Updates on research activities of wet snowfalls in Italy: snow load map reanalysis, forecasting and monitoring

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Abstract— **Wet snowfalls in Italy are still one of the main causes of power failures for both transmission and distribution energy networks. The resilience plans of electrical operators must consider this extreme weather threat and find solutions to mitigate its effect through either the strengthening of the networks or by active solutions. RSE is involved through three main research lines: a historical reconstruction of wet snow loads through the MEteorological Reanalysis Italian DAtaset (MERIDA), a forecast system Wet-snow Overload aLert and Forecasting (WOLF) for the identification of conditions favorable to the formation of wet snow sleeves on the overhead conductors and finally monitoring systems of sleeve formations on test spans. For the first activity, the reanalysis reconstruction of the main snow events of the last 21 years (2000-2020) combined with the ice accretion model for wet snow (Makkonen model, ISO12494:2017), made it possible to update the wet snow load map contained in the National Normative Aspects for Italy (NNA, 50341-2-13). Moving on to the second activity, the forecast system WOLF has recently been updated with additional criteria for the identification of wet snowfall based on the use of vertical thermal gradients obtained from the WRF-ARW Numerical Weather Prediction (NWP) model. Furthermore, the forecast of freezing rain conditions has been introduced and integrated into the WOLF alert system. Finally, as a third activity, in addition to the Wet-snow Ice Laboratory Detection station (WILD) dedicated to the measurement of the sleeve accretion on High Voltage (HV) overhead conductors and to the field test of ice-phobic coatings, WILD 2.0 stations have been installed in different climatic areas of Italy where major electrical faults have occurred. The experimental spans, 75 m long, provide measurements of the snow sleeve load on different Medium Voltage (MV) diameter conductors with sections between 16 mm^2 and 150 mm^2, together with the main weather parameters involved during the snow accretion. WILD 2.0 have been equipped with ice-free meteorological sensors, cameras on the towers, load cells, IoT on conductors and aerial cables for monitoring the sleeve load and the tilt of test span.**

Keywords— ***wet snow, reanalysis, NWP modelling, snow load maps, forecasting systems, monitoring snow accretion***

I. Introduction

This work fits into the indications that emerged from the Working Group "Resilience of the electricity system" set up by the National Regulatory Authority for Energy, Networks and Environment (ARERA) which highlight how, in the last 20 years in Italy, there has been a significant increase in long-term outages mainly due to wide and particularly strong meteorological events as the wet snowfall.

RSE has been involved by ARERA through three main research activities:

- a historical reconstruction of wet snow loads through the MEteorological Reanalysis Italian DAtaset (MERIDA [1]) to update the 50-year return time wet-snow load maps contained in the National Normative Aspects [2] for Italy (Section II).
- A detailed forecast system Wet-snow Overload aLert and Forecasting (WOLF [3] [4]) for the identification of conditions favorable to the formation of wet snow sleeves on the HV and MV overhead conductors (Section III).
- The design and installation of monitoring systems of snow sleeve formations on test and real spans named WILD 2.0 (Wet-snow Ice Laboratory Detection) located in different climatic areas of Italy where major electrical faults were occurred (Section IV).

Fig. 1 Nice wet snow sleeve formation on overhead lines (OHL) in the Dolomite region. 3 January 2022.

II. Historical reconstruction of wet snow loads through the MEteorological Reanalysis Italian DAtaset (MERIDA)

This activity has been aimed at revising the sleeve thickness and load values envisaged by the CEI EN 50341-2-13 Standard (National Normative Annex - NNA) with reference to wet snowfalls. The methodology has allowed the reconstruction of snow events in the last 21 years (2000-2020) with a spatial resolution of 4 km*4 km and an hourly time step by using MERIDA and the Makkonen model for wet snowfall [5] [6]. Subsequently, a probabilistic estimate of the expected sleeve mass values for a return time of 50-year has been obtained through the Block Maxima method in Generalized Extreme Value theory (GEV [7] [8] [9]).

A. MERIDA

The historical meteorological dataset consists of a dynamical downscaling of the ERA5 global reanalysis fields using the mesoscale model WRF-ARW. The computational domain is defined using two grids with a spatial resolution of 21 km and 7 km respectively, with the internal grid centered over Italy as shown in Fig.2. For the reconstruction of wet snowfall, the numerical simulations are carried out for the period 2000-2020.

