On the Modelling Chain for Production Loss Assessment for Wind Turbines in Cold Climates

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Abstract— **This paper presents results from a validation study of the EMD-WRF OD ICING modelling chain for production loss assessment for wind turbines in cold climates. The emphasis has been on validating the modelled seasonal instrumental icing using 29 meteorological masts and 49 seasons. The instrumental icing is based on standard meteorological masts using windPRO. The study showed very good performance of the modelling chain and confirmed the industry threshold limit of 10 g (for a 1-m-high standard cylinder) to be the best match for Sweden, whilst a limit of 50 g provided the overall best result. The IEA Task 19 Ice Class system for translating modelling icing into a production loss was evaluated, and it was found that using meteorological icing is the desired and recommended solution.**

Keywords— ***Wind turbine icing, icing losses, production data, meteorological data, instrumental icing, , windPRO***

I. Introduction

Wind power in cold climate regions has become a natural part of the modern world of wind energy. This is due to the climate of the cold climate sites, which offers an attractive combination of high wind speeds and high air densities, caused by the low temperatures. In addition to the climate, cold climate regions are often remote and sparsely populated, which has motivated the expansion of wind power, especially in Europe [1]. Utilities and other investors have high ambitions on expanding onshore wind power in cold climates [2], and wind installations in the Nordic countries of Sweden, Norway and Finland were set to double from 2020-2025, reaching 28.2 GW installed capacity in 2025 [3]. However, harvesting wind energy in cold climates is not trivial and the wind farms are challenged by several icing related issues during the wintertime, which is challenging the expansion of wind power in cold climates. The industry and operators are getting more experience on topic and risk management, best practices on common and even very special issues have been openly published by, amongst others, the "recommendation documents" by the IEA Task 19 [4].

Common for wind farms located in cold climates is the exposure to atmospheric icing and thereby ice accretion, leading to challenges such as safety issues (ice shedding), blade fatigue and the loss of production. In this study we will focus on the production losses and their assessment as part of the pre-construction yield estimation. Icing has high interannual variability and the response of wind turbines is highly dependent on the wind turbine type. Therefore, it is not easy to estimate the production loss due to icing over a long (typical 20 years) time horizon [5], [6], [7]. However, we have seen that establishing a long-term climatology of a site, can provide a solid foundation of the icing (production loss) assessment and it is also the starting point of most production loss models used today in the wind industry.

Models for production loss assessment due to icing have been established over the past one and half decade and consist in general terms of three overall steps: 1) a site-specific meteorological model configured for icing [8], [9]; 2) modelling of ice accretion on a standard object [10] or simplified wind turbine blade [11]; 3) translation of modelled icing into a production loss, where different approaches are seen in the industry *e.g.*: simplified empirical derived methods [12], machine learning models trained with mast or SCADA data [13], [14] or the use of the IEA ice classification system [15] introduced by the IEA Task 19, see Table I. From modelled or measured meteorological or instrumental icing the yearly percentage can be calculated, which translates as an IEA Ice-Class and into a production loss given as a percentage of the annual energy production (AEP) of the site.

An icing event can be divided into meteorological icing and instrumental icing [16]. Meteorological icing is the period where the meteorological conditions are favourable for ice accretion and thereby ice formation on structures [15]. Instrumental icing is the period during which ice is present and visible on the instrument. It covers the persistence of ice after ice accretion and until the ice starts ablating. Ice might be removed during the persistence period by erosion, sublimation, or ice shedding. The IEA Task 19 has adopted the definitions [15] and created the IEA Ice Classification system [17], as presented in Table I.

TABLE I. IEA Task 19 ice classes [15]. Production loss estimate as percentage of the annual energy production.

