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TRANSMISSION OVERHEAD LINE DESIGN & EXTREME EVENT MITIGATION INTEREST GROUP (TODEM)

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STATE OF THE ART REPORT ON DESIGNING TRANSMISSION LINES FOR WET SNOW ACCUMULATION

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ABSTRACT

Wet snow occurs in any region of the world where snow falls at ambient temperatures of around 0ºC. Wet snow may be sticky and easily adhere to exposed objects, such as electric transmission lines. Significant loading on transmission lines may result from wet snow accumulation, especially on conductors and ground wires; therefore, transmission lines must be designed to withstand such loads.

It has been identified that wet snow accumulation is not sufficiently addressed in the current transmission line design standards. As such, this project aims to identify the gaps that must be closed in order to improve the reliability of modern transmission networks.

The objective is to prepare a state of the art report for designing transmission lines for wet snow accumulation and make recommendations to improve current industry standards.

Keywords:

Wet Snow, Transmission Line Design, Ice Loads, Modeling, Standards, Mitigation Methods

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EXECUTIVE SUMMARY

Wet snow icing appears to be a widespread phenomenon that must be considered in all regions where snowfall may occur during the winter season. It has been identified that wet snow is handled in an insufficient manner in several current standards for transmission line design. It is therefore the purpose of this report to identify the gaps that must be closed in order to improve the reliability of modern transmission networks.

The scope of the investigation includes reviewing generally available and relevant information on the occurrence of wet snow on transmission lines, failures caused by wet snow events, utility design practices, methods and models for predicting anticipated loads caused by wet snow events, as well as conducting a comparison of the ice load requirements between the national and international codes and guides, and recommending a methodology to determine the probabilistic wet snow loadings to be considered in the design of transmission lines. Furthermore, methods for the refurbishment of existing installations will be identified and improved design requirements for new and existing lines will be recommended. Finally, "knowledge gaps" in current design standards will be determined and methods for closing the "gaps" will be indicated.

A detailed literature review on the physical phenomenon of “wet snow icing” is conducted and presented in Section 2. While aspects of the literature review are devoted to understanding wet snow icing and its relation to meteorological conditions, important methods are described for taking wet snow icing into account in the design of transmission lines.

- Compared to other icing types, wet snow has a lower adhesive force and will more easily shed from torsional rigid cables. Thus, wet snow icing is primarily a problem on single phase conductors and overhead earth wires. It may also occur on bundled conductors, but to a lesser extent.
- Wet snow icing on transmission lines only occurs in a very narrow range of atmospheric conditions, including a combined range of temperature, relative humidity, wind speed and precipitation rate, along with the vertical distribution of these meteorological changes in the atmosphere. Thus, wet snow icing may be infrequent in many regions, such that it is nonexistent for many years or even decades. However, over the expected life time of a transmission line, the probability of a severe wet snow event remains significant and must be considered in its design.
- The density of accumulated wet snow may vary within a wide range, depending upon meteorological conditions. Therefore, a fixed ice density of 900 kg/m^3, which is used in many standards for calculating wind pressure on iced conductors, is not applicable for wet snow icing. Density in the range of 500 – 700 kg/m^3 is more accurate for wet snow icing. A site specific value can be calculated from meteorological data.
- Joule heating may be effective during the early stage of an icing event in preventing or delaying icing. However, as soon as a cylindrical wet snow sleeve has been formed around the conductor, Joule heating is less efficient as a mitigation method.

Section 2 also deals with several issues related to the modeling of wet snow icing based on meteorological data.

- Aspects of the wet snow accretion mechanisms are complex, such that practical models require a combination of theory and empirical relations. Therefore, a variety of models and parameter settings have been proposed in the literature. Based on a review of the literature, the most recently published papers on the respective subject are recommended (e.g. Ducloux and Nygaard, 2014).

- When using weather station data as input to wet snow icing models, care should be taken regarding the quality of meteorological measurements during wet snow storms since the wet snow itself could affect instrumentation (e.g. under-catch (underestimation) of precipitation amounts and slowdown of wind anemometers). These effects could cause an underestimation of the modeled wet snow loads if not properly taken into account.
- Numerical weather prediction (NWP) models show promise for predicting the necessary meteorological data to model wet snow icing. However, these methods are at a very early stage of development, and the use of such models should be carried out in collaboration with NWP experts.
- Regional or national maps of wet snow occurrence and its extreme value distribution can be made based on a dense network of weather stations and/or hindcast archives from NWP model simulations. Mapping of wet snow icing should be carried out in all regions where it may occur and affect the reliability of power lines.

Severe events of wet snow are reported for all continents in the northern hemisphere; several cases have also been registered in New Zealand and South Africa. Section 3 describes wet snow storms of significance that have been recorded throughout history. A wet snow storm in Germany and some neighboring countries in 2005 was the most severe wet snow storm in terms of total damage and economic consequence. This case clearly illustrates that wet snow icing can suddenly strike a region where past experiences has been limited.

Wet snow loads are mentioned as one possible icing type to consider in international standards, such as IEC 60826 or CENELEC (EN 50341-1). Several European countries treat wet snow specifically in their “National Normative Annex (NNA),” included in EN 50341-1. Wet snow loads are considered differently amongst utilities, varying from country to country. In some wet snow prone regions, a map or tabulated reference values of characteristic wet snow loads are provided according to area and altitude, while in other regions wet snow load is indirectly taken into account through line design.

From the author’s point of view, it is necessary to treat the load case of wet snow according to the climatic conditions of the specific region or country simply because wet snow may vary by an order of magnitude in density, while its frequency, magnitude and duration is highly variable between different climatic zones. This also affects a combined load case with extreme wind and the specific reduction factors that should be applied.

A review of mitigation methods is presented Section 5. Regarding the reviewed literature, no fully reliable method for preventing icing on overhead line conductors or for removing formed ice was found. The most effective mitigation method seems to be designing the line according to the expected loadings in the area. This includes determining the configuration and taking into account the topography and the prevailing exposure and wind direction. In critical situations, de-icing measures such as joule heating or mechanical ice removal are actively used in various countries.

In case of failure or collapse due to wet snow, it is important to review designs for wet snow loadings in the restoration process. Analyses of design loads should take local conditions into account, including prevailing wind direction during icing and its normal component to the transmission line. If there is a lack of reliable and representative weather station data, studies using NWP models must be considered.

The general conclusion from the utility survey is that most utilities do not distinguish individual icing types. The main reason for this is that for a specific utility (region) or country there is only one dominant type of ice, whether it is wet snow or freezing rain. In areas where freezing rain dominates, wet snow may certainly occur as well; however, since it is often less significant than freezing rain it is typically not taken into account.

Considering the literature review and responses to the utility survey, several observations and recommendations can be concluded:

- Since wet snow, freezing rain and rime ice result from different physical processes, their statistical properties accordingly differ. Extreme values must therefore be calculated individually for each process.
- Where occurrence is rare, it is generally very difficult to collect data from wet snow icing events.
- Measurements of wet snow icing can be performed where icing is frequent, preferably through the use of test spans instrumented with load cells and data loggers. Heated web-cameras should be included to improve data during the ice shedding process.
- The greatest potential for improving the data collection of local wet snow icing conditions is through combining a measurement campaign with a model study such that a wet snow accretion model is coupled to an NWP model. Long time-series of gridded weather data (re-analyses) are publicly available and can be used for further downscaling to a local level.
- Reliable extreme value calculations can be performed in all types of terrain with such models.

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1.0 INTRODUCTION

Wet snow accretion occurs when partly melted snowflakes collide with an object and adhere to its surface after collision. Accretion tends to build on the tops and windward surfaces of structures, as well as in the form of cylindrical accretions around high voltage conductors and overhead ground wires. It also forms on trees and can cause them fall onto distribution lines.

The density of wet snow can vary from 100 - 850 kg/m3, with the highest density usually relating to high wind speeds that compress the accreted snow layer. A process of cylindrical accretion can lead to very high loads being reached in a matter of hours (Makkonen 1989, Makkonen and Wichura 2010). The physical process of wet-snow accretion is generally recognized (Poots, 1996, Sakamoto 2000); however, comprehensive details are not fully understood. The formation of large cylindrical wet snow accretions is aided by a low torsional cable stiffness, but may also result from the sliding of wet snow along and around a stranded cable with sag. Thus, the surface properties of the cable may also affect the accretion process (Makkonen 2012).

Photos shown in Figure 1-1 illustrate the problem. Considering that these five images are from different countries across Europe, with similar reports from areas such as Japan and North-America, wet snow icing appears to be a widespread phenomenon that must be considered in all regions where snowfall can occur. It has been identified that wet snow is not sufficiently addressed in many current standards for transmission line design. Therefore, the purpose of this report is to identify gaps that must be closed to improve the reliability of modern transmission networks.