An Optimal Interpolation (OI) technique has been applied to the WRF model output fields of 2-m temperature and precipitation starting from validated stations data of the Regional Agencies for Environmental Protection (ARPA). In this process, 2-m temperature and precipitation model outputs are first downscaled from 7 km to a regular 4 km resolution grid with a bilinear remapping and, secondly, the OI technique is applied to the downscaled fields. For 2-m temperature the orographic differences between grid points at the two different resolutions are taken into account considering the model lapse rate. For a more detailed description of the post-processing of WRF model outputs of 2-m temperature and precipitation and of OI technique see [1].

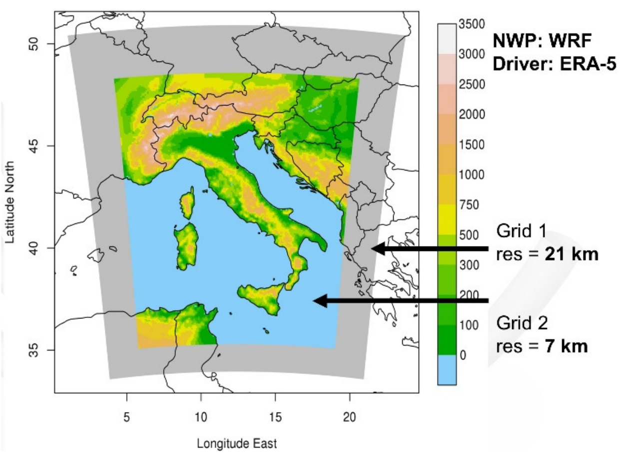

Fig. 2 Computational domain of WRF model over Italy. Driver model: ERA5.

The so-called MERIDA consists of OI-based 2m-temperature and precipitation, while the wind intensity has been derived on the same 4 km grid through bilinear interpolation of 7 km WRF wind field. MERIDA constitutes the reference meteorological reanalysis at national level for the reconstruction of the wet snowfall and the estimation of their return times through GEV analysis.

B. The wet snow accretion model

The wet snow accretion model used in this study follows the ISO 12494 standard. Wet snow conditions not interrupted by rain create the conditions for the growth of a cylindrical sleeve on the conductors, as shown in Fig.3.

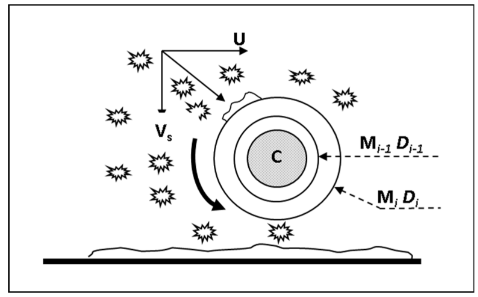

Fig. 3 Representation of cylindrical and conservative snow sleeve accretion on overhead conductor during a wet snowfall.

The equation used to reconstruct the sleeve with the Makkonen model ISO12494:2017 fed with data from the meteorological reanalysis are the following:

$$\rho_s = 300 + 20 * V \quad (1)$$

$$\alpha_2 = 1/\sqrt{V} \quad (2)$$

$$I = \alpha_2 I_0 \sqrt{1 + \left(\frac{V}{V_s}\right)^2} \quad (3)$$

$$M_i = M_{i-1} + I_i D_{i-1} \Delta t \quad (4)$$

$$D_i = \left[\frac{4(M_i - M_{i-1})}{\pi \rho_s} + D_{i-1}^2\right]^{1/2} \quad (5)$$

where:

ρ_s is the density of snow sleeve accreted on conductors

α_2 is the sticking coefficient of snowflakes on cable

V is the wind intensity (m/s)

V_s is the vertical velocity of snowflakes (V_s=1.7 m/s)

I_0 is the water equivalent of the snowfall intensity (mm/h)

I is the total precipitation flux on the conductor (mm/h)

M_i is the increased mass of snow sleeve per hour (kg/m)

I_i is the precipitation flux (mm/h) at the time *i*

D_i is the snow sleeve diameter per hour (m)

Considering the typical meteorological conditions of a wet snowfall i.e., 2m-air temperature between -1°C and +1.5°C and wet bulb temperature above -1°C, the sleeve model reconstructs the event through the hourly data coming from MERIDA. An example of the reconstruction of the snow sleeve mass with MERIDA and Makkonen model is available in Fig.4 for the extreme wet snowfall of January 2017. During the event reported in Fig.4, the Italian TSO reported the formation of a snow sleeve with a mass close to 15 kg/m in the areas where the simulation indicates values between 10 kg/m and 15 kg/m.

