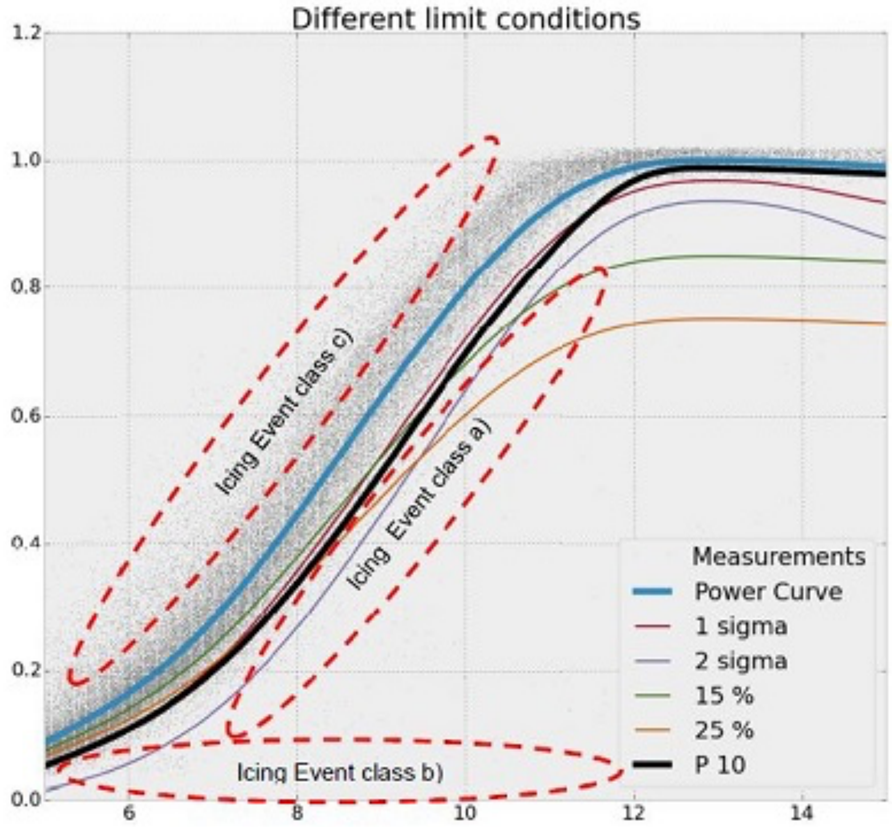


source: Thomson et al., 2015, Life Cycle Cost and Carbon Emissions of Onshore Wind Power

ICING Losses

T19IceLossMethod:

A standardized method for assessment of production losses due to icing from wind turbine **SCADA** data.

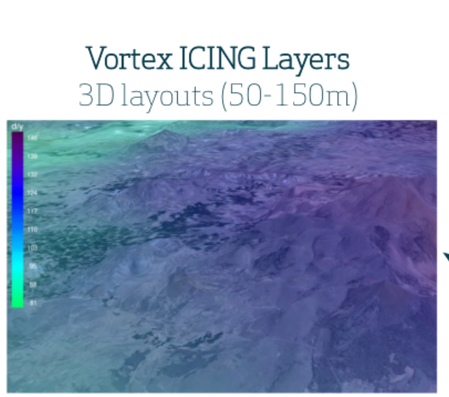


source: https://community.ieawind.org/task19/t19icelossmethod

Modelling

Overview of the model

- The model uses WRF driven by **ERA5** Reanalysis
- **NO** on-site measurement **data is needed** as input
- In-cloud icing using the **Thompson microphysics** scheme
- Ice accretion using the **Makkonen model**



Vortex ICING Layers
3D layouts (50-150m)

ERA5 Reanalysis
0.25x0.25 degrees

ECMWF

Cold weather events selection:
Vortex SERIES
WRF:10years @3km;
T(°C), M(m/s), RH (%)

Vortex ICING Series :
Ice-accretion 10-years time-series

Lat= Lon= Height= Timezone=0

YYYYMMDD HHMM	dmdt(g/h)	T(C)	M(m/s)	RH(%)
20180416 0000	2.2	5.3	13.0	83.4
20180416 0100	0.0	4.6	10.8	85.5
20180416 0200	0.0	3.7	9.9	79.3
20180416 0300	0.1	2.6	9.6	82.4
20180416 0400	1.6	1.8	10.2	88.4
20180416 0500	17.0	1.1	10.5	94.8
20180416 0600	38.2	0.5	11.3	98.9
20180416 0700	61.3	0.1	11.4	100.0
20180416 0800	104.9	-0.4	11.4	100.0
20180416 0900	157.8	-0.8	10.9	100.0
20180416 1000	177.6	-1.2	11.1	100.0
20180416 1100	130.4	-1.4	10.2	100.0
20180416 1200	38.2	-1.2	8.4	100.0
20180416 1300	1.4	-1.2	6.7	
20180416 1400	0.1	-1.4	7.1	
20180416 1500	0.1	-1.3		
20180416 1600	2.4	-1.0		
20180416 1700	20.6	-0.6		
20180416 1800	13.9	-0.1		
20180416 1900	3.1	0.7		
20180416 2000	0.0	1.2		
20180416 2100	0.0	1.9		
20180416 2200	0.0	2.6		
20180416 2300	0.0	2.8		
20180417 0000	-	2.5		
20180417 0100	-	2.1		
20180417 0200	-	1.2		
20180417 0300	-	0.5		

Vortex ICING:
Makkonen Model
(wind & humidity)

$$\frac{dm}{dt} = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \omega \cdot M$$

Pre-selected
Icing episodes

(M)

(ω)

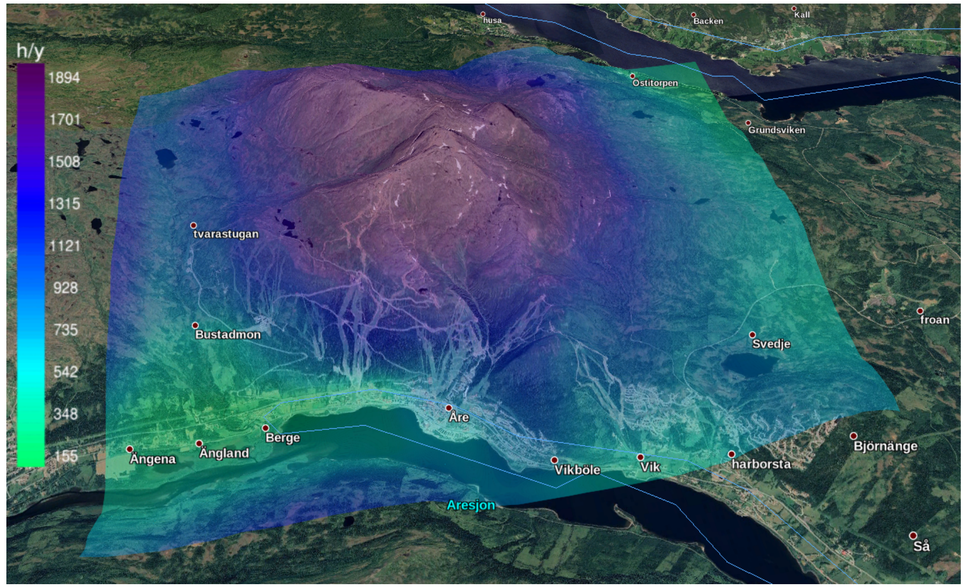
Wind & temperature high resolution calculation :
Vortex FARM
(WRF @100m)