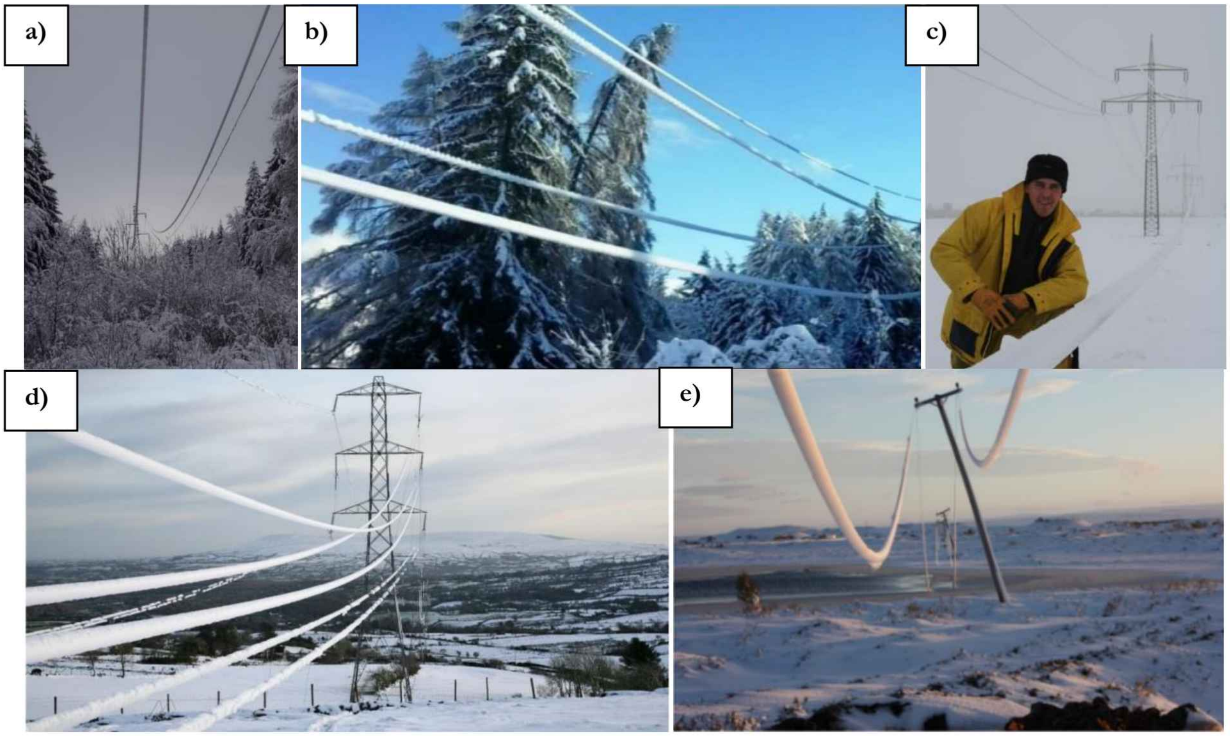

Figure 1-1: Examples of wet snow accumulation on overhead power lines.
Photos from France (RTE) (a), Italy (b), Germany (c), Great Britain (d) and Iceland (e).

1.1 Objectives and scope

The objective of this project is to prepare a state of the art report for designing transmission lines for wet snow, including recommendations to improve current industry standards. The scope of the investigation includes reviewing generally available and relevant information on the occurrence of wet snow on transmission lines, failures caused by wet snow events, utility design practices, methods and models for predicting anticipated loads caused by wet snow events, as well as conducting a comparison of the ice load requirements between the national and international codes and guides, and recommending a methodology to determine the probabilistic wet snow loadings to be considered in the design of transmission lines. Furthermore, methods for the refurbishment of existing installations will be identified and improved design requirements for new and existing lines will be recommended. Finally, "knowledge gaps" in current design standards will be determined and methods for closing the "gaps" will be indicated.

The report is structured as follows: A comprehensive review of the physical understanding of the wet snow phenomenon is given in Section 2, along with a description of wet snow accretion models and their coupling to weather station data or to data from numerical weather prediction models. Section 3 provides a list of selected well known historical wet snow storms from various countries. The treatment of wet snow loads in industry standards are presented in Section 4. Mitigation methods are discussed in Section 5, while a summary of the conducted utility survey is presented in Section 6.

2.0 WET SNOW ICING

This section provides an overview of the physical understanding of wet snow icing, how to model wet snow based on meteorological data, either from weather stations or from numerical atmospheric models, and how these models can be utilized for the estimation of climatic loads for the design of transmission lines. The information is primarily based on a review of available literature; however, many aspects are also based on the authors' personal experience and unpublished work. In this report the term "ice load" is used as a common term for all loadings from atmospheric icing, including wet snow loads.

2.1 The physics of wet snow icing

A comprehensive understanding of the physics of wet snow icing is relatively recent. Although the engineers facing wet snow problems on the first overhead lines probably had some understanding of the physics involved, in scientific literature the discussion on wet snow as a unique physical process and loading issue began as late as around 1970 (e.g. Kuroiwa (1965), Dranevic (1971), Bauer (1973), Goto (1976), Wakahama and Kuroiwa (1977), Koshenko and Bashirova (1979).

A clear separation of wet snow accretion mechanisms from icing at sub-zero temperatures was made when Makkonen (1981), in a reply to an article by Kemp (1980), argued that wet snow can only accumulate when the wet bulb temperature in air is above 0^o C. Thus, freezing of the water that occurs during rime and glaze icing does not occur during a wet snow accretion event, only (possibly) after. Rather, wet snow accumulates due to capillary forces that make the snowflakes attach to a cable surface and to each other.

This basic aspect of wet snow accretion was corroborated by later studies in the 1980s (Colbeck and Ackley 1984, Sakamoto and Ishihara 1984, Admirat 1986, Grenier et al 1986). During this time, detailed experimental studies on the wet snow accretion process also began in Japan (Admirat et al. 1986a, Sakamoto et al. 1986), which produced valuable ideas and evidence of the actual physical phenomena involved (Admirat and Sakamoto 1988).

However, the wet snow accretion process is very sensitive to the properties of snowflakes, and producing or harvesting representative and controllable wet snow for wind tunnel experiments proved difficult. Hence, experimental inquiries could not provide a widely applicable quantitative model for wet snow accretion, although limited locally calibrated models could be carried out and compared to actual cases (Admirat et al. 1986b). Due to experimental difficulties, theoretical models have an important role in understanding wet snow accretion physics, even though direct verification remains inadequate for the reasons mentioned above.

Modeling requires understanding the physics. Since some aspects of the wet snow accretion mechanisms are very complex, the practical models require a combination of theory and empirical relations. These modeling efforts are further discussed in Section 2.2., while some process fundamentals are first described below.

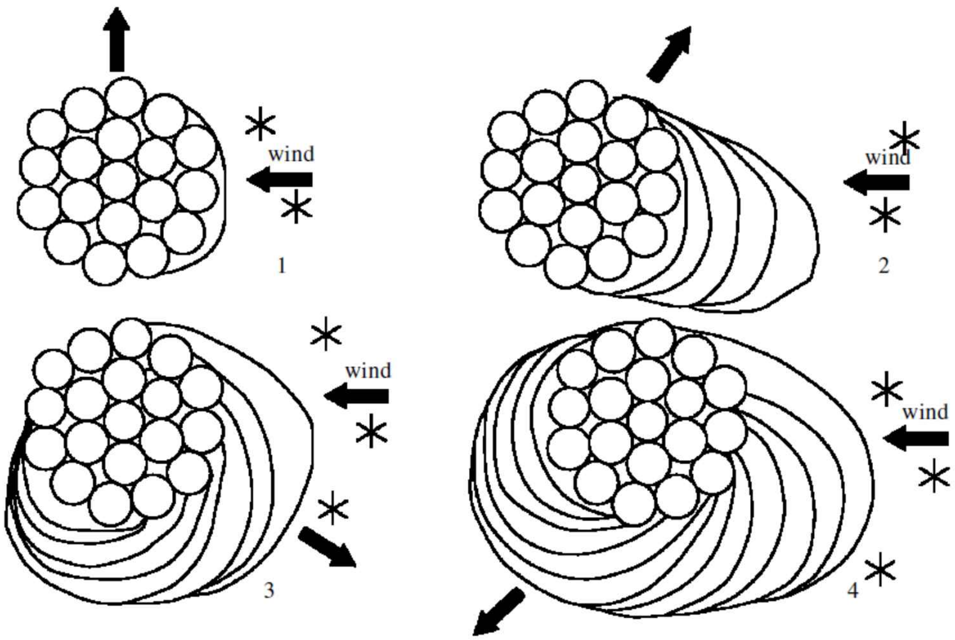

Figure 2-1: Wet-snow accretion on a stranded wire having low torsional rigidity
(Sakamoto, 2000).