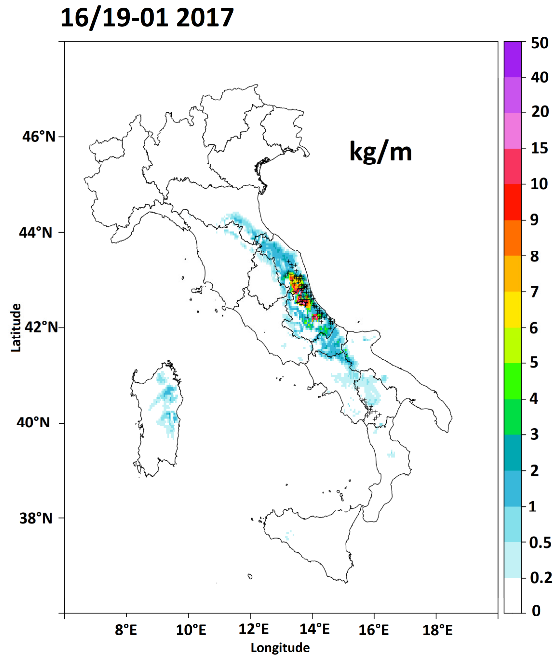

Fig. 4 Reanalysis reconstruction of sleeve mass (kg/m) on ACSR585mm^2 conductor for the exceptional wet snowfall occurred in January 2017. The + symbols indicate the location of prolonged blackouts.

C. Update of NNA wet snow maps

The update of NNA consists of a new maps of the 50-year return time of sleeve thicknesses and snow overload for overhead power line conductors that takes into account the intense wet snow events that occurred in the last twenty years as required by ARERA and shared within the Technical Committee 11/7 of the Italian Electrotechnical Committee (CEI).

The current standard NNA 50341-2-13:2017 assumes the division of the national territory into two macro-zones for wet snow conditions (Fig.5, on the left). The 20-years historical reconstruction of wet snowfall by using MERIDA reanalysis dataset has allowed the identification of four similar climatological areas for wet snowfall in Italy (Fig.5, on the right).

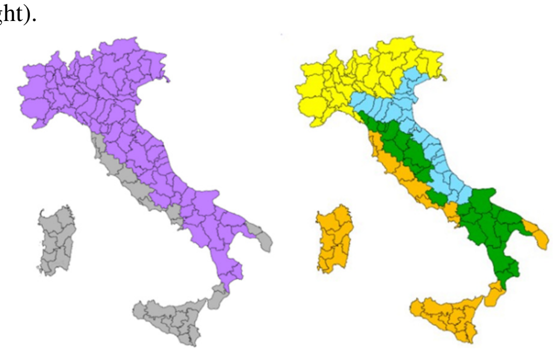

Fig. 5 Geographical distribution of the Italian territory in 2 macro-areas for the current standard CEI EN 50341-2-13:2017 (on the left) and the new proposal subdivision for similar wet-snow climatic zones (on the right).

The proposed methodology by RSE made it possible to obtain the expected thickness values on the MERIDA 4km*4km grid with a return time of 50-years using Block Maxima method. Subsequently, the expected values have been aggregated for each of the four climatic zones. Using the same criterion present in the standard, a relationship between thickness (mm) and the altitude (m.a.s.l.) of the grid points has been obtained for each of these zones. In this way, once the altitude and the area are known, it is possible to obtain the radial thickness value for each type of conductor. The results and the comparison with the previous values of sleeve thickness and load are available in the next figures, respectively Fig.6 and Fig.7.