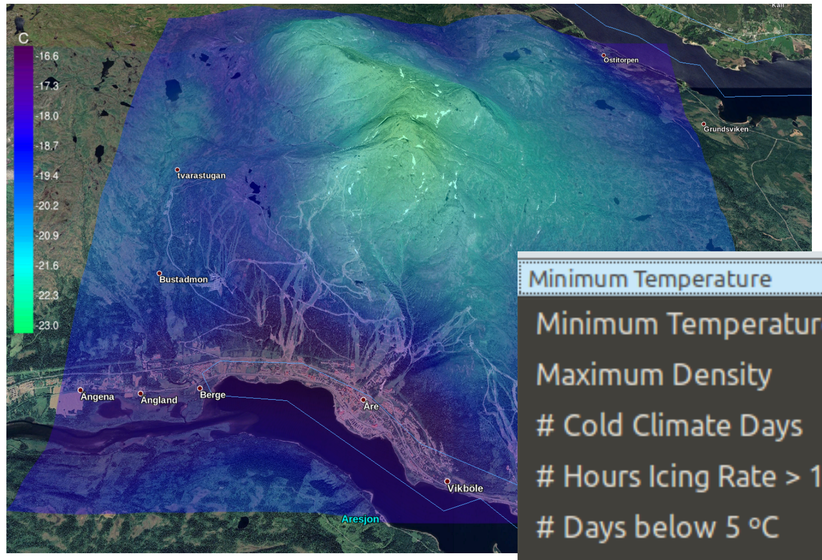
Selected
Icing episodes

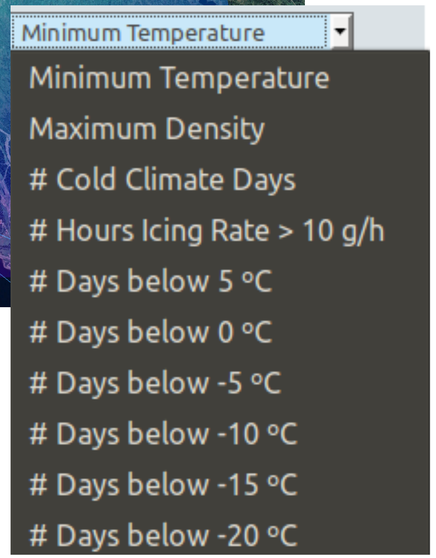
Humidity calculation:
WRF + Thompson Scheme
(WRF @ 1km)

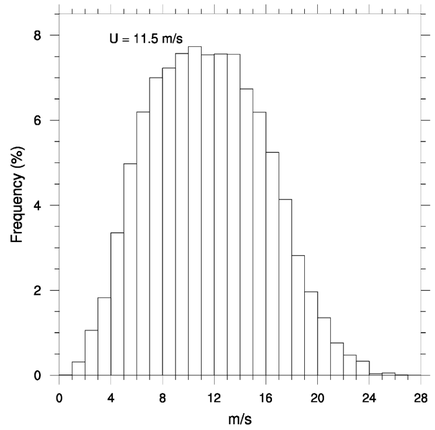
VORTEX

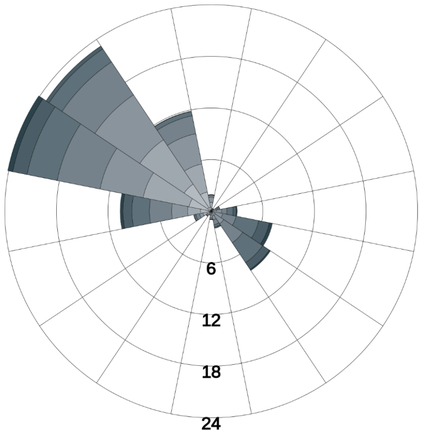
Modelled ICING averaged indicators









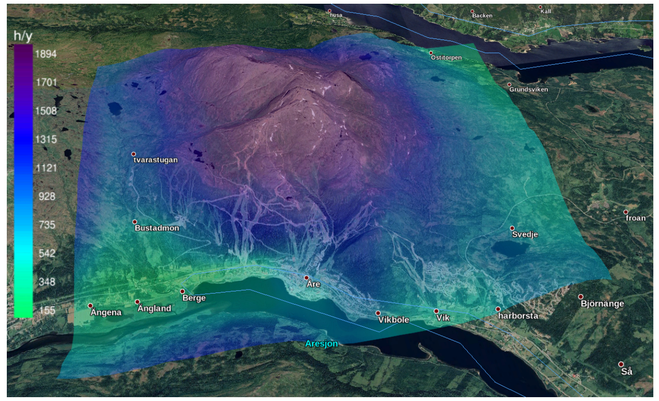


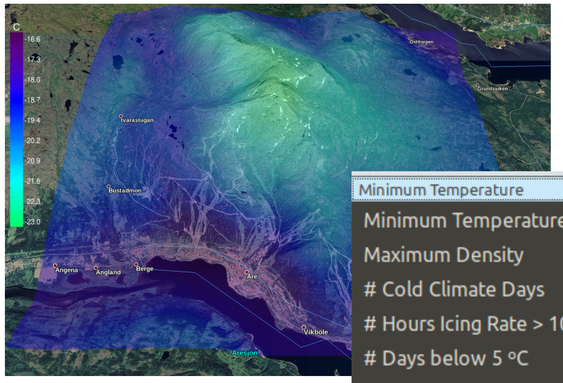
#	Latitude	Longitude	Wind	Icing
1	63.400024	13.073078	9.7	644.7
2	63.427874	13.0943	15.2	1,843.6
3	63.432634	13.053788	11.5	1,680.3
4	63.450364	13.065289	15.4	1,766.3
-	deg.	deg.	m/s	hours/year