It has been observed that dry snowflakes effectively bounce at impact (Kuroiwa 1965, 1977, Kobayashi 1987). Therefore, dry snow will accumulate on a cable only when fall velocity is low and little wind is present. Furthermore, the density and strength of dry snow accumulations are very low, resulting in shedding before a significant weight can be reached. On the other hand, when the snowflakes are very wet, they readily slide off the cable. Thus, there is a range of the liquid fraction of snowflakes where significant snow accretion on cables can occur. In addition, there is a meteorological range of conditions where wet snow can exist in the atmosphere. These together determine the "window" for wet snow accumulation on power line cables.

The liquid water fraction of snowflakes depends on their descent history. This history is governed by a slow, complex and partly random process including sublimation, coalescence with other snowflakes or water drops, melting, etc. In addition, the process of ice crystal growth results in no two snowflakes being alike. Due to these complexities, only approximations can be made on the actual size, shape and liquid fraction of snowflakes when they reach ground level (Matsuo and Sasyo 1981, Mellor and Mellor 1988). Fortunately, the fall velocity of snowflakes is relatively small, even when they are wet, which allows them time to adjust to the surrounding atmospheric conditions; thus, reasonable estimates of their basic state (wet vs. dry) at impact can be made based upon the atmospheric conditions.

The heat balance of a snowflake has two major components: the transfer of sensible heat and the transfer of latent heat related to evaporation/condensation. Radiation can be neglected during the actual snow accretion process due to cloudiness. This heat balance results in a specific wet snow criterion set by the temperature T_a and relative humidity RH of air (Matsuo and Sasuo, 1981, Makkonen 1989). A commonly used meteorological parameter, the wet bulb temperature T_w is based on the same balance and is conventionally measured as the temperature of a thermometer that is wetted. Thus, the theoretical criterion above can be expressed as:

$$T_w \geq 0\ ^{\circ}\mathrm{C} \qquad (1)$$

For practical modeling, the fact that RH is never above 100% in cloudy conditions at ground level can be used, and it could then be estimated that, for example when Ta > 2 ºC, the snowflakes are too wet for any snow accretion to occur. Furthermore, to estimate on the safe side, it could be said that snowflakes at T_w slightly below 0 ºC may still be wet at the ground level when they fall through a warmer air layer close to the ground (Makkonen and Wichura 2010). Allowance may also be given to the fact that the accuracy of measuring or estimating air temperature is seldom better than 0.2 ºC. Taking this "safety limit" into account, along with the aspects mentioned above, provides an approximate wet snow window as shown in Fig. 2-2.

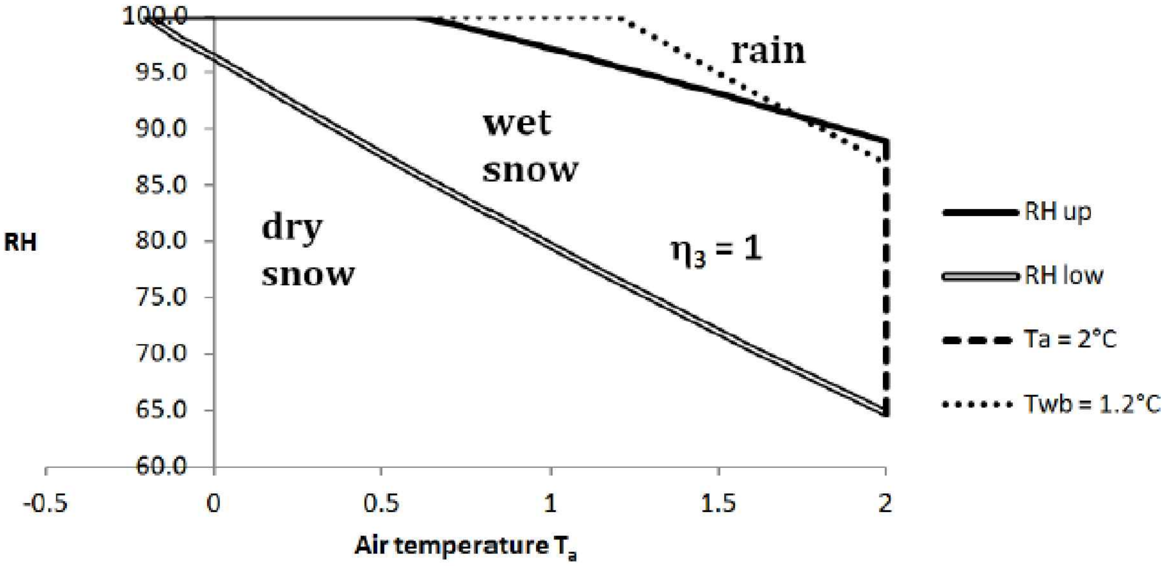

Figure 2-2: Meteorological "window" for occurrence of wet snow
(Ducloux and Nygaard, 2014)

Note that the right hand limit of air temperature of 2ºC in the window of Figure 2-2 is arbitrary. Wet snow precipitation is occasionally observed at ground level at temperatures as high as 5ºC (Matsuo et al 1981) in cases of low RH.

Generally speaking, wet snow accretion is a mechanical process dealing with the flux, impact and attachment of snowflakes. In general, thermodynamics come into play only when the deposit starts to melt or refreeze. However, the limiting temperature at which accretion is possible can be considered through the thermodynamics of wet snow accretion, first described by Grenier et al. (1986) and Yukino et al. (2007). The heat flux that is available for melting the accretion coming from the air is:

$$Q_{conv} = h\,(T_a - 0^{\circ}\mathrm{C}) \qquad (2)$$

Q_{conv} is the convective heat flux, where h is the convective heat transfer coefficient. For simplicity, we neglect sublimation (i.e. it is assumed that the dew point temperature T_d is close to 0ºC). The flux of ice to the surface is (1-f) V w, where f is the liquid fraction of the snowflakes, V is the impact speed of the snowflakes and w [kgm^{-3}] is the concentration of snow in air. Consequently, the heat required to melt all ice that is accreting on the surface is:

$$Q_{melt} = L\ (1\text{-}f)\ V\ w \qquad (3)$$

where L is the latent heat of fusion. The situation where the two terms are equal provides the limiting condition for possible accretion as:

$$T_a^{limit} = L\ (1\text{-}f)\ V\ w\ /\ h \qquad (4)$$

We can estimate h by $C_1\ D^{-0.15}\ V^{0.85}$, where D is the cylinder diameter and C_1 is a constant (Makkonen 1984). Inserting these at $T_a^{limit} = T_a$ gives:

$$T_a^{limit} = C_2\ w\ (1\text{-}f)\ V^{0.15}\ D^{0.15}\text{, where } C_2 \text{ is a constant.} \qquad (5)$$

This shows that the temperature limit T_a^{limit} of wet snow accretion is relatively insensitive to the impact speed ($T_a^{limit} \sim V^{0.15}$); thus, it is also insensitive to the wind speed. The cable diameter is unimportant here ($T_a^{limit} \sim D^{0.15}$). This analysis shows that T_a^{limit} depends linearly on the concentration of snow in the air, w. At a given w, it also depends linearly on f.

Inserting the relevant physical constants into equation (5) gives the numerical value of $C_2 = 7.5\ 10^3$ in SI units. For example, if $D = 3\ 10^{-2}$ m, V = 10 m/s and f = 0.3, then $T_a^{limit} = 4.4$ w where w is in g/m^3 and T_a^{limit} is in °C. This result means that during intense snow fall episodes (high snow concentration); wet snow may accumulate at higher temperatures compared to cases of lower snow fall rates.

Damaging wet snow events may occur at snow concentrations as low as 0.3 g/m^3 (Makkonen and Wichura 2010), which corresponds to $T_a^{limit} = 1.3$°C. This suggests that the upper temperature limit of wet snow accretions may actually be controlled by the heat balance of the deposit surface. The heat balance of the snow deposit is similar to that of the snowflakes, which is demonstrated by the finding that air temperature and the liquid fraction of the snowflakes f are statistically linked (Mastsuo et al, 1981). It has been suggested that they could be approximately connected by a linear relationship $f \approx 0.3$ Ta (Ueno et al. 2015).