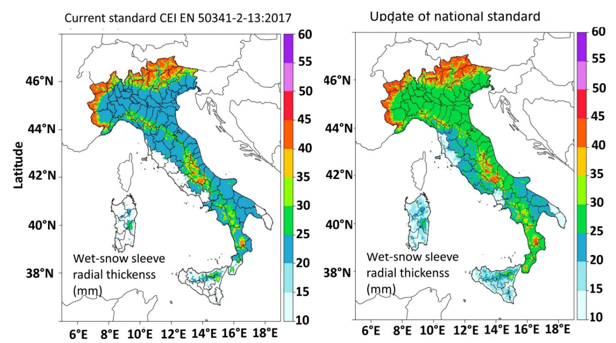

Fig. 6 Expected values of radial thickness (mm) at 50-years return time for ACSR-585 mm^2 conductor in the current standard (on the left) and in its update (on the right).

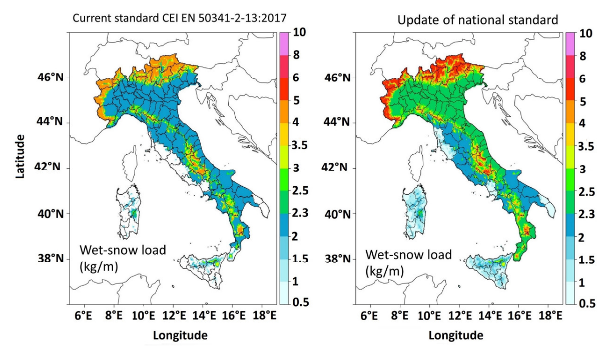

Fig. 7 Expected values of wet snow load (kg/m) at 50-years return time for ACSR-585 mm^2 conductor in the current standard (on the left) and in its update (on the right).

In general, the new maps tend to describe in a more adequate way the wet snow events on the whole national territory with extension of the snow phenomenon even at the lowest altitudes and with a general increase in the thickness values (between 2% and 13%), depending on the definition of the new areas and altitude ranges.

III. Updates of the Forecasting and Alert System WOLF

WOLF aims to forecast the wet-snow conditions favorable for ice/snow accretion on existing OHL in Italy. The algorithm provides an estimation of the ice-load and the ice-sleeve thickness on conductors. A thermal model simulates the anti-icing current (AI) necessary to maintain the cables free of snow in the expected weather conditions. Every day, the forecasted ice-load hazard levels have been plotted on a WEB-

GIS map, easily accessible to the power lines' operators (Fig.8).

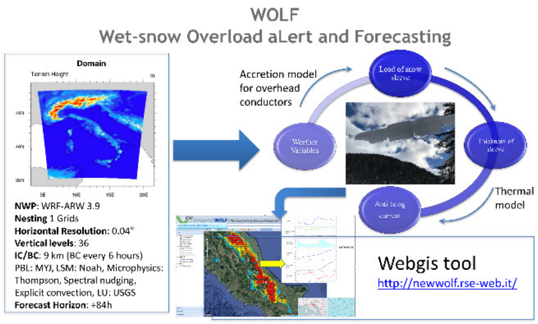

Fig. 8 WOLF forecast system operating at RSE. Driver model: ECMWF-IFS h.res. 9km. Local area model: WRF-ARW h.res. 4km. Forecast horizon: +84h. Accretion model: Makkonen ISO12494:2017; Thermal model for anti-icing current: Schurig & Frick [12].

The forecast system WOLF has recently been updated with additional criteria to evaluate whether it is possible to use alternative methods for the determination of wet snow in addition to the already used thermal window method. The well-known *Area Method* [13] has been widely used to discriminate cases of precipitation of the *ice pellets* or *freezing rain* based on the vertical thermal profile from a meteorological model. This method also discriminates against other types of precipitation, such as simple *snowfall*, *snow* mixed with *rain* and *rain*. The methodology is based on the calculation of *positive* (PA) or *negative* (NA) areas generated by the vertical thermal profile of a meteorological model around the 0°C isotherm. Depending on the value of the areas along the vertical profile, the different types of precipitation indicated in Fig.9 are determined.

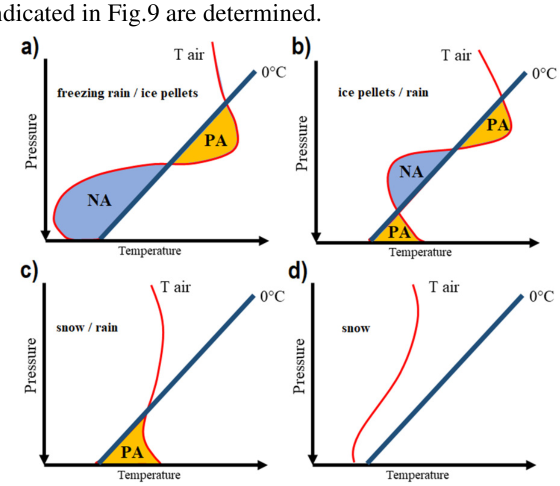

Fig. 9 Schematic diagram showing typical vertical temperature profiles leading to (a) freezing rain or ice pellets, (b) ice pellets or rain, (c) snow or rain, and (d) snow. Positive (PA) and negative (NA) areas are indicated. The figure is inspired by the study of Bourgouin [13].