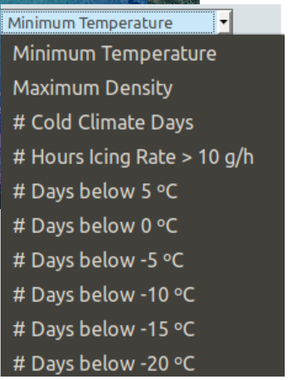
Modelled ICING averaged indicators

Averaged indicators at each turbine locations during icing episodes:

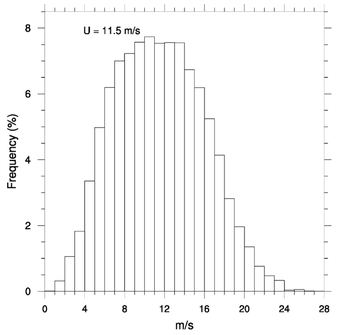
- Wind Speed Histograms
- Wind Direction Roses
- Icing hours per year
- Other cold climate indicators

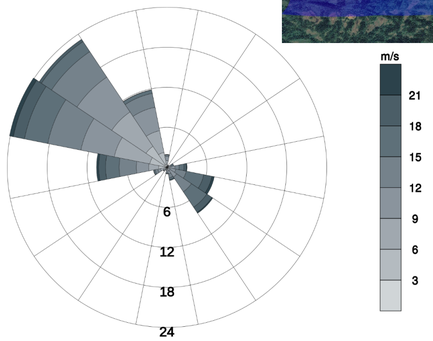






#	Latitude	Longitude	Wind	Icing
1	63.400024	13.073078	9.7	644.7
2	63.427874	13.0943	15.2	1,843.6
3	63.432634	13.053788	11.5	1,680.3
4	63.450364	13.065289	15.4	1,766.3
-	deg.	deg.	m/s	hours/year





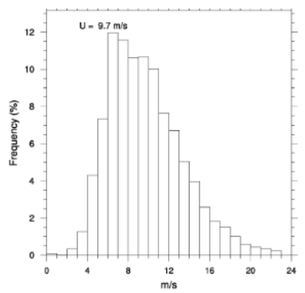
Modelled ICING averaged indicators

Averaged indicators at each turbine locations during icing episodes:

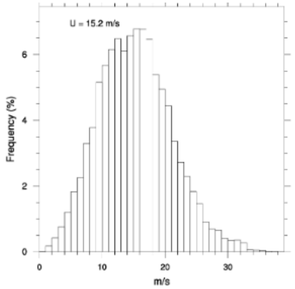
- **Wind Speed Histograms**
- Wind Direction Roses
- Icing hours per year
- Other cold climate indicators

#	Latitude	Longitude	Wind	Icing
1	63.400024	13.073078	9.7	644.7
2	63.427874	13.0943	15.2	1,843.6
3	63.432634	13.053788	11.5	1,680.3
4	63.450364	13.065289	15.4	1,766.3
-	deg.	deg.	m/s	hours/year

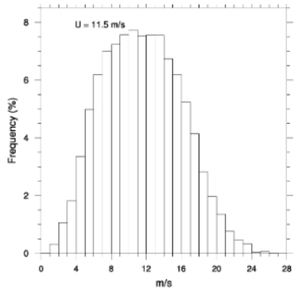
Point 1
Lat. 63.400024
Lon. 13.073078



Point 2
Lat. 63.427874
Lon. 13.0943



Point 3
Lat. 63.432634
Lon. 13.053788



Point 4
Lat. 63.450364
Lon. 13.065289

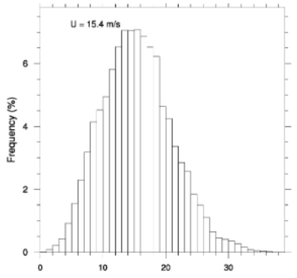


Figure 11: Wind Speed Histogram during Icing Episodes (*). Please note that no Weibull fitting is performed since wind speed distribution during icing episodes do not necessarily correspond to Weibull distribution of the wind associated with mean wind speed.

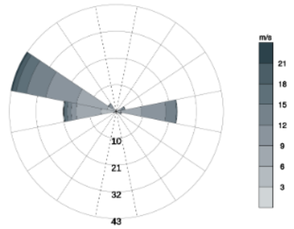
Modelled ICING averaged indicators

Averaged indicators at each turbine locations during icing episodes:

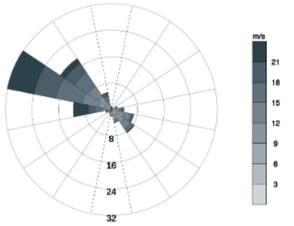
- Wind Speed Histograms
- **Wind Direction Roses**
- Icing hours per year
- Other cold climate indicators

#	Latitude	Longitude	Wind	Icing
1	63.400024	13.073078	9.7	644.7
2	63.427874	13.0943	15.2	1,843.6
3	63.432634	13.053788	11.5	1,680.3
4	63.450364	13.065289	15.4	1,766.3
-	deg.	deg.	m/s	hours/year