However, in extreme cases, snow concentration may be above 3 g/m^3 (Ramussen et al 1999), which gives $T_a^{limit} = 13$°C. Snow accretion has never been reported at temperatures this high, which suggests that, at least under high snow concentrations, the upper temperature limit is set by a factor other than the heat balance of the snow sleeve on a cable.

This factor has an absence of a sufficient portion of ice in the precipitation (i.e. a high f). At high enough air temperature, the snowflakes have melted during their fall, either entirely or to the extent that they slide and drip off of the impacted surface. The value of f for the accretion not to occur is unknown for natural wet snow. Hefny et al, (2009) find that the adhesive and tensile strength of manufactured accreted wet snow has a maximum at liquid water fraction (LWF) of around 20-25 %, while Wakahama (1979) found a maximum of around 12-15 %. A similar result was found by Sakikabara et al. (2007) who reported a maximum in adhesive strength at LWF of around 10-15 %. Common to all of these studies is that the adhesive and tensile strength decreased rapidly at LWF-values higher than 35-50 %. This is consistent with the lowest measured values of f in snow shed from a cable, which are 40-50 % (Hefny et al, 2009). During wet snow accumulation, the LWF of the accumulated snow will never be lower than the f of the incoming wet snow. Hence, it is reasonable to assume that under constant conditions, snowflakes with f higher than approximately 40 % are too wet to accrete on cables.

The analysis above shows that the snow concentration in air, w, is very important in determining the temperature range of wet snow accretion when w is relatively low, whereas this limit is set by f when w is high. High w is required for wet snow accretion to occur at temperatures well above 0°C. This partly explains why wet snow problems on power lines are uncommon in some countries (e.g. Sweden and Finland) when general atmospheric conditions, such as moderate snow fall, seem to favor it.

As discussed earlier, the upper temperature limit of the wet snow "window" has not been quantified by the literature. Assuming that f of the incoming snowflakes must be below 40 %, there are some physical considerations that can be made to estimate an upper temperature limit. Snowflakes begin to melt when they cross the T_w=0°C line, which defines the top of the melting layer. Under normal atmospheric conditions the lapse rate of T_w is close to the moist adiabatic lapse rate in the melting layer (i.e. ~0.6°C/100m). Based on the size distribution and terminal velocity of the melting snowflakes, the melting distance (distance below the 0 °C level) can be calculated. Mitra et al., (1989) found a melting distance of a maximum of 200m to reach f=40 % of the snowflakes; thus, a maximum 200m melting distance corresponds to a maximum T_w of 1.2°C. This result is fairly consistent with the model results of Szyrmer and Zawadzki (1999), where f of the melting snow reaches 40 % at Ta = 0.9°C under moist adiabatic conditions. These upper temperature limits indicate that wet snow with an f favorable to accretion on cables mostly occurs near the top of the melting layer, with a maximum vertical distance of ~200m from the T_w=0 °C level.

Figure 2-3 shows the relation between the ice fraction (SR=1-f) of snow and T_w based on a simulated wet snow storm that caused the collapse of a 300 kV overhead line in Norway in December 2015. In the model, the melting rate of the snow is calculated in the time domain as a function of the atmospheric conditions. There is some spread in the results, but the best fit line corresponds relatively well with the limits found in the discussion above. Based on the fitted line, f=40% is obtained at T_w=1.3°C. Also, above T_w=0.1 there are no cases of dry snow predicted by the model, which is consistent with the criteria for wet snow defined in Makkonen (1989).

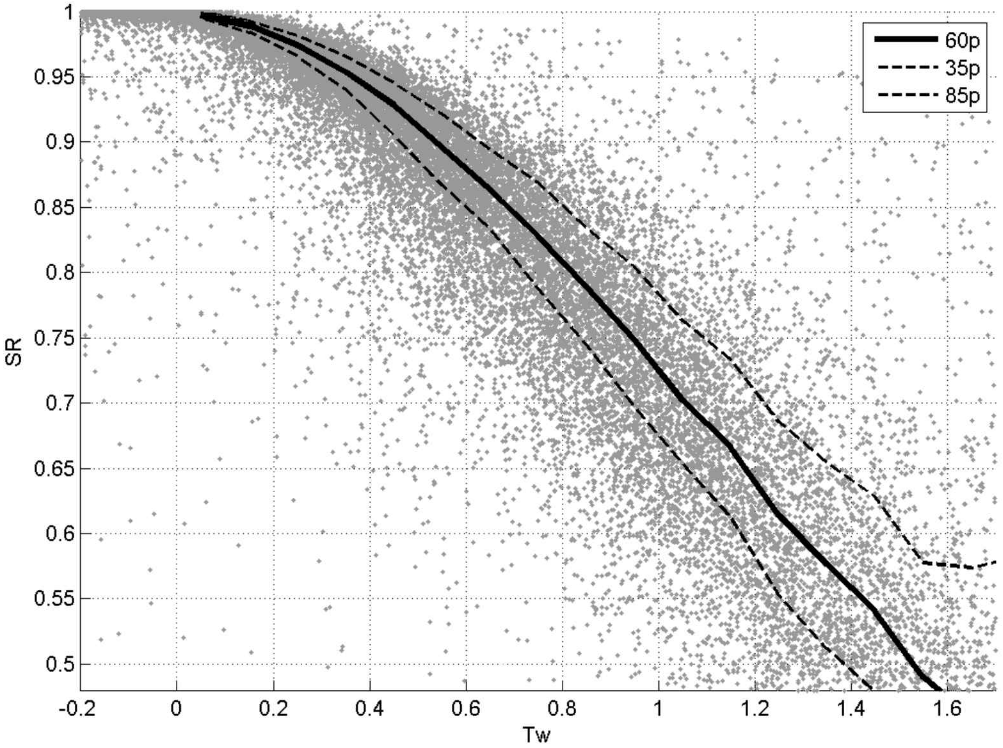

Figure 2-3: Relation between solid fraction (SR=1-f) of snow and wet-bulb temperature (T_w) based on a case study with the NWP model WRF at 500m grid spacing.
Grey dots show model results where snow content is higher than 0.3 g/m^3. The black line is a line of best fit to the distribution, obtained by calculating the 60^{th} percentile inside each temperature bin. The dashed lines indicate the 35^{th} and the 85^{th} percentile.

2.1.1 Thermodynamic considerations

An interesting observation is that based on photographic material and other examinations there is seldom an indication of water dripping from wet snow deposits. This would seem to suggest that the liquid water content of the accreted snow is always quite low, since water should slowly percolate through snow already at a liquid water content of about 15 %, according to laboratory experiments (e.g. Brun 1989). Also, values higher than this are not measured in natural snow on the ground; however, such measurements have not been made *during* wet snow accretion events, where it appears that fresh natural snow may retain higher fractions of liquid water, at least for a short period. Studies made at VTT in Finland on making snow using snow guns showed that artificial snow can retain water up to 30 % for at least 24 hours. According to the experimental snow density vs. liquid water content relationship from Hefny et al. (2009), f = 30 % corresponds to a snow density of 700 kg/m^3, which is close to the highest reported wet snow accretion densities. This further supports the conclusion that the liquid fraction of natural wet snow can be up to approximately 30 %, and that under such conditions the tensile strength, as well as the adhesion to a cable, are quite sufficient. Higher LWF is less likely due to the rapid decrease in adhesive and tensile strength.

In the discussion above, the effect of the heating from an energized electric cable has not yet been considered. Though it can be included in the heat balance (e.g. Grenier et al. 1986), it is noteworthy that "Joule heating" is negligible compared to Q_{melt} unless the snow concentration is very small.

Thus, Joule heating may have an effect on the least intense wet snow events and could be used to avoid wet snow accumulation from starting under special conditions; however, it has a negligible practical effect on the heavier wet snow events with a high precipitation rate, high wind speed and large icing diameters. For calculating design ice loads, severe wet snow events are of most importance.

Although snow is melted at a cable-snow interface by the Joule heating coming from the cable, this alone is unlikely to make the snow deposit shed from the cable. This is because wet snow has a high tensile strength that may be increased by melting, since it has a maximum at a certain LWF. A typical range for the maximum values of tensile adhesive strength is 1000 – 5000 Nm^2, depending on surface roughness (Hefny et al. 2009).

Related to shedding, it is very important to acknowledge the fact that the bulk of a wet snow deposit cannot be affected by the conduction of heat. This aspect is not appropriately considered in the present models of wet snow shedding (Grenier et al. 1986, Poots 1996, Olqma et al. 2009, Ueno et al. 2015). Wet snow is, by definition, a mixture of ice and water, and this mixture is at 0 °C. Thus, wet snow is an isothermal material (i.e. it cannot contain a temperature gradient and it cannot conduct heat); therefore, the bulk of a wet snow deposit cannot be melted (only its surface can).