The method has been implemented starting from the outputs of the WRF-ARW meteorological model at 4 km spatial resolution, initialized with the ECMWF boundary conditions. Maps are produced for the prediction of the main hydrometeors mentioned above. We report a case study related to a significant episode of *freezing rain* that took place in Northern Italy between the evening of 10 and the morning of 11 December 2017 affecting lower Piedmont, Liguria, and Emilia-Romagna. Maps relating to the 3 most critical episodes for this event are reported in Fig.10.

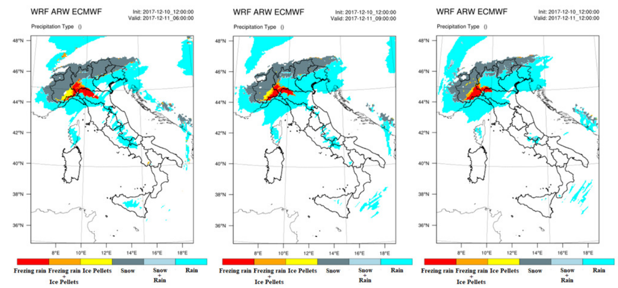

Fig. 10 Precipitation type maps obtained with the area method from the outputs of the WRF-ECMWF model and for the case study of 10-11 December 2017.

The red areas are those where *freezing rain* has been predicted, the yellow one those related to *ice pellet* and in orange those related to a mix between the two hydrometeors. Finally, gray and blue areas are associated to snow and rain respectively. The *freezing rain* areas identified by the *area method* correspond to those where news and articles report actual conditions of frost occurred, with important repercussions on rail and motorway road traffic and disruptions to the electricity system, especially on the distribution network.

In the following, a series of case studies are examined to assess whether the *area method* above mentioned can give added value to the prediction of *wet snow*. The cases examined are different and have been recorded at the WILD station of Vinadio (44°18′N 7°10′E), in Piedmont region (Table I), both with wet and dry snow conditions to assess whether the method can be used to discriminate between the two snow types. The type of precipitation has been obtained through the dimensional distribution of the snowflakes measured by the disdrometer, snow density measurements and through images recorded by the web cameras.

TABLE I. SNOW EVENTS AT WILD STATION WITH TYPE CLASSIFICATION

Start date	End date	Snow type
07/02/2016 - 00:30	07/02/2016 - 13:30	wet
27/02/2016 - 16:30	29/02/2016 - 09:00	wet
08/02/2017 - 09:00	10/02/2017 - 10:00	wet
13/02/2017 - 22:30	14/02/2017 - 05:00	wet
05/02/2018 - 03.00	05/02/2018 - 23.00	dry
28/02/2018 - 13:30	02/03/2018 - 08:00	dry
11/04/2018 - 16:45	12/04/2018 - 16:30	wet
31/01/2019 - 18:30	02/02/2019 - 09:45	dry
01/12/2019 - 04:00	01/12/2019 - 21:00	wet

For the events examined, only the cases with a non-zero "*Positive Area (PA)*" values and without "*Negative Area*" were considered. These are the cases in which you could observe snow, snow mixed with rain or rain depending on the positive area values indicated in (6) [13]

$$
\begin{array}{ll}
0 \le PA < 5.6 \text{ J kg}^{-1} & \textit{Snow} \\
5.6 < PA \le 13.2 \text{ J kg}^{-1} & \textit{Rain and Snow} \\
PA > 13.2 \text{ J kg}^{-1} & \textit{Rain}
\end{array} \qquad (6)
$$

Fig.11 shows the PA values related to the events shown in Table I. The colored bands indicate the range of variability of PA that represent the categories mentioned above (dark grey, snow; light gray, snow mixed with rain; blue, rain). The values of PA on Vinadio were not considered exactly on the point of its correct geographical coordinates, but on the closest grid point with the most similar altitude. The real point, in fact, shows a remarkable orographic difference and it would make no sense to make assessments on a thermal profile at such a different altitude. The grid point analyzed is located further east at about twenty kilometers.