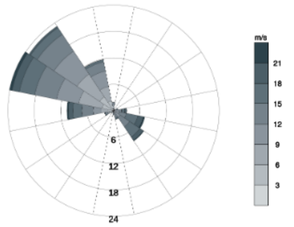
Point 1
Lat. 63.400024
Lon. 13.073078



Point 2
Lat. 63.427874
Lon. 13.0943



Point 3
Lat. 63.432634
Lon. 13.053788



Point 4
Lat. 63.450364
Lon. 13.065289

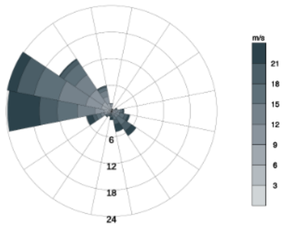


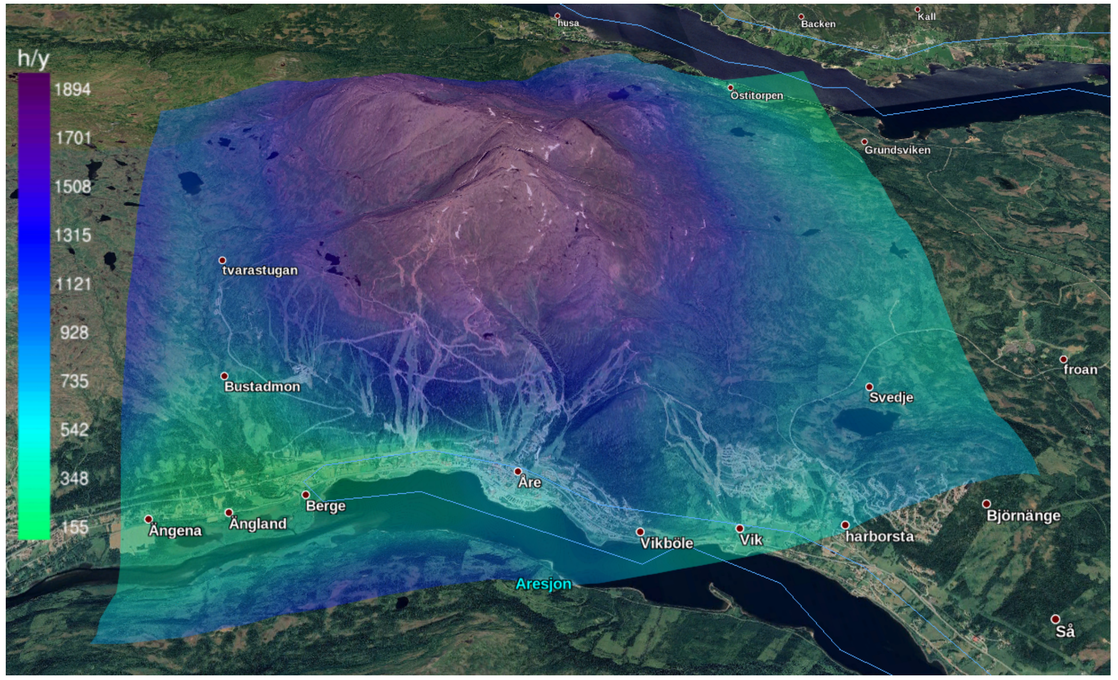
Figure 10: Wind Direction Rose during Icing Episodes (*). The radius of each sector is proportional to its frequency in the total wind speed distribution. The color of each bin depends on the wind speed as referred in the legend.

Modelled ICING averaged indicators

Averaged indicators at each turbine locations during icing episodes:

- Wind Speed Histograms
- Wind Direction Roses
- **Icing hours per year**
- Other cold climate indicators

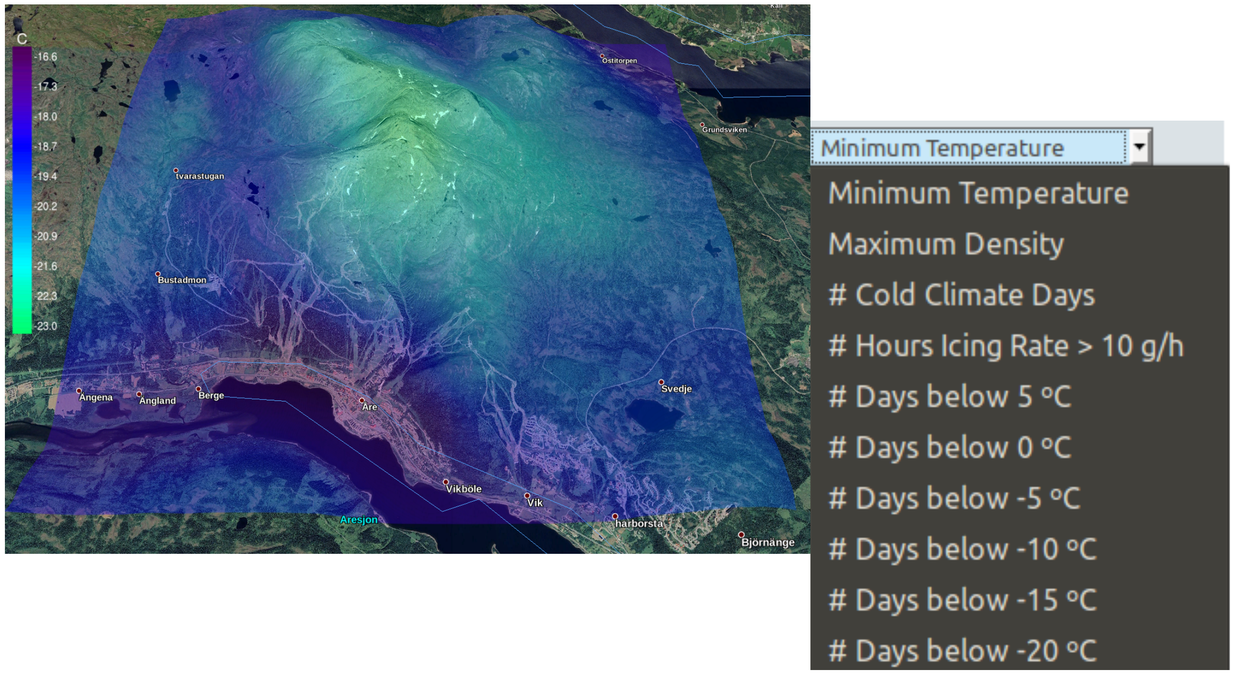
#	Latitude	Longitude	Wind	Icing
1	63.400024	13.073078	9.7	644.7
2	63.427874	13.0943	15.2	1,843.6
3	63.432634	13.053788	11.5	1,680.3
4	63.450364	13.065289	15.4	1,766.3
-	deg.	deg.	m/s	hours/year