This raises the question of how the bulk of a snow sleeve is weakened so that it can shed from a cable, noting that the shedding typically occurs so that the cable penetrates through the entire deposit (Roberge et al. 2007). Since there is no heat conduction within the snow, and metamorphosis is slow, the only possible mechanism is the percolation of water from the surface into the bulk of the snow sleeve. Percolation may occur partly by capillary suction, mostly downwards due to gravity. In other words, none of the meltwater formed during the melting phase of a wet snow deposit is actually produced within the bulk of the deposit. All melt water is produced at the surface and percolates through the bulk of the snow sleeve. At high liquid water contents, gravity induced water percolation also occurs along the cable toward the middle of the span due to the sag of the cable (Fonyó et al. 2009).

As such, it would seem that the weakening of the critical upper section of a wet snow deposit is controlled by melting at the upper surface of the deposit. This is not difficult to model by using meteorological conditions as input. A much improved model of wet snow shedding may thus be developed, and should replace the presently used criteria T_w above a certain threshold or if the deposit persists at subzero temperatures for more than 24 h. (Nygaard et al. 2014, Eliasson et al. 2015). An attempt towards a detailed physical model of snow shedding has been made by Ueno et al. (2015), where a time dependent LWF of the snow deposit is modeled based upon the full energy balance on the surface of the snow deposit.

The assumption behind the previously simplistic criteria for snow shedding is that melting or sublimation would remove the deposit in some relatively short time, possibly during the snow accumulation event itself. In this case, the shedding event would be important mainly in determining the end of a single event. Also in the literature, relatively little attention has been paid to the long-term persistence of wet snow loads on cables. This is somewhat surprising considering that the highest engineering load may well occur as a combination of snow and wind load *after* the active wet snow accumulation event (Makkonen and Wichura 2010). Moreover, in some cases, a significant wet snow load has been observed on a cable four weeks after its formation (Eliasson et al. 2013a).

That no detailed studies have been made on this persistence issue may be due to the fact that wet snow events are often synoptically related to the passage of a warm front. Thus, the most common sequence of affairs would be that eventually air temperature increases turn wet snow into liquid precipitation. However, this being the most common sequence does not necessarily mean that it is the most relevant in regard to the extreme loads on structures. It appears that, at least in complex terrain, severe snow loads can form on cables in many different synoptic weather situations (Eliasson et al. 2013b, 2015). Further statistical analyses of the weather conditions prevailing following wet snow events should be conducted in order to evaluate the importance of the persistence issue. Model generated hindcast archives may be well suited for such studies (see Section 1.2.2).

A related issue, also requiring further study, is the role of liquid precipitation in the shedding and persistence of wet snow. If a typical wet snow event is in fact such that wet snow precipitation eventually turns into liquid precipitation, then one would expect the rain water to percolate into the snow deposit and increase its liquid fraction f. As discussed above, the percolation of water into the snow sleeve is essential for shedding to occur. Simple calculations show that rain or drizzle may add more water into a snow sleeve than what is produced by melting on its surface. Thus, liquid precipitation that occurs after a wet snow event can be more significant in making a wet snow deposit shed than melting. This should be taken into account in further modeling.

2.1.2 Density of wet snow

The density of snow turns out to be a factor in the formation of the loads on cables, see Section 2.2; therefore, it is of interest to consider the mechanisms that control the density of a wet snow sleeve. There are few direct measurements of falling snowflakes; however in regard to density, the measurements of freshly fallen snow on the ground are representative. These measurements are plentiful and show a range of 10 to 350 kg/m^3, the lowest range being for dry snow (Judson and Doesken 2000); however, wet snow events may not be well represented in these datasets. Furthermore, there are reasons to suspect that the density of wet snow on a cable is systematically higher than on the ground. First, wet snow density measured on a cable is often much higher than 350 kg/m^3, and can be typically higher than this in some areas (Gonchar 1979). Second, empirical observations on cables show a clear dependence of the wet snow density on the wind speed (See Section 2.2), whereas the density and type of snowflakes themselves appear to be independent of wind speed (Matsuo et al 1981).

These observations point to the conclusion that, while the density of wet snow may depend on the initial state of the snowflakes, the density is significantly increased when accumulating on a cable, or soon after. The potential physical processes involved here include packing by wind pressure, snow metamorphosis, melting by increased heat transfer from the air, and deformation or fracture of the snowflakes at impact. Packing by wind pressure is unlikely to be significant, since the compressive strength of wet snow (Watanabe 1975) is orders of magnitude higher than a typical high wind pressure. Metamorphosis of wet snow increases the density, but is not quick enough to significantly affect the density during an actual wet snow accumulation event. One way to consider the effect of heat transfer from the air is noting that the time between two consecutive snowflakes on the same spot is small, so the heat transfer from air during this time is limited. More specific considerations, such as those related to the temperature limit T_a^{limit} above, show that a higher wind speed during a wet snow event tends to slightly reduce the liquid fraction of the snow sleeve (under the assumption that no condensational heating takes place). This would be expected to result in a decreased density, opposite to what is observed.

Thus, it appears that the difference between the density of the snowflakes and that of the snow deposit on a cable is controlled primarily by what occurs at impact. Unfortunately, this impact process is poorly understood and should be studied further. This is also the same process that determines the sticking efficiency of snow. Topics requiring further research include: Are the snowflakes simply compressed at impact, or do they break into fragments? Out of which, are those with the lowest density blown away? Or, is there some type of selective re-bouncing playing a role?

Supposing that the relevant physical process is the compaction of snowflakes at impact, a qualitative estimate can be determined. Denoting the mass by m and volume by V, and using subscripts i, W and a for ice, water and air, respectively, we have for the snowflake density ϱ, where:

$$\varrho = m/V = 1/[V/m] = 1/[(V_i + V_w + V_a)/m] \approx 1/[(V_i + V_w)/m + V_a/m] \qquad (6)$$

The term $(V_i + V_w)/m \approx 1/(950\ \mathrm{kg/m^3})$ is a weak function of the liquid fraction, but does not vary in the compaction process in which the air volume decreases to V_a^D. Supposing that the compaction (i.e. the change in the air volume $\Delta V_a = V_a - V_a^D(U)$) is essentially related to the impact speed U of the snowflakes, the deposit density is ϱ^D

$$\varrho^D(U) \approx 1/[(V_i + V_w)/m + V_a^D(U)/m] = 1/[(V_i + V_w)/m + V_a/m - \Delta V_a(U))/m] \qquad (7)$$

so that

$$\varrho^D(U) = 1/[(1/\varrho - \Delta V_a(U)/m] = 1/[(1/\varrho - \Delta(1/\varrho)] \qquad (8)$$

This equation shows that the initial density of the snowflakes affect the deposit density, particularly when the wind velocity is low. Thus, local conditions that determine the typical wet snowflake density are important. However, at high wind velocities, the initial snowflake density has a smaller effect and the impact process becomes a dominant factor. Interestingly, as will be seen in Section 2.2, this theoretical form of the dependence of the wet snow deposit density on wind speed is not used in any of the present wet snow models.

2.1.3 Accretion mechanisms

This section discusses the sticking efficiency α that largely controls the growth of a wet snow deposit. Sticking efficiency refers to the ratio of the mass flux of snowflakes that are permanently collected to the mass flux of snowflakes that impact with the object. Using this concept, the growth rate of the mass per unit time of a wet snow sleeve, dM/dt can be expressed as:

$$dM/dt = \alpha V w A \qquad (9)$$

Where, A is the cross-sectional area perpendicular to the direction of the impinging snowflakes and w is the wet snow content in the air [$\mathrm{kgm^{-3}}$]. This equation is based on the following assumptions: First, the collision efficiency is unity (i.e. wet snowflakes have a high enough inertia so that their trajectories can be considered as straight near to the object). This also means that the snowflake speed at impact equals its speed V further away from the object. Second, the freezing efficiency is unity (i.e. no melt water is dripping from the snow deposit during its growth). The validity of these assumptions in actual wet snow accretion has been verified in a number of studies (see Poots (1996), Makkonen (2000), Admirat (2009)).

The impact speed V is the vector sum of the wind speed and the fall velocity of the snowflakes, where A depends on the angle between the line orientation and V. The lower value of the impact speed is equal to the fall velocity of the snowflakes (typically 1.5 m/s). The growth rate is time-dependent, since A changes with a growing snow sleeve. Apart from this, the equation above appears to make a clear distinction between the input variables V, w, wind direction and line specifications. However, the physics embedded in the sticking efficiency α are complex, and involve processes that may depend on various parameters of the system.