IEA Ice-Class	Meteorological icing (% of year)	Instrumental icing (% of year)	Production loss (% of AEP)
5	> 10.0	> 20.0	> 20.0
4	5.0 – 10.0	10.0 – 30.0	10.0 – 25.0
3	3.0 – 5.0	6.0 – 15.0	3.0 – 12.0
2	0.5 – 3.0	1.0 – 9.0	0.5 – 5.0
1	0.0 – 0.5	< 1.5	0.0 – 0.5

Uncertainties are present throughout the explained three-step modelling chain and validation of the entire chain is still a major challenge but a strict necessity for the community. In this study we will focus on the validation of modelled instrumental icing followed by an analysis of the translation from yearly percentage instrumental icing to a production loss (% of AEP), as proposed in Table I by the IEA Task 19.

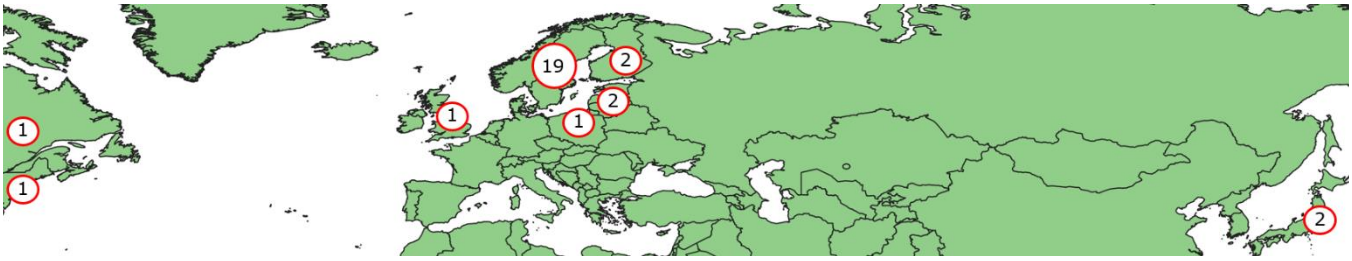

Fig. 1 The total 29 masts cover: 19 masts in Sweden, two in Finland, one in Poland, two in Lithuania, one in the United Kingdom, two in Japan, one in Canada and one in the USA.

II. Methodology and Data

An icing event can be divided into meteorological icing and instrumental icing [16]. Meteorological icing is the period where ice accretion happens due to favourable meteorological conditions and covers the time of active ice formation [15]. Instrumental icing is the period during which ice is present and visible on the instrument. It covers, the persistence of ice after ice accretion and until the ice starts being removed. Ice might be removed during the persistence period by erosion, sublimation, or ice shedding. The IEA Task 19 use the definitions [15] and have defined the IEA Ice Classification system [17] (Table I). As meteorological icing cannot be identified by standard met mast measurements, this validation study will only focus on validating the modelled *instrumental* icing.

A. Approach for Validation of Instrumental Icing

This validation study is based on measurements from 29 meteorological masts (met masts) primarily from Scandinavia, but also, Eastern Europe, North America, the UK, and Japan are represented – please see map in Fig. 1. The met mast data was used to identify instrumental icing by analysing and filtering the measurements of wind direction, wind speeds and temperature.

The met mast data was filtered using windPRO which is the industry leading software suite for design and planning of wind energy projects [18]. Filtering and cleaning met mast data is a necessity when using met mast data in a wind project, and in this study the met mast data was filtered by independent consultants at EMD. The data was loaded in windPRO and manually inspected where the overall mast behavior was screened to search for abnormalities on the individual signals. Typically, abnormalities in the behavior of the wind vane are the starting point of an icing event. Abnormalities of the wind vane will most often coincide with the anemometer(s) being affected by icing - even though there might be some time delay. The anemometer icing can be seen based on periods of double anemometry (i.e., disagreements between pairs of heated and unheated anemometers). If a signal is concluded to be affected by icing it will be disabled and thus flagged as an icing event. If the data set also contains temperature measurements, the signal help support the decision of disabling a signal due to icing or not. When the manual filtering is done, one has a met mast data set filtering for icing and thereby a signal for instrumental icing. The data sets have full lengths varying from one to five seasons and the minimum requirement for data availability during winter seasons was set to a minimum of 80%. The met mast instrumental icing hours was validated against the modelled number of instrumental icing hours on a seasonal basis.