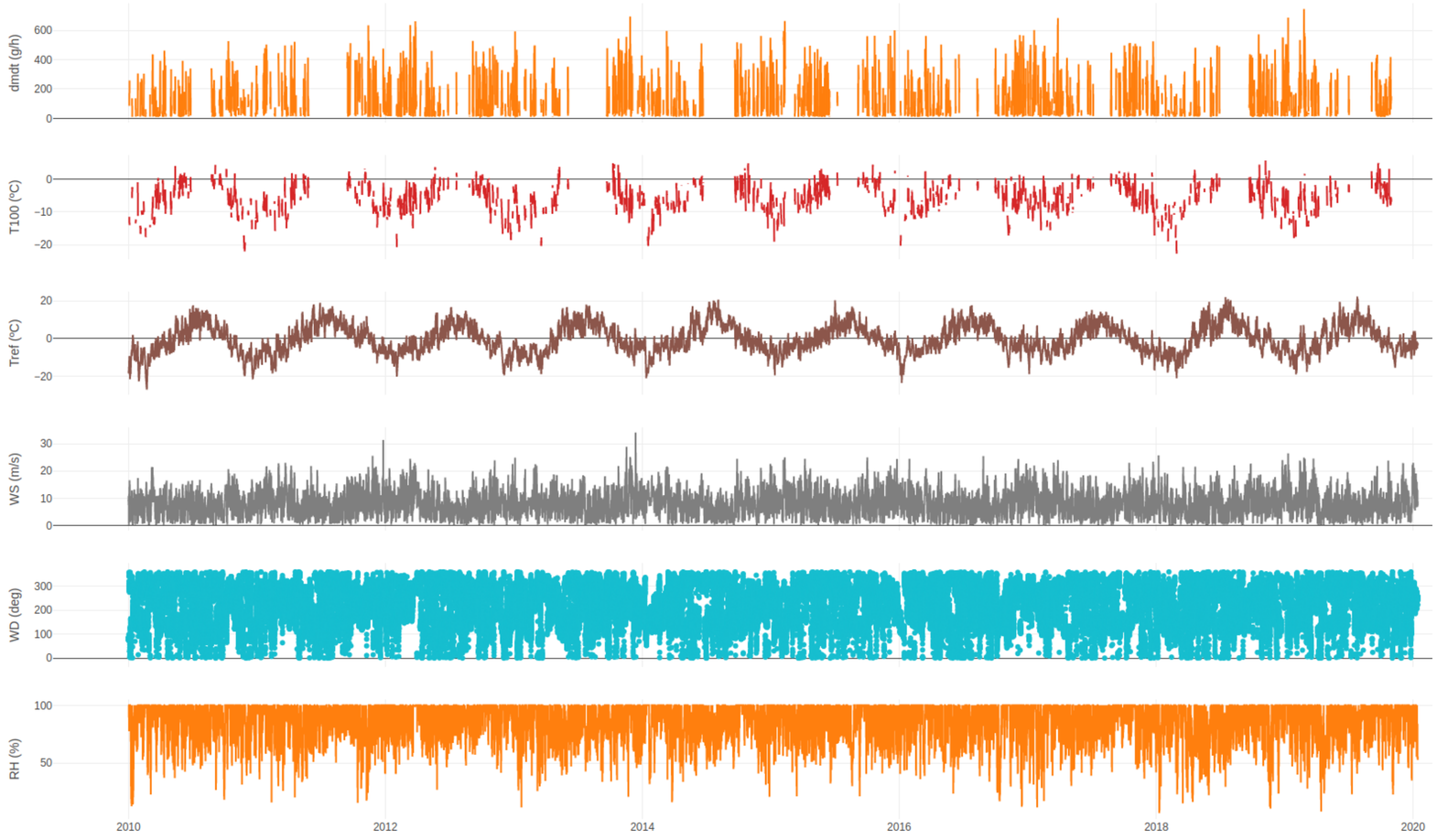
Modelled ICING averaged indicators

Averaged indicators at each turbine locations during icing episodes:

- Wind Speed Histograms
- Wind Direction Roses
- Icing hours per year
- **Other cold climate indicators**



Modelled ICING time-series



Lat=63.450364 Lon=13.065289 Height=100 Timezone=0

T100: Temperature at 100m horizontal resolution
ref: Vortex-SERIES variables at 3km horizontal resolution as climate reference

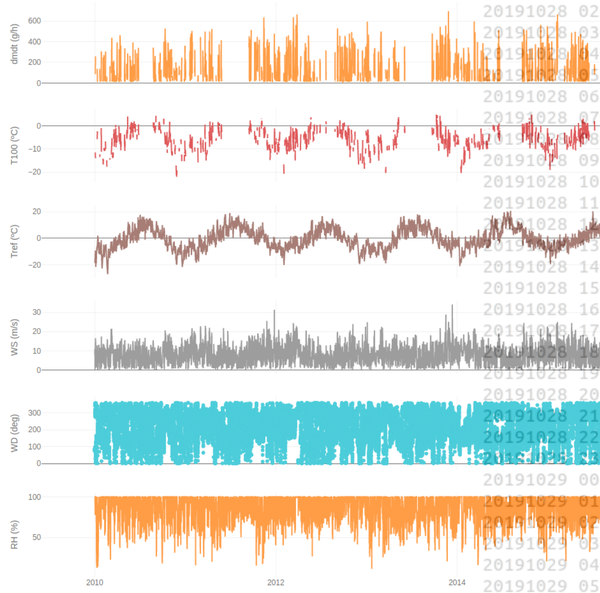
YYYYMMDD HHMM	dmdt(g/h)	T100(C)	Tref(C)	Mref(m/s)	Dref(deg)	RHref(%)
20191028 0000	86.1	-7.2	-4.8	10.6	314	100.0
20191028 0100	95.8	-7.3	-5.0	10.8	311	100.0
20191028 0200	107.3	-7.3	-5.0	10.8	309	100.0
20191028 0300	131.2	-7.2	-5.0	10.7	308	100.0
20191028 0400	165.6	-7.2	-5.2	10.7	305	100.0
20191028 0500	190.3	-7.3	-5.2	11.0	303	100.0
20191028 0600	220.0	-7.3	-5.2	11.3	300	100.0
20191028 0700	266.0	-7.5	-5.2	11.8	297	100.0
20191028 0800	298.9	-7.6	-5.2	12.7	294	100.0
20191028 0900	294.3	-7.6	-5.3	12.8	291	100.0
20191028 1000	268.7	-7.4	-5.2	12.6	291	100.0
20191028 1100	241.0	-6.8	-4.7	12.1	293	100.0
20191028 1200	280.7	-6.5	-4.2	12.1	295	100.0
20191028 1300	309.0	-6.5	-3.9	12.3	297	100.0
20191028 1400	317.8	-6.6	-3.9	12.4	298	100.0
20191028 1500	316.0	-6.6	-4.0	12.5	299	100.0
20191028 1600	297.5	-6.6	-4.2	12.8	304	100.0
20191028 1700	287.5	-6.5	-4.2	13.0	309	100.0
20191028 1800	289.1	-6.6	-4.2	13.0	313	100.0
20191028 1900	263.1	-6.7	-4.2	12.9	318	100.0
20191028 2000	185.9	-6.8	-4.5	12.6	322	100.0
20191028 2100	170.8	-7.0	-4.7	12.4	322	100.0
20191028 2200	207.4	-7.2	-4.8	12.4	324	100.0
20191028 2300	226.5	-7.2	-4.8	12.7	321	100.0
20191029 0000	207.5	-7.2	-4.7	12.8	312	100.0
20191029 0100	200.5	-7.2	-4.5	13.9	309	100.0
20191029 0200	226.4	-7.1	-4.5	14.5	308	100.0
20191029 0300	244.8	-7.0	-4.5	14.6	308	100.0
20191029 0400	303.8	-7.0	-4.5	14.7	306	100.0
20191029 0500	373.8	-7.2	-4.8	14.8	305	100.0
20191029 0600	378.8	-7.2	-4.8	14.9	305	100.0
20191029 0700	363.7	-7.2	-4.7	14.6	305	100.0
20191029 0800	341.7	-7.3	-4.7	14.2	306	100.0
20191029 0900	281.1	-7.3	-4.7	13.6	307	100.0
20191029 1000	202.7	-7.4	-4.5	13.0	311	100.0
20191029 1100	167.3	-7.3	-4.3	12.3	316	100.0
20191029 1200	142.9	-7.2	-4.2	11.3	317	100.0