Unfortunately, the impact process of wet snowflakes is poorly understood. Therefore, the relationship between the sticking efficiency α and the snowflake impact speed, liquid water content and other potential influencing factors cannot be properly described by theory.

Qualitatively, the following alternative, or simultaneous processes, may be speculated. First, the impinging snowflakes may re-bounce effectively. Second, the impact of an impinging snowflake may release snow crystals already attached to the surface. Third, the impinging snowflakes may break into smaller fragments, which are then scattered into the airflow. Finally, high wind shear alone may release ice crystals from the surface during the accumulation process.

Considering these mechanisms, it could be expected that the higher the wind speed (and consequently the impact speed), the lower the sticking efficiency. Increasing the liquid fraction of the snowflakes (typically a higher air temperature) would likely have an opposite effect (i.e. would tend to act as a buffer and diminish the above mentioned mechanisms). At the lower limit, the sticking efficiency of dry snow is essentially zero. It may also be expected that a larger cable diameter would typically have a higher α, since the particles released or re-bounced from the surface could be recollected on the larger object. Experiments by Wakahama et al. (1977) suggest a reverse behavior, however, demonstrating an inadequate understanding of the mechanisms involved. Nevertheless, there is direct experimental evidence for the significant re-bouncing of wet snowflakes, as well as for particles already attached to the surface being released into the air flow due to the impact of new particles (Wakahama et al. 1977).

Attempts to quantify the effects mentioned above by empirical equations are discussed in Section 2.2.

An essential feature of wet snow accretion on cables is that a cylindrical snow sleeve is formed. This sleeve extends around the cable, remaining even when the adhesion of the snow on the cable surface is very weak. That the deposit remains cylindrical also prevents it from growing eccentrically to the extent that it is shed by its own weight or wind drag. Thus, growing into a cylindrically shaped deposit explains why wet snow may be accreted in large amounts on overhead cables, but not on other types of objects including cables and poles that are vertically oriented.

Experiments have shown that there are two possible mechanisms by which a cylindrical snow sleeve can form on a cable (Kuroiwa 1965, Goto 1976, Wakahama et al. 1977). First, as a consequence of the initially eccentric snow loading, the conductor, having finite torsional stiffness and finite span, rotates about its axis. During the rotation, the gravitational torque is further enhanced by the aerodynamic torque. The rotation is most pronounced in the region of mid-span, however when the torsional stiffness of the conductor is low, a cylindrical sleeve forms around almost the entire the span. During this process, the cable typically makes several full rotations (Figure 2-4, upper). Second, an eccentric snow accretion may slide on the conductor towards its bottom surface. The snow may nevertheless remain attached on the bottom of the cable due to capillary adhesion, which is higher in tension than in shear; this allows more snow to accumulate on the windward side. On a stranded cable, sliding includes a lateral motion, since the snow will tend to slide along the strands in "a cork screw" manner, as show in Figure 2-4 (lower). When there is considerable sag (enhanced by the snow load), sliding will occur towards the mid-span, where the strands will force the deposit to rotate around the cable.

Figure 2-4: Upper: cylindrical wet snow deposit caused by rotation of conductor. Lower: "Cork screw" wet snow on a stranded conductor cable. (Photos: A-J. Eliasson, Iceland).

Both of these modes of the formation of a cylindrical snow sleeve have been verified experimentally (Wakahama et al. 1979, Yoshimatsu et al. 2011) and can be described in detail by rigorous mathematical analysis and modeling (McComber 1984, Poots 1995, 1996). However, their relative importance in practice is poorly understood, which hampers the application of counter-measures for snow loads on cables. This is unfortunate, since the torsional mechanism could be prevented by counter-weights, and the sliding mechanism by plastic rings attached to the cable (see Sakamoto 2000, Dalle and Admirat 2011).

In theory, it would not be difficult to determine which mechanism causes the formation of the cylindrical sleeve, since the torsional shear can be compared with the adhesional shear at the cable-snow interface. However, this would require as input the adhesion strength of the wet snow deposit, which is not readily available and varies across a wide range as a function of the liquid water content of the snow (Sakakibara et al. 2007; Hefny et al. 2009).

However, in terms of modeling wet snow loads, the role of the two mechanisms is less important since they both typically result in a snow sleeve that is nearly symmetrical to the cable axis. This is particularly true when the snow load is large (i.e. approaches a relevant design load). Hence, when modeling the time-dependent growth of snow sleeves for design purposes, a cylindrical accretion model (Makkonen 1984) can be used with good accuracy. Indeed, a cylindrical snow model is applied in all practical wet snow accretion models discussed in Section 2.2 below (see eq. (10)). In Figure 2-5, it can be seen that the cylindrical approximation is also relevant for bundled conductors, despite the higher torsional stiffness compared to single conductors.

Figure 2-5: Wet snow accretion on a 300 kV twin bundle conductor (Kleppe, 1984).

2.2 Modeling wet snow icing

In Section 2.1 the physics of wet snow accretion were discussed in general and in terms of understanding when and how it occurs. In this section, the focus is on modeling the accretion process with the aim of estimating the growth rate of the snow load on a cable. Figure 2-6 shows the schematic process of wet snow accretion, including the various meteorological and thermodynamic variables involved.

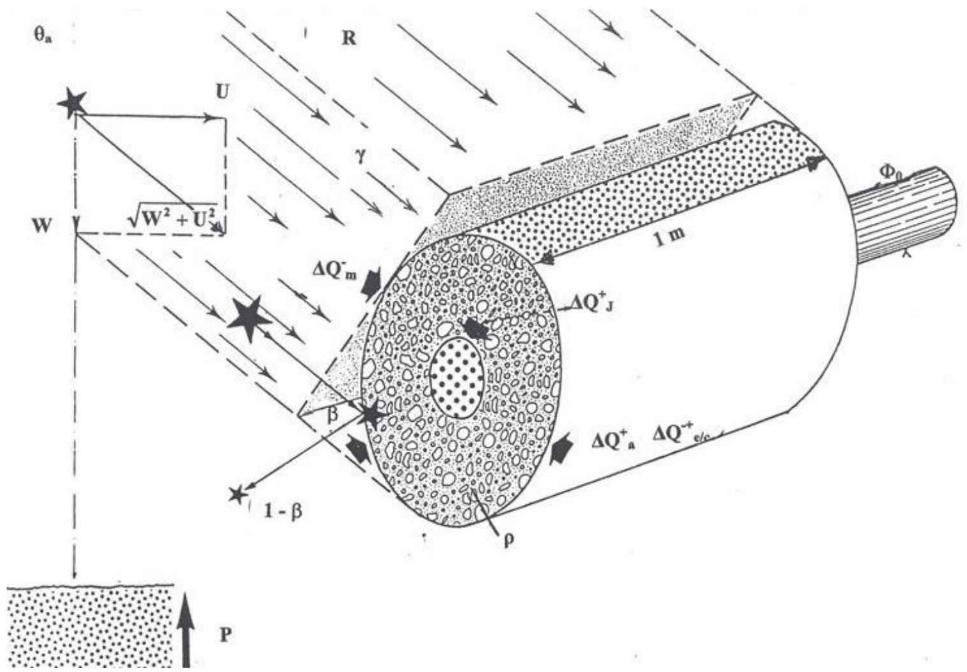

Figure 2-6: Schematic figure of wet snow accretion on a single conductor (from Admirat, 2008).

In this figure the symbols[1] are as follows: U=horizontal wind speed, W=vertical velocity of snowflakes, R=the flux of wet snow passing through the cross sectional area of the snow sleeve, γ=liquid water fraction of the snowflakes, P=surface precipitation, Θ_a=air temperature, β=sticking efficiency, ϱ=density of accreted snow, Φ_0=conductor diameter, and ΔQ_J, ΔQ_M, ΔQ_a and $\Delta Q_{e/c}$ represent the heat exchange by joule heating, melting, convection and evaporation/condensation, respectively.

When simulating the time-dependent growth of a snow load on a cable, the evolution of the snow mass M [gm^{-1}] accreted during a time-step i of duration $\Delta\tau$ on a conductor is calculated by using the icing intensity I [kgm^{-2}s^{-1}], the snow deposit diameter D [m] and the density of the wet snow deposit ρ_i:

$$M_i = M_{i-1} + I_i D_{i-1} \Delta\tau \qquad (10)$$

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

The icing intensity I is dependent upon the snowflake impact speed V [ms^{-1}], the concentration of snow in the air w [kgm^{-3}] and the sticking efficiency α:

$$I = \alpha V w \qquad (11)$$

The snowflake impact speed is the vector sum of the horizontal wind velocity perpendicular to the

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[1] The symbols used in the figure differ from the symbols used in this report.

cable U_n and the terminal velocity W of the wet snowflakes $V=(U_n^2+W^2)^{0.5}$

It is understood from wind tunnel experiments (Sakamoto et al., 2005) and the analysis of field data (Admirat, 2008) that the snow density on a cable depends on wind speed, air temperature and precipitation rate. However, during typical wet snow conditions, it only seems possible in practice to take into account the wind speed, which is considered to be the most significant variable.