B. Modelling Chain for Production Loss Assessment due to Icing

Icing was modelled for every mast location using EMD's in-house icing model. The model follows the three-step approach described in the introduction with the emphasis on using industry accepted standards *only*. The icing model is driven by an icing configuration of the EMD WRF On-Demand service [19] available within the windPRO software and will be referred to as: EMD-WRF OD ICING. The hindcast atmospheric data are obtained using the Weather Research and Forecasting model (WRF) [20], which is a state-of-the-art atmospheric model and the industry standard for similar models (see e.g. [13] and [21]). The model is run with a spatial resolution of 3x3 km with an hourly temporal resolution and the ERA5 data from ECMWF are used as the global boundary data set. The Thompson microphysics scheme is used for parameterization of the cloud physics and the MYJ scheme for the planetary boundary layer physics [22], [23]. The median volume diameter (MVD) by [24] was used, with a constant droplet concentration (N_c) of 100 cm^{-3} and the liquid water content (LWC) in kg/m^3 [8]. The atmospheric data feeds into the standard cylinder-based model [10], [25], [26] including melting and shedding [27]. The WRF grid point (latitude, longitude) closest to the mast location or site location is used as a default. The grid point holds a certain elevation above sea level and icing was modelled as a default for 15 heights in the vertical direction above ground level (agl.).

The modelled ice load (kg) was used to identify hours of instrumental icing based on the industry standard thresholds of 10 g for a 1-m-high standard cylinder [28]. And similar from the modelled ice accretion rate (g/h), hours of meteorological icing [15] is found using the threshold of 10 g/h for a 1-m-high standard cylinder [26]. Studies have shown that the industry standard thresholds might not fit all icing conditions/regions [13] and as the in-house experiences have also indicated that the IEA classification system seems to overestimate the losses when using instrumental icing as input, a sensitivity study for the thresholds (limits) of instrumental icing is of interest for the modelling chain.

The final step of EMD's modelling chain, is an estimate of the expected production loss of a site which is found by using the IEA Ice Classification system seen in Table I.

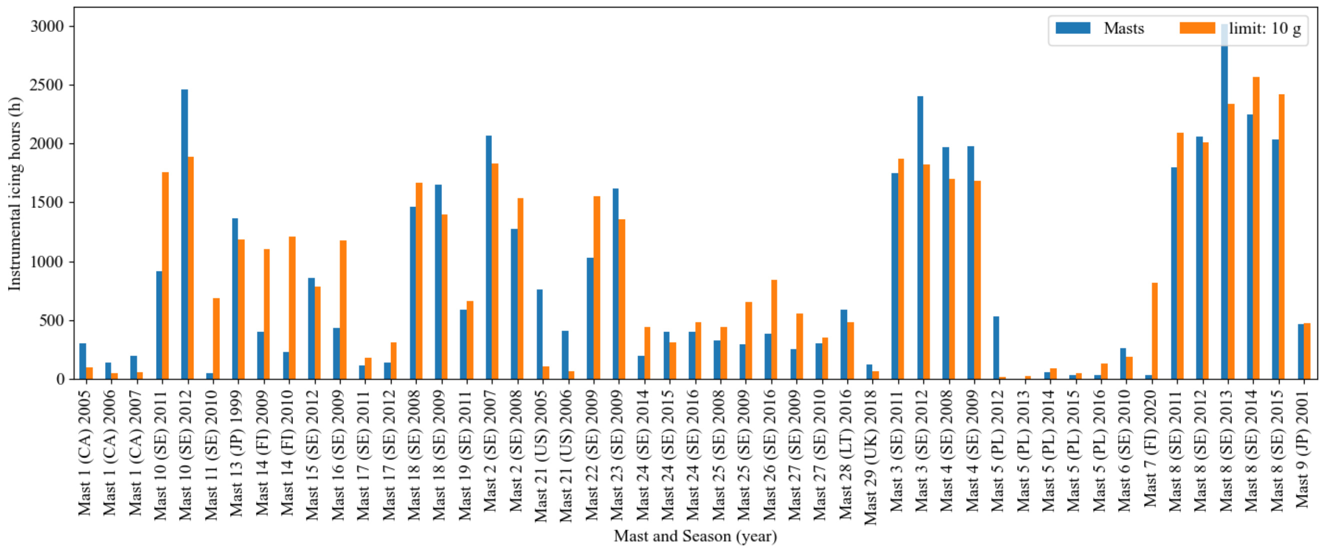

Fig. 2 Mean seasonal instrumental icing hours as a function of the mast and season. The blue bars are the met mast instrumental icing and orange is the model instrumental icing using the industry standard limit of 10 g.