Considering the events showing a formation of snow sleeve, and that have therefore to be considered ascertained wet snow events, we can note that this method shows in only one case (11-04-2018) PA values in the range of snow mixed with rain, while all the others are values in the snowfall range just above zero. In *dry snow* events, instead, PA values remain constantly zero. The cases of 28-02-2016 and 01-12-2019 seem to start instead in *dry snow* and then evolve into *wet* with the last hours in rain mixed with snow.

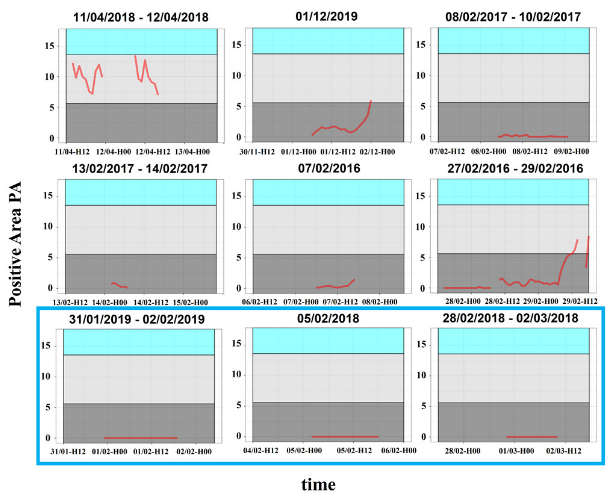

Fig. 11 *Positive Area* (PA) values associated with the different *wet* and *dry snow* events for Vinadio station. The colored bands indicate respectively snowfall (dark gray), rain mixed with snow (light gray) and rain (light blue) according to the *area method*. The blue box indicates the *dry snow* events.

What can be deduced from the study conducted is that *wet* snow could be identified by the *area method* with PA included in the range between values just above zero and 5.6 J kg^{-1}, while when the values of PA are strictly equal to zero then the snowfall is probably *dry*. The minimum value of PA to have *wet snow* was arbitrarily chosen equal to 0.1 (7).

$$
\begin{array}{ll}
PA < 0.1 \text{ J kg}^{-1} & \textit{Dry Snow} \\
0.1 \le PA < 5.6 \text{ J kg-}^{1} & \textit{Wet Snow} \\
5.6 < PA \le 13.2 \text{ J kg}^{-1} & \textit{Snow and rain} \\
PA > 13.2 \text{ J kg}^{-1} & \textit{Rain}
\end{array} \qquad (7)
$$

It should be noted that this result is valid for the specific model used for forecasts. Another meteorological model with a different resolution could give different values. The results come from a qualitative *'calibration'*, which consist in the correspondence between the PA values and the actual experimental observation of the snow sleeves formation in Vinadio. Obviously, this rule could be refined considering additional case studies and additional sites and eventually also increasing the spatial resolution of the meteorological model, so that it can better describe the complex orography typical of alpine valleys, hence reducing the differences between the altitude of model grid point and the station one.

IV. Monitoring wet snowfall and sleeve accretion at the WILD station

The lack of sleeve load measurements on the Overhead Transmission Lines (OHTL) in Italy doesn't allow to evaluate the dynamics of the accretion over spans and compare these to the simulations. Only the most relevant events could be validated indirectly by means of the failures data occurred on overhead power lines.

To overcome this problem, a collaboration agreement was signed in 2019 between RSE and the most important energy distributor in Italy (e-distribuzione), to develop the project NEWMAN (Near real time Extreme Weather events MANagement). In this project, three WILD 2.0 stations with 75-80 m length MV conductor span and 130 m aerial cables, have been installed in different climatic areas characterized by high failure rate (Fig.12).

Fig.12 Location of the three WILD 2.0 stations. Map: Google.

The stations are equipped with ice-free meteorological sensors, load cells on conductors and aerial cables for monitoring the snow sleeve load, cameras on the towers and

IoT sensors. The typical experimental field setup of the stations is shown in Fig.13.