VORTEX

Modelled ICING time-series

Time-series at each turbine locations allows deeper analyze:

- Service and repair scheduling
- Daily profiles analysis
- Cost of energy evaluation per time slots
- Long term performance optimization
- Flag indicators testing



Lat=63.450364 Lon=13.065289 Height=100 Timezone=0

T100: Temperature at 100m horizontal resolution
ref: Vortex-SERIES variables at 3km horizontal resolution as climate reference

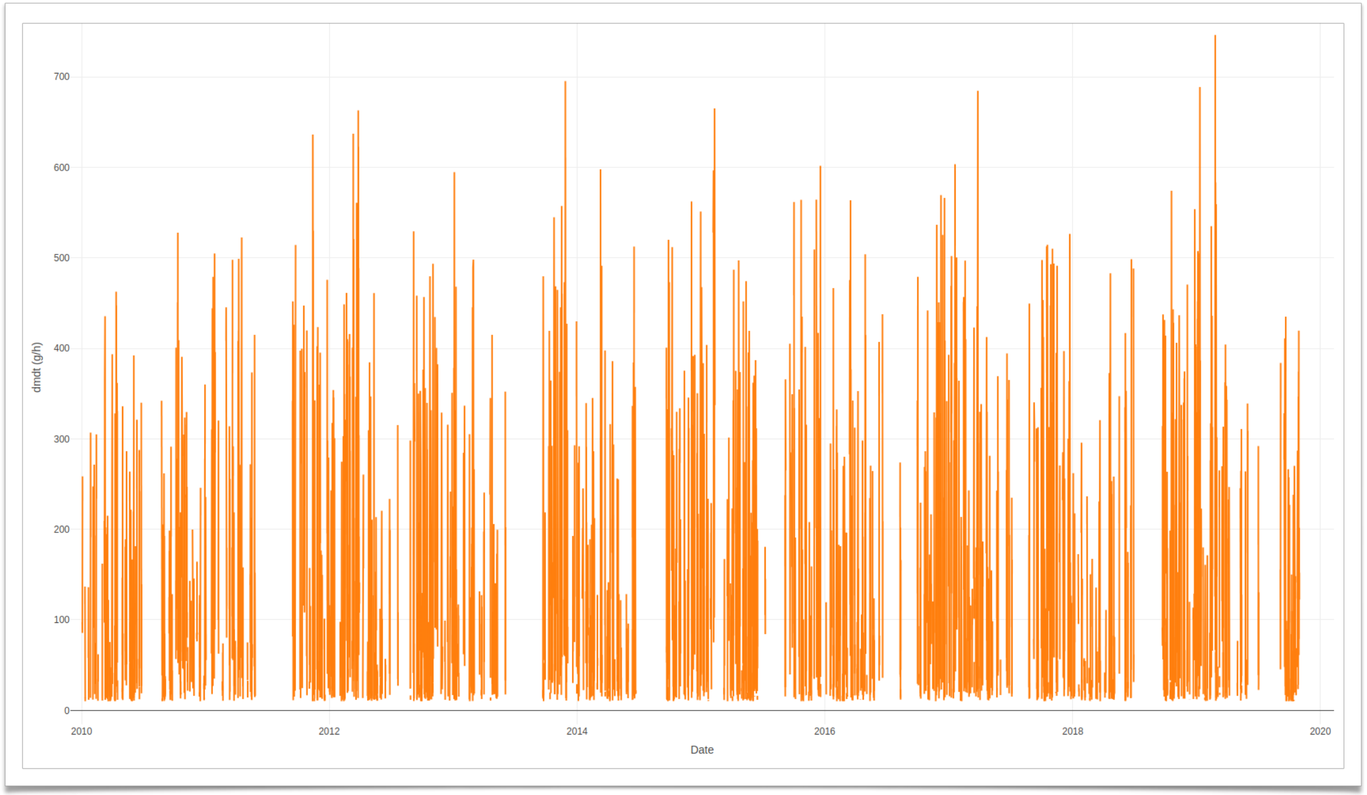
YYYYMMDD HHMM	dmdt(g/h)	T100(C)	Tref(C)	Mref(m/s)	Dref(deg)	RHref(%)
20191028 0000	86.1	-7.2	-4.8	10.6	314	100.0
20191028 0100	95.8	-7.3	-5.0	10.8	311	100.0
20191028 0200	107.3	-7.3	-5.0	10.8	309	100.0
20191028 0300	131.4	-7.2	-5.0	10.7	308	100.0
20191028 0400	165.6	-7.2	-5.1	10.7	305	100.0
20191028 0500	196.3	-7.3	-5.2	11.0	303	100.0
20191028 0600	220.0	-7.3	-5.2	11.3	300	100.0
20191028 0700	266.8	-7.5	-5.2	11.8	297	100.0
20191028 0800	298.6	-7.6	-5.3	12.7	294	100.0
20191028 0900	294.3	-7.4	-5.3	12.8	291	100.0
20191028 1000	268.7	-7.4	-5.2	12.6	291	100.0
20191028 1100	241.0	-6.8	-4.7	12.1	293	100.0
20191028 1200	239.7	-6.5	-4.3	12.1	295	100.0
20191028 1300	305.3	-6.4	-4.1	12.3	297	100.0
20191028 1400	317.8	-6.6	-3.9	12.4	298	100.0
20191028 1500	316.0	-6.6	-4.0	12.5	299	100.0
20191028 1600	297.5	-6.6	-4.2	12.8	304	100.0
20191028 1700	287.7	-6.5	-4.2	13.0	309	100.0
20191028 1800	284.1	-6.6	-4.1	13.0	313	100.0
20191028 1900	285.1	-6.7	-4.2	12.9	318	100.0
20191028 2000	185.9	-6.8	-4.5	12.6	322	100.0
20191028 2100	170.8	-7.0	-4.7	12.4	322	100.0
20191028 2200	207.4	-7.2	-4.7	12.4	324	100.0
20191028 2300	224.1	-7.2	-4.7	12.7	321	100.0
20191029 0000	207.5	-7.2	-4.7	12.8	312	100.0
20191029 0100	200.5	-7.2	-4.5	13.9	309	100.0
20191029 0200	278.8	-7.3	-4.5	14.5	308	100.0
20191029 0300	341.8	-7.3	-4.5	14.6	308	100.0
20191029 0400	303.8	-7.0	-4.3	14.7	306	100.0
20191029 0500	373.8	-7.2	-4.8	14.8	305	100.0
20191029 0600	378.8	-7.2	-4.8	14.9	305	100.0