C. Approach for Validation of production losses using SCADA Records

SCADA records from 6 windfarms in Sweden (four wind farms) and Norway (two wind farms) were used. The SCADA data was in form of 10 min mean values and alarm codes (error signals). The so-called "T19 Ice Loss Method" published by the IEA Task 19 [29], was used to assess the production losses due to icing from the SCADA records. The T19 Ice Loss Method (T19 method) was chosen as it serves as a state-of-the-art in the wind turbine icing community. The T19 method is published as an open-source Python code by the IEA Task 19. The code was used as published but modified to make it suitable for running multiply wind farms in an automated way for our specific purpose.

SCADA data from different providers was used and before running the T19 method the data was pre-processed and filtered. The data was preprocessed to only include 10 min mean values of the specific signals of wind speed, nacelle temperature, ambient temperature, wind turbine status and wind turbine state. From the documentation of the T19 method, the difference between status and state and how the user should address them was not straight forward. However - in this study we see State as; normal operation or not normal operation, meaning a flag to exclude the data. And we set the State and Status to "0" when the data must be excluded. The data was also filtered, using the error codes and their explanation from the dataset. Getting the full explanation of the SCADA error codes was a challenge, but for some of the sites the data providers helped providing a list of error-codes that are typical for icing events and should thus remain in the dataset. After testing, we ended up with two options for error signal filtering: 1) all data is allowed regardless of the error code and 2) use a list of error codes that are allowed as they are deemed to be related to icing - we used filtering option 2 when possible. Furthermore, derated scatter was also filtered out. Table II summaries the use of filter options for the sites, the country and number of seasons available for the study.

TABLE II. SITES USED IN STUDY, NUMBER OF SEASONS AVAILABLE AND THE TYPE OF FILTERING USED.

Name	**Country**	**Seasons**	**Filter**
Site 1	(SE)	2	2
Site 2	(SE)	3	1
Site 3	(SE)	2	1
Site 4	(SE)	3	1
Site 5	(NO)	2	2
Site 6	(NO)	2	2

From running the T19 method we get a total production loss due to icing for every wind turbine of the sites. The losses can be extracted as mean during the period run and as timeseries. The total production loss is divided into losses during operation and losses due to stops and/or shut down. The final validation data set was made by creating multidimensional data sets for each site by merging; 1) EMD-WRF OD ICING (raw WRF outputs and timeseries of modelled icing in 15 heights agl.) and the results from the T19 method. As the T19 method was run on a wind turbine level, each wind turbine holds a location (latitude, longitude), an elevation and a hub height. To compare the modelled results with the T19 method results, the modelled results were downscaled to the wind turbine hub height above sea level.

III. RESULTS AND DISCUSSION

A. Validation of Modelled Instrumental Icing

Instrumental icing from the met masts was compared to the modelled instrumental icing using the mean seasonal value. The modelled icing was interpolated to the height of the measurements and six different limits: 0.0 g, 10 g, 50 g, 100 g, 250 g and 500 g, to identify instrumental icing in the modelled ice load. As mentioned, the used industry limit is 10 g (for a 1-m-high standard cylinder). Fig. 2 shows mast instrumental icing and modelled instrumental icing for all 49 seasons in the industry limit of 10 g which indicates an overall good consistency between the met mast instrumental icing and the modelled instrumental icing. Fig. 3 shows the variation in correlation of the met mast instrumental icing to the modelled instrumental icing using the six limits. Inspecting the plots of Fig. 3, the limits of 10 g and 50 g seem to give the best positive correlation.