Accordingly, a relationship between snow density ρ [kgm^{-3}] on an overhead cable and wind velocity has been recommended by several authors, and was summarized by Admirat (2008):

$$\rho = k + 20U \tag{12}$$

The constant k was found to be 100 kgm^{-3} in France and about 300 kgm^{-3} in Japan. Admirat (2008) concludes that these differences in k are not physical but reflect the effect of the other variables in the data sets. This conclusion is supported by the fact that the density of wet snow is closely related to the liquid water content of the accreting snow, where the latter varies in a wide range (Admirat et al., 1986, Admirat, 2008).

The effect of wind speed on snow density is mainly due to the high impact speed of the snow flakes, causing their fragmentation, and the high wind pressure that compresses the snow deposit. Therefore, it is reasonable to conclude that without wind the snow density on a cable ρ should be approximately equal to the constant k. Furthermore, one can postulate that the scenario of snowflakes impacting the ground could correspond to a no wind condition. This is because the velocity of snow impact and the wind pressure on the snow at ground level are very small, even at wind speeds typical to wet snow events. This approach provides a method for estimating the snow density on cables by using the snow density on the ground as k in eq. (12). Note, however, that the functional form in eq. (12) does not correspond to the theoretical result presented in Section 2.1.

As discussed in the previous section, a physical model for the sticking efficiency is not available. Thus, various approximations have been suggested. Admirat et al. (1986a) proposed the sticking efficiency to be approximated by the inverse value of the wind speed, assuming that the fall velocity of the snowflakes is 1 m/s.

$$\alpha = \frac{1}{U} \tag{13}$$

This sticking efficiency has been adopted in numerous subsequent studies as well as the ISO standard for the atmospheric icing of structures (ISO12494, 2001).

Inserting (13) in (11) gives an icing intensity that is nearly independent of wind speed. Furthermore, by allowing the snow density to increase with an increased wind speed, the accumulated ice load is in fact decreased if other parameters are held constant. This outcome is not in accordance with the experiences in windy areas (e.g. Japan and Iceland), where the highest loads are often experienced during windy conditions (Sakamoto and Miura, 1993; Nygaard et al. 2013).

According to Admirat (2008), equation (13) seemed to correspond very well with accretion rates both created in laboratory experiments and measured during real wet snow events in Japan and

France. However, despite a careful and detailed review of the original results (e.g. Admirat et al. 1986c; Sakamoto et al. 1986), the correlations published by Admirat (2008) are not able to be obtained or identified. In fact, the laboratory experiments presented in Sakamoto et al. (1986) partly contradict (13), and show much higher accretion rates. This may in part be explained by the effect of temperature, which could not be controlled in the laboratory tests. Nevertheless, considering the lack of reliable verification data to confirm (13), this parameterization should be used with care as it may lead to an underestimation of accretion rates, particularly at high winds speeds.

Such an underestimation was demonstrated in Nygaard et al (2013), where 50 years of observed wet snow data was used for validation. The paper emphasized two conservative assumptions in the wet snow models that may have compensated for the underestimation in previous studies: the terminal velocity of wet snowflakes, and the criteria used for identifying wet snow occurrence.

The study by Ducloux and Nygaard (2014) used a slightly modified expression for the sticking efficiency based on the snowflake impact speed V [m/s] (based on the results of Nygaard et al. (2013)):

$$\alpha = V^{-0.5} \tag{14}$$

Where, V is the vector sum of the horizontal wind speed U and the terminal velocity of the snowflakes W, assumed equal to 1.7 m/s.

Finstad et al. (1988) suggested the following formula for the sticking efficiency, attempting to reflect its dependency on the air temperature (Ta) and the diameter of the obstacle (D):

$$\alpha = \frac{0.038 T_a}{UD} \tag{15}$$

They also set up ranges of validity: 0°C ≤ Ta ≤ 4°C, 5 ≤ U ≤ 15 m/s, and 0.01 ≤ D ≤ 0.04 m, where all values of α above 1 are taken as 1. According to this expression, the coefficient will increase with the temperature and will have its maxima at the end of the accepted temperature range.

Sakamoto and Miura (1993) emphasized the reasonable dependence of α on the conductor diameter, but criticized its constant increase with the air temperature. They pointed out that, according to their observations, there should be a temperature point where the coefficient achieves its maximum and decreases on both sides. They proposed the following approximations based on wind tunnel experiments as well as observations of several natural wet snow events:

$$\alpha = \exp(-1.01 + 4.37Tr - 6.89\ Tr2 - 0.0168PUt) \tag{16}$$

Where, t is the time step, U is the wind speed, P is the precipitation rate, Tr = T/Td, T is the air temperature and Td is the upper temperature limit above which snow turns to rain. The proposed expression for this coefficient accounts for the expected behavior of a maximum at a certain temperature point, which is dependent upon the chosen upper temperature limit. With other conditions fixed, the maximums shift in the direction of the positive temperatures. The curves become wider and more flat at the top but the maximum values remain almost the same. This is presented in Figure 2-7.

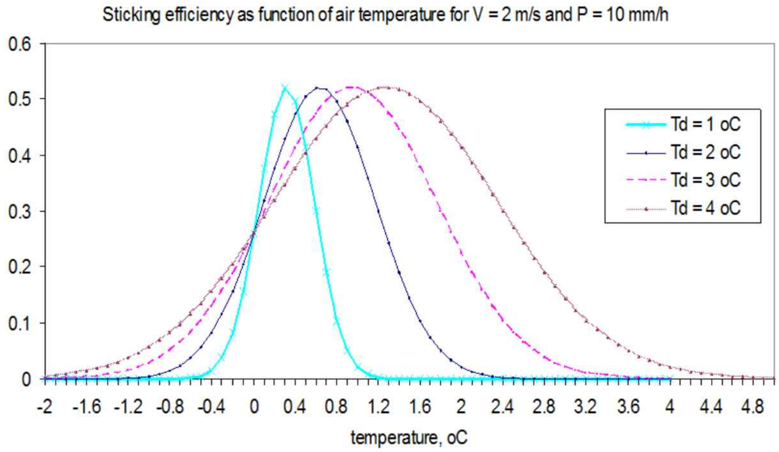

Figure 2-7: The curves for α (y-axis) according to equation (16) for four different upper temperature limits. Tr on the x-axis.

The sticking efficiency, according to equation (16), decreases with an increasing wind speed and precipitation rate, but is independent of the diameter of the obstacle. Its absolute maximum is in the corresponding temperature points for low precipitation rates and low wind speeds; however, high wind speeds and/or precipitation rates may compensate for the decrease of the sticking efficiency and lead to an increase of the total ice load along with increasing values for both parameters up to a certain level before decreasing. This was pointed out by the authors themselves, who stated that according to their calculations the estimated snow mass begins to decrease when the total precipitation exceeds 30 and 60 mm for a wind speed of 16 and 8 m/s, correspondingly. It should be noted that for very small precipitation rates (i.e. 1 mm/h), the maximum values of α are very high even for strong wind speeds (remaining above 0.5 up to 23 m/s, see Figure 2-8).