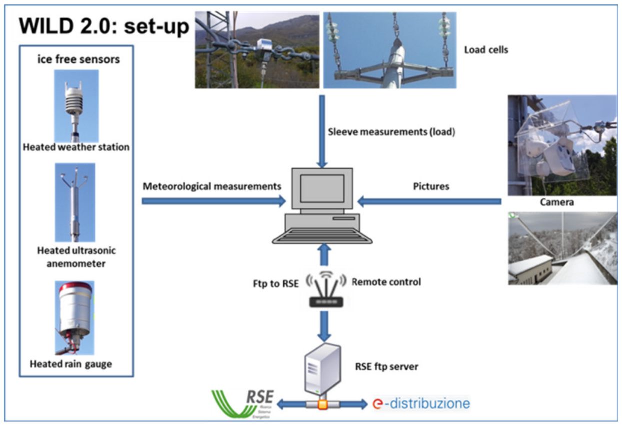

Fig.13 Experimental field setup of WILD 2.0 stations. Load cells, weather instruments and web camera are collected and sent every 15 minutes via FTP to RSE's server.

Weather and accretion measurement are acquired every minute together with images by camera every 15 minutes. The most typical conductors for MV lines (Copper "CU" and Aldrey "AA") are tested, with sections between 16 mm^2 and 150 mm^2. The CU35 mm^2 conductor is common to all three sites. It is also investigated the possible correlation between sleeve load and conductors' diameters, as suggested by Brian Wareing at 2015 IWAIS [14]. The first experimental evidence indicates that, although at the beginning there is a lower accumulation, instead at the end of a snowfall the growth on the smaller conductors is equivalent or even greater to the larger cables as shown in Fig.14.

Fig.14 Snow sleeve accretion on different diameters MV conductors during a wet snowfall event at Frabosa Soprana station, Piedmont Region, west Alps (960 m a.s.l.)

Another important experience is carried out on an aerial cable (3x95mm^2, 130 m length), the most relevant mitigation system for wet snowfall adopted in Italy for MV lines. Distributors report an excellent performance against sleeves, but further measurement campaigns are still needed to evaluate to define a typical mitigation coefficient for design standards. The first preliminary evaluations at WILD station indicate that the initial accumulation of sleeves on aerial cables is significant due to their high surface area of exposure to the snow flow. Subsequently, due to the shape and their high torsional rigidity, frequent detachments occur which do not allow a cylindrical formation of the sleeve (Fig.15).

Fig.15 Typical non-cylindrical snow sleeve accretion on 3x95 mm^2 130m length aerial cable during a wet snowfall event occurred at Isola del Gran Sasso station, Abruzzo region, center-east Apennines.

An example of the growth on an aerial cable (blue curve) and on a traditional one (red curve) is shown in Fig.16. At the beginning there is a strong weight increase on the aerial cable, subsequently there is a faster detachment compared to the common one. It should be noted that a specific model for the growth of the sleeve on aerial cable does not exist yet and will be studied in the next research activity.

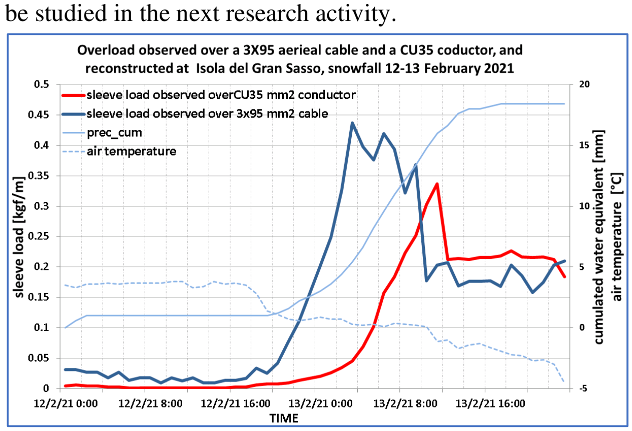

Fig.16 Measurements of snow sleeves load on 3x95 mm^2 aerial cable (blue curve) and on CU35 conductor (red curve), at Isola del Gran Sasso station. 12-13 February 2021.

The WILD stations allow the verification of the Makkonen accretion model, using both the measured data and those predicted by the WOLF system. An example of this comparison is shown in Fig.17. Using the meteorological data recorded at the station, the Makkonen model fed with these data (green curve) exactly reproduces the measured curve (red curve). Instead, using the forecasted data, a slight underestimation of the sleeve load is observed (blue curve).