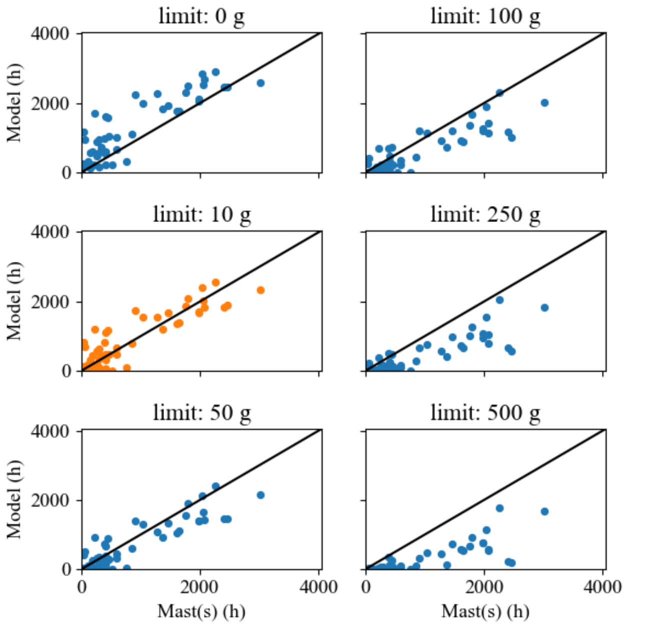

Fig. 3 Relationship between instrumental from the met masts and the model using six different limits. The industry standard limit of 10 g is highlighted in orange.

To quantify the linear correlation between the two datasets (masts and model), the Pearson correlation coefficient [30] was evaluated (Fig. 4) to find the best score between the met masts and the six individual model data sets. Fig. 4 presents the ranked correlation scores of the analysis and indicates that the limit of 50 g results in an overall best score against all used masts.

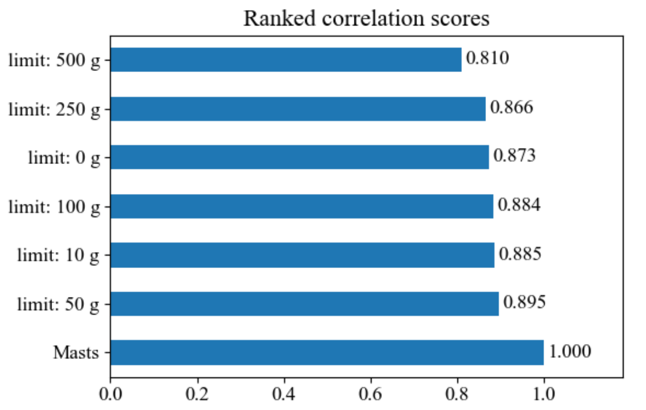

Fig. 4 Pearson correlation coefficient (r) scores of the two datasets (masts and model).

As 19 out of the 29 mats were in Sweden, the linear correlation analysis was repeated for the Swedish masts only. Here the best correlation was found in the industry standard of 10 g, but the values of 50 g and even 0 g, *i.e.*, using all hours with values above 0 g, would be reasonable choices for Sweden. However, we can conclude from Fig. 4 and Fig. 5 that the limits of 10 g and 50 g provide good general results and that the limits > 100 g does not correlate with the real met mast instrumental icing.

In the next section, we analyse production losses from SCADA data from six windfarms using the T19 method. The SCADA losses will be compared to modelled losses, obtained using modelled instrumental icing and the IEA Ice Classes, see Table I.

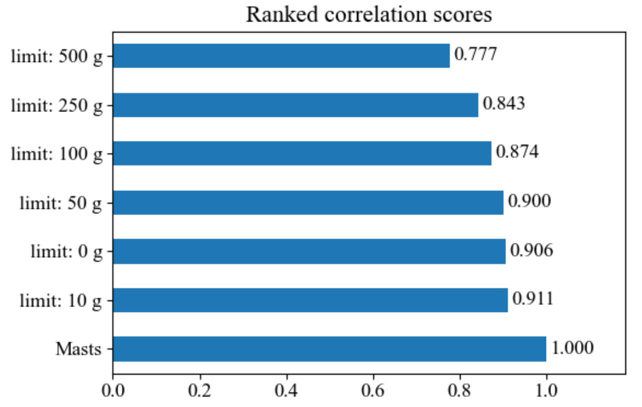

Fig. 5 Pearson correlation coefficient (r) for Swedish masts only.