VORTEX

Modelled ICING time-series

Time-series at each turbine locations allows deeper analyze:

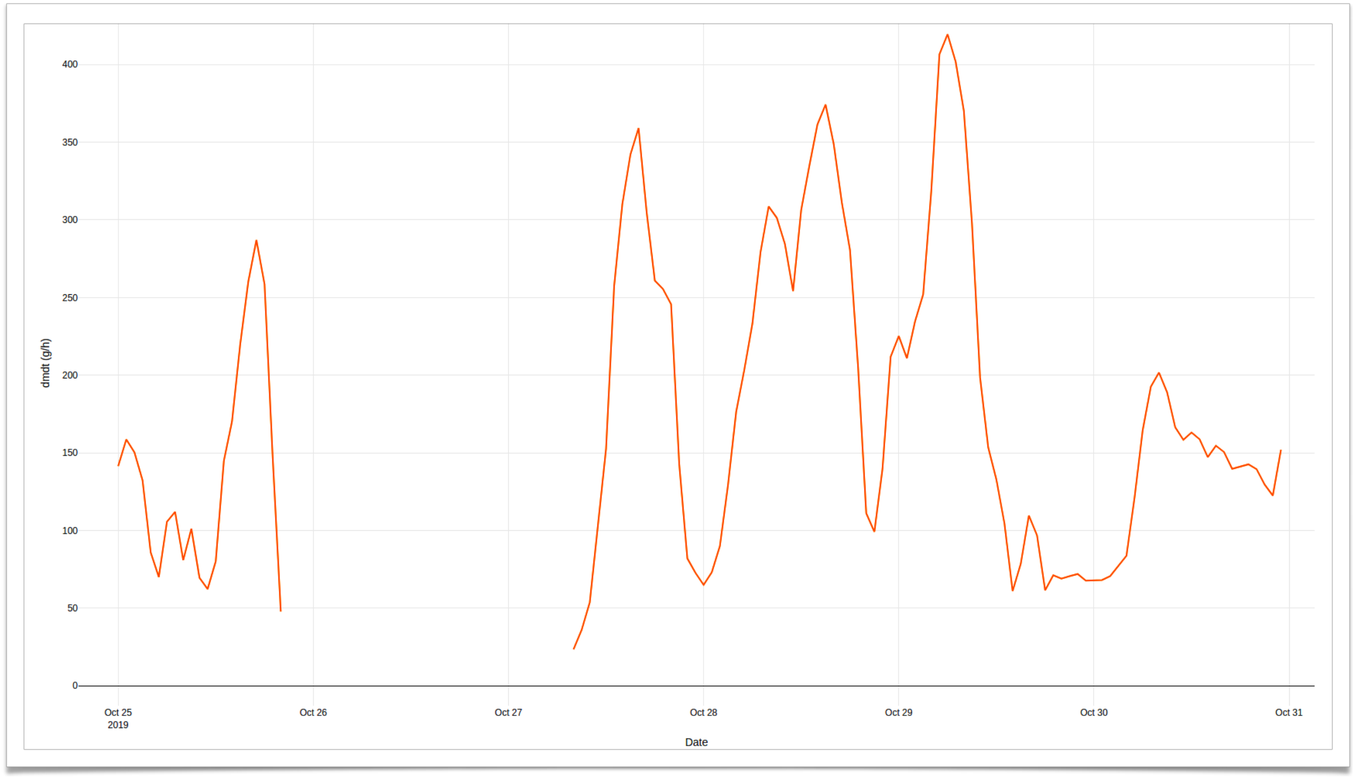
- **Service and repair scheduling**
- Daily profiles analysis
- Cost of energy evaluation per time slots
- Long term performance optimization
- Flag indicators testing



Modelled ICING time-series

Time-series at each turbine locations allows deeper analyze:

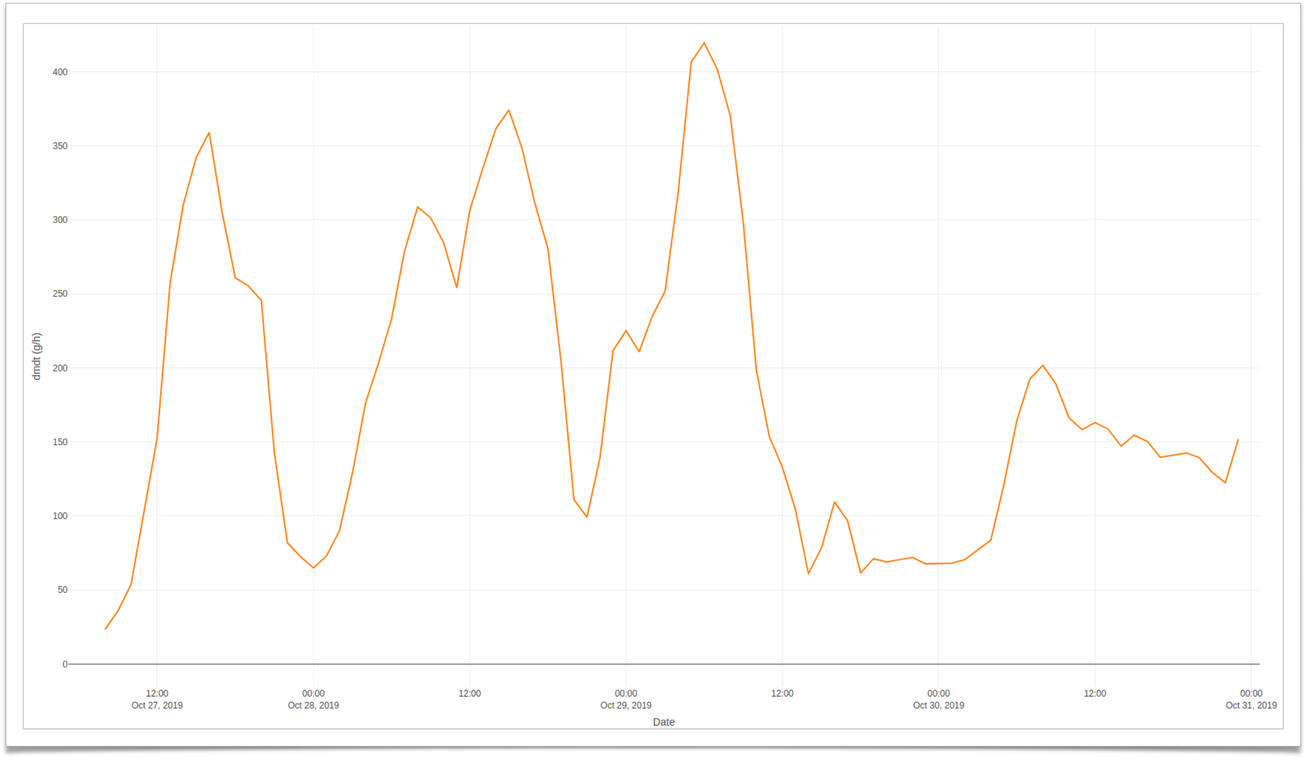
- Service and repair scheduling
- **Daily profiles analysis**
- Cost of energy evaluation per time slots
- Long term performance optimization
- Flag indicators testing