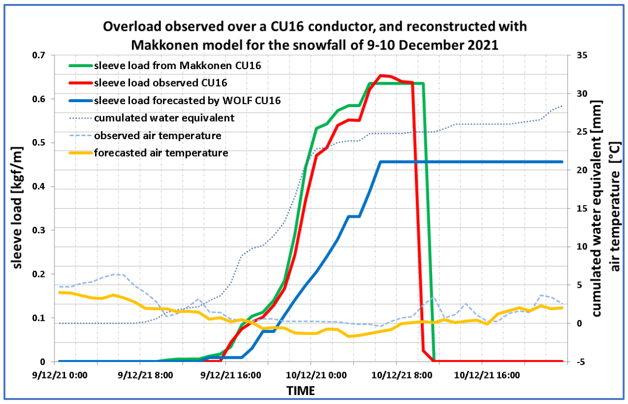

Fig.17 Comparison between the registered overload of snow on CU 16mm² (red curve), the simulated one with measured data at WILD station (green curve) and the predicted one with the forecast system (blue curve). Cecita, south Apennines. 9-10 December 2021.

To compare the observed data and the predictions produced by the WOLF forecast system, a real time monitoring has been implemented for the three stations. It is necessary to understand where is better to act in case there is a need to correct the forecast chain for the sleeve accretion. A continuous comparison with the forecasts up to three days before the current day are compared with the observed variables coming from the station in real time as shown in Fig.18. Observations are integrated with a camera image of the span to better understand the wet snow events.

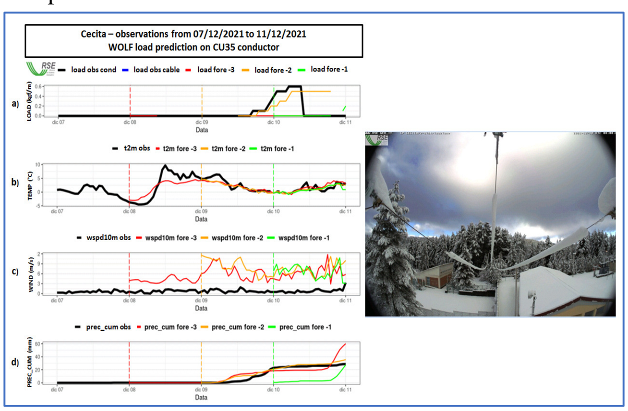

Fig.18 Snow diagram of the forecasts of the wet-snow event three days away (red), two days (orange) and one day before (green) compared to measurements (black curve). a) load (kg/m), b) 2m-temperature (°C), c) wind intensity (m/s), d) accumulated precipitation (mm. eq.). Wet snowfall at Cecita station, south Apennines (1200 m a.s.l.). 07-11 December 2021.

V. Conclusions

RSE research activities allow to predict and monitor in real time the most significant icing meteorological phenomena in Italy, with a focus on wet snowfall.

The methodology proposed by RSE based on MERIDA and the Makkonen model made it possible to reconstruct the most significant wet snow events in the last 21 years. This reconstruction has allowed to define more accurately climatologically similar areas for wet snowfall in Italy. For each of these zones, the expected sleeve thickness and mass values have been obtained through the Block Maxima method. Subsequently, for the same four areas, the relationships between thickness and elevation have been found for the update of the NNA wet snow load maps.

WOLF has been integrated with a forecasting system for freezing rain and further methods for the identification of wet and dry snow phenomena have been analyzed and will soon be implemented in the algorithm.

The WILD 2.0 stations constitute an open-air laboratory for the study of the formation of sleeves on real spans in which different mitigation solutions are also tested (hydrophobic coatings, aerial cables, etc.). Preliminary results indicate good mitigation of aerial cables with frequent detachments due to a non-cylindrical formation of the snow sleeve. Cables with different diameters indicate that even for the smallest cables at the end of the snow event they lead to the formation of large snow sleeves, comparable to those grown on conductors with larger diameters. The stations constitute a test bench for the verification of the meteorological and accretion forecasts of the sleeve and it is expected in the upcoming activity research that the forecasting system will be updated and integrated with the measurements coming from the field to obtain more accurate prediction at the WILD stations.

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