B. Verification of Modelled Production Losses due to icing

Table II shows that four out of the five sites are in Sweden. Based on this, the modelled instrumental icing is obtained using the limit of 10 g, as was shown in Fig. 5, to give the best correlation score for Sweden. Modelled meteorological icing is obtained using the industrial standard of 10 g/h [26]. Fig. 6 shows a comparison of the normalised SCADA derived losses using the T19 method and the normalised modelled losses using the IEA ice class system, Table I. The losses are normalised by the highest SCADA loss (site 4) and modelled IEA losses using modelled instrumental icing and from using modelled meteorological icing are shown. Fig. 6 shows that using instrumental icing clearly overestimates the losses for five out of six sites, whereas losses found from using modelled meteorological icing and the industry limit seem to match the SCADA losses quite well.

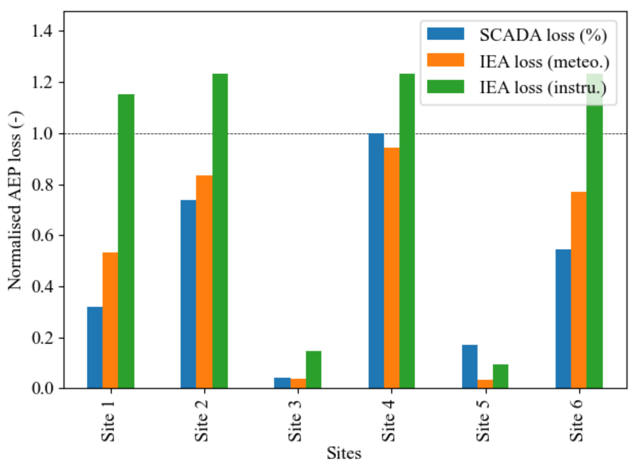

Fig. 6. Comparison of SCADA losses, blue bars and modelled losses using the IEA Ice class system, Table I and industry limits of 10 g for instrumental icing (instru.), green bars and 10 g/h for meteorological icing (meteo.), orange bars.

It is surprising that the IEA losses from instrumental icing overestimates the SCADA losses to the extent as seen in Fig. 6, whilst the IEA losses from meteorological icing seem reasonable. To understand the translation of instrumental icing to AEP losses using Table I, we have repeated the production loss calculation using more thresholds. We have used the results found in Fig. 4 and Fig. 5, which showed that the best limits were: 10 g, 50 g and 100 g for the 1-m-high standard cylinder and that the worst limit was 500 g. The results of the comparison are shown in Fig. 7 for the six sites. The figure shows, that none of the three best limits (10 g, 50 g and 100 g) provide satisfying results, whilst the worst of 500 g provides the best results.

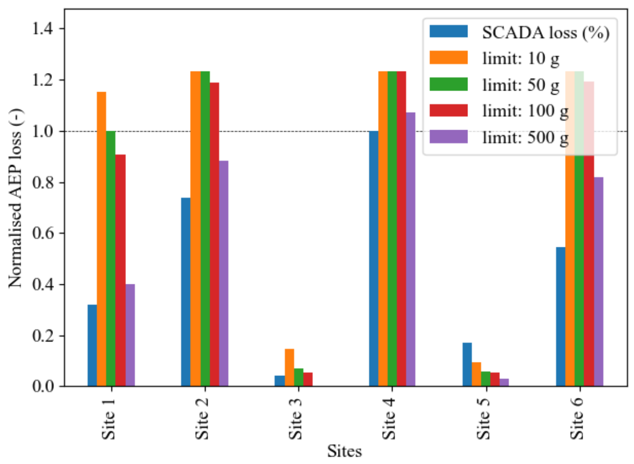

Fig. 7 Comparison of SCADA losses and modelled losses using the three best limits (10 g, 50 g and 100 g) and the worst limit (500 g).