Modelled ICING time-series

Time-series at each turbine locations allows deeper analyze:

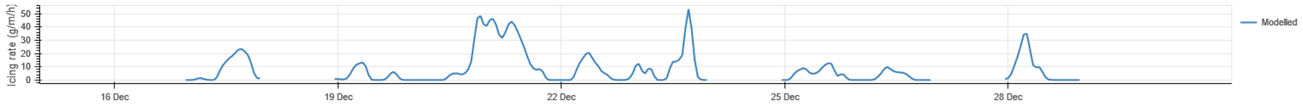
- Service and repair scheduling
- Daily profiles analysis
- **Cost of energy evaluation per time slots**
- Long term performance optimization
- Flag indicators testing

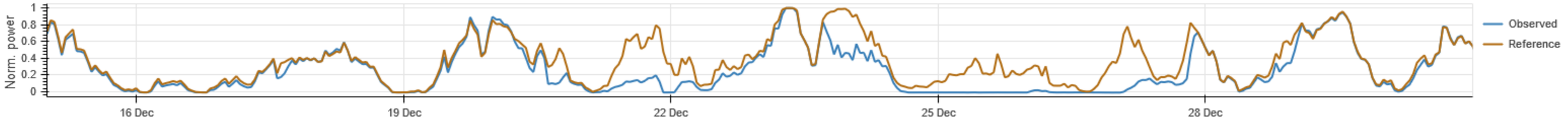


Modelled ICING time-series

Time-series at each turbine locations allows deeper analyze:

- Service and repair scheduling
- Daily profiles analysis
- Cost of energy evaluation per time slots
- **Long term performance optimization**
- Flag indicators testing



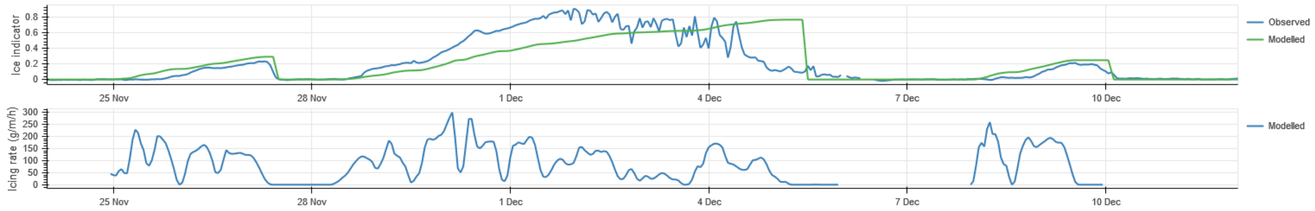


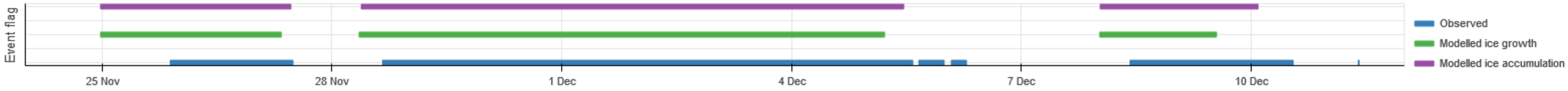
from: Christian Jonsson (ABO Wind), Effective validation for time series icing modelling using operational SCADA data, WinterWind 2019.

Modelled ICING time-series

Time-series at each turbine locations allows deeper analyze:

- Service and repair scheduling
- Daily profiles analysis
- Cost of energy evaluation per time slots
- Long term performance optimization
- **Flag indicators testing**



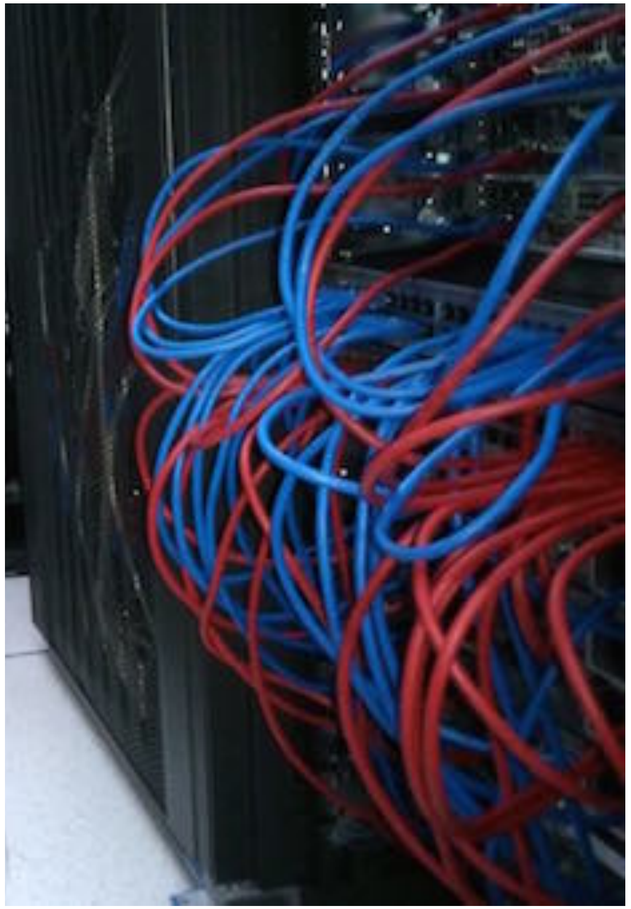


from: Christian Jonsson (ABO Wind), Effective validation for time series icing modelling using operational SCADA data, WinterWind 2019.

Machine Learning

Machine learning (**ML**) is the scientific study of **algorithms** and **statistical models** that computer systems use to perform a specific task without using explicit instructions, relying on patterns and inference instead.
(…)
Machine learning is closely related to **computational statistics**, which focuses on **making predictions** using computers.

(**source**: wikipedia)



Albert Bosch i Mas
albert.bosch@vortexfdc.com

www.vortexfdc.com


VORTEX