To understand the results from Fig. 6 and 7, we are going back to results from the instrumental icing on met masts in Fig. 3. Fig. 3 shows that using the limit of 500 g gives a very poor correlation. It is contradictory that the worst correlation on the measurements gives the best results for the AEP loss (Fig. 7). This is most likely due to an inaccuracy of the IEA conversion table (Table I). We have shown in this study that the used modelling chain can predict instrumental icing reasonably. We have also shown that the AEP loss seems too high when using the IEA conversion table on instrumental icing. From instrumental icing, we expect ice to be present on a surface/instrument, but wind turbines can operate with ice on the blades and might be better at it than assumed. Furthermore, we have validated instrumental icing on anemometers but icing on a wind turbine is likely very different, especially the melting and shedding processes. This leads to the conclusion that instrumental icing does not seem to be the best proxy for estimating wind turbine production losses.

Meteorological icing is a measure that ice accretion is happening, it is not dependent on melting or shedding processes and it is less dependent on the shape of the surface. It was shown in Fig. 2 – 4 that we can model instrumental icing. Based on this fact we conclude that our model is also getting meteorological icing correct, as this is the basis for instrumental icing. In contrast to the instrumental icing, we see that the AEP loss translation between EMD-WRF OD icing compared with SCADA losses is much better using the meteorological icing on the IEA conversion table (Table I).

Finally, a 1:1 comparison of the normalised SCADA losses and the normalised model losses is shown in Fig. 8. The figure shows a general good behaviour of the model on the used six sites.

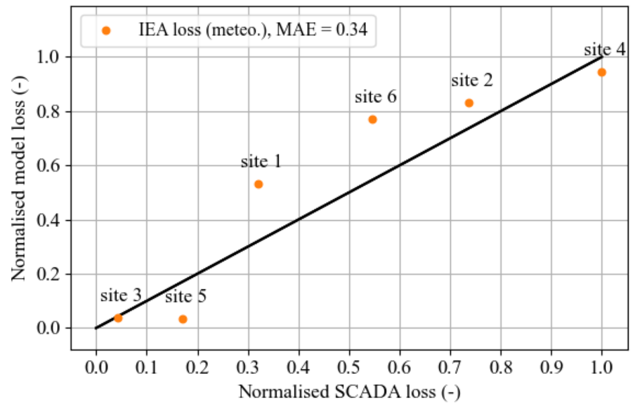

Fig. 8 Comparison, 1:1 plot of normalised SCADA losses and normlalised modelled losses for the used six sites. The mean absolute error (MAE) between the normalised modelled losses to the best fit of the normalised SCADA was found to be 0.34

IV. CONCLUSIONS

From the validation study of the modelled instrumental icing, it can be concluded based on the data from the 29 met masts and the 49 seasons, that a threshold of 50 g provides the best correlation to the met mast instrumental icing (Fig. 4). However, using only the 19 Swedish met masts the industry standard threshold of 10 g for the 1-m-high standard cylinder gave the best correlation (Fig. 5). Based on this validation we conclude that EMD-WRF OD ICING modelling chain can model the seasonal instrumental icing very well.

From the validation of production losses, we can conclude that using the EMD-WRF OD ICING modelling chain and IEA Ice Class system, we are able to model site production losses (% AEP). Using the standard IEA Ice Class system with instrumental icing seems to give too conservative icing loss estimates, whilst using meteorological icing at the standard rate of 10 g/h gives reasonably good consistency. As turbines are reacting very differently to icing events it is imperative to include the manufacturer in the discussions of potential icing losses.

We recommend estimating production losses with meteorological icing as proxy. To aid the wind industry in assessing icing losses during preconstruction, this data service is now available within EMD's windPRO software and as a standalone web-based API. For future analysis on the topic, we aim to include more met masts and a higher geographical spread as they become available, alongside with additional SCADA records.

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