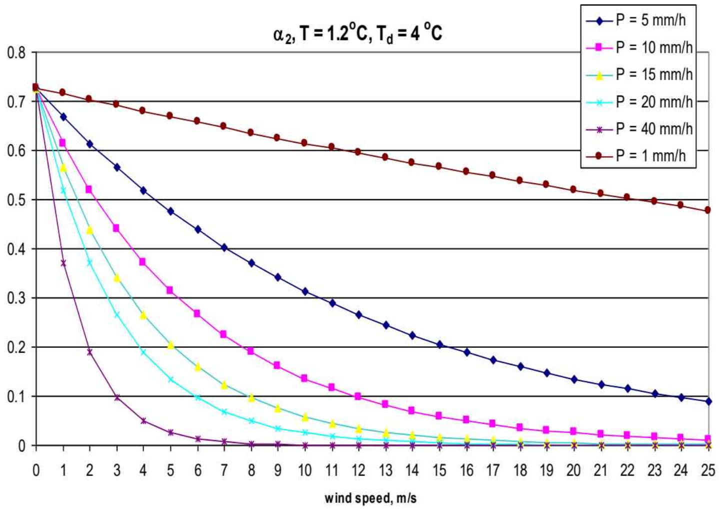

Figure 2-8: Change of α (y-axis) according to equation (16) with the wind speed for different precipitation rates, Td = 4 °C and fixed air temperature T = 1.2 °C

The strong decrease in α with increasing precipitation rate is not physically explained, however, the term self-limiting behavior of the model was introduced for expressing the fact that very heavy snow loads had never been observed in practical conditions. Another method for limiting the growth rate is to make α dependent on the sleeve diameter, as carried out by Finstad et al. Admirat and Sakamoto (1993), combining the advantages of their model with those of Finstad et al., recommending for α:

$$\alpha = 4.5 \frac{\exp\left[-6(T / T_d - 0.320)^2\right]}{U^{0.2} D} \qquad (17)$$

According to this formula, α always has its maximum at the same temperature as (17), but provides low values for α. This underestimation of α results in lower ice loads and diameters of the depositions. It should also be noted that although the dependence on the diameter is now included in formula (17), the dependency on the precipitation rate is excluded.

Nygaard et al. (2013) suggested a parameterization of the sticking efficiency as a function of both wind speed and the liquid water fraction f of snowflakes predicted from a NWP model. The parameterization is shown in Figure 2-9. The dependence of α on f was based on measurements of adhesive forces in accreted snow, which has a maximum value at a certain water content. The assumption is that impinging snowflakes will have the highest probability of sticking to the snow sleeve at the same snowflake liquid water content. The effect of wind speed was calibrated based on a comparison between the measured and modeled distribution of extreme loads (Nygaard et al, 2013).

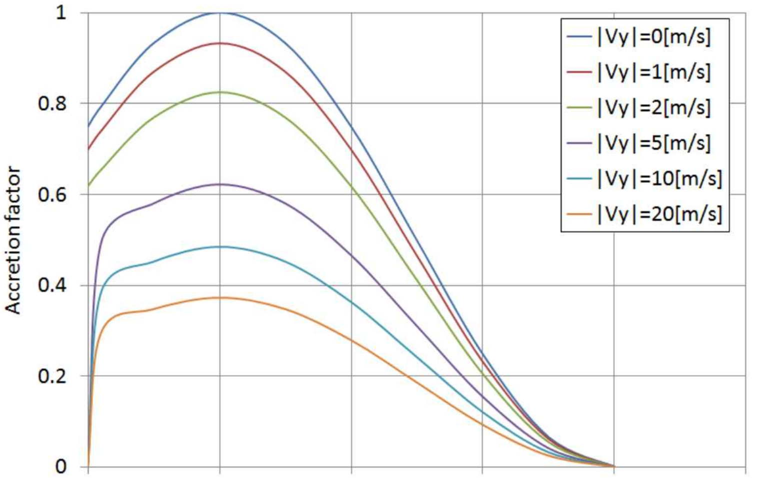

Figure 2-9: Sticking efficiency from Ueno et al. (2015) based on Nygaard et al (2013). In this figure the wind speed is denoted by |Vy|.

For identifying wet snow periods, either direct or indirect information for the liquid water fraction f of the snow is required. Furthermore, to determine whether or not the wet snow will begin to accumulate on a cable, the full energy balance of the accumulated snow mass must be considered. The energy balance is maintained by the continuous melting of a certain fraction of the accreted snow. If the LWF of the accreted snow increases above the critical limit (40-50%), shedding will occur and further accretion is no longer possible without a change in the environmental conditions. If the LWF of accreted snow initially increases above the critical limit, accretion will not begin at all. Hence, a physically consistent criterion for wet snow accretion requires the full energy balance calculation together with the incoming flux of precipitation particles and their liquid fraction (Sakamoto, 2000). For a practical example of this calculation see Ueno et al. (2015).

To summarize, the following meteorological variables are required for modeling wet snow icing:

- Wind speed (U), and direction relative to the cable
- Snow content in the air (w)
- Liquid water fraction of the snow (f)
- Air temperature (Ta)
- Air humidity (RH)
- Terminal velocity of wet snow (W)

These variables are rarely measured directly; therefore, parameterizations based on the standard meteorological measurements are widely applied. From numerical atmospheric models predictions can be obtained for all parameters directly; however, individual uncertainties are not yet fully documented.

For the wet snow accretion model itself, further validation using actual observations of wet snow accumulation is needed to determine the parameter settings and efficiency coefficients. However, based on the most recent publications, the authors recommend applying the sticking efficiency described in equation (14) to the wet snow identified and measured from weather station data. If explicit data for the liquid water fraction f of the snow is available (e.g. from a numeric weather prediction model), the sticking efficiency presented in Figure 2-9 is recommended. For an estimation of wet snow density, equation (12) should be used until more sophisticated models have been developed and validated.

In the next two sections examples are provided for modeling wet snow icing, based on:

1. Weather station data
2. Data from Numerical Weather Prediction (NWP) models

2.2.1 Models based on weather station data

Due to the importance of wet snow accretion on overhead lines and the need for design loads, several attempts have been made to estimate the wet snow accretion rate based on standard meteorological measurements (e.g. Finstad et al. 1988; Makkonen, 1989; Sakamoto and Miura, 1993; Admirat, 2008; Makkonen and Wichura, 2010; Ducloux and Nygaard, 2014). In addition to the differences in the parameterization of α (Section 2.2), the models also differ in their estimation of the wet snow mass concentration in the air (w), determination of the snow wetness f and/or identification of wet snow occurrence.

The most widely used parameterization of w is based on the measured water equivalent precipitation intensity at ground P (mms^{-1}) together with an assumed average mass weighted terminal velocity (W) of wet snow flakes:

$$w = P/W \tag{18}$$

This means that w is directly proportional to the inverse of the terminal velocity of the snow. Most models have used W=1 m/s, based on data by Koh et al (1988) and Mellor and Mellor (1988). However, Nygaard et al (2013) and Ducloux and Nygaard (2014) suggested that the typical terminal velocity of wet snow flakes may be considerably higher (i.e. W = 1.5 – 1.7 m/s), and thus, w could have been significantly overestimated in previous models.

A wet snow model that uses visibility V_m [m] as an input parameter for the estimation of w was presented by Makkonen (1989). The model determines the intensity I of accretion based on empirical equations for snow fall velocity, the concentration of snow in air vs. visibility, and the sticking efficiency of snow particles vs. wind speed. Its revised version follows from the findings by Rasmussen et al. (1999) that the wet snow model must take into account the various snow concentration vs. visibility relationships throughout the day and night (Peabody et al. 2007). The most recent version of the model (Makkonen and Wichura 2010) calculates the wet snow accretion intensity I as:

$$\begin{aligned} I &= 2100\,[V_m]^{-1.29} \qquad day-time \\ I &= 2100\,[0.5\,V_m]^{-1.29} \qquad night-time \end{aligned} \tag{19}$$

The model can be run, for example, by utilizing the synop code WW (present weather) to determine the precipitation type, and thus identifies the periods of wet snow.

This model has provided good results when compared to the observed wet snow loads for single cases (Makkonen and Wichura, 2010; Nikolov and Makkonen, 2015). However, the model applies a sticking efficiency with reference to Admirat et al. (1986), discussed in the previous section, and thus, there may be compensating effects that need to be tested by further sensitivity studies.

Examples of practical applications of simple wet snow accretion models run with weather station data for the purpose of mapping design loads have been presented by several authors (e.g. Admirat, 2008; Nygaard et al. 2014; Ducloux and Nygaard, 2014). In areas where sufficiently long, continuous and homogeneous time series of weather data are available, the wet snow results can be subjected to an extreme value analysis with the aim of estimating design wet snow loads with a selected return period (see Makkonen and Wichura (2010) or Ducloux and Nygaard (2014)).

An example from Nygaard et al. (2014) is shown in Figure 2-10 where modeled 50 year wet snow loads from 131 weather stations have been horizontally interpolated to a high resolution grid using the method of regression kriging. The map provides useful information about expected wet snow loads for planning, the design of new lines as well as for refurbishing old lines.

An important aspect to consider when using weather station data for wet snow modeling is that the quality of the measurement data itself could be affected by the wet snow. When wet snow accumulates on the power lines it is also likely to accumulate on the meteorological instruments. This can lead to the slowdown or malfunction of wind anemometers, and/or the under-catchment of precipitation amounts and meltwater affecting the temperature sensor. These issues are further discussed in Nygaard et al (2013) and Ducloux and Nygaard (2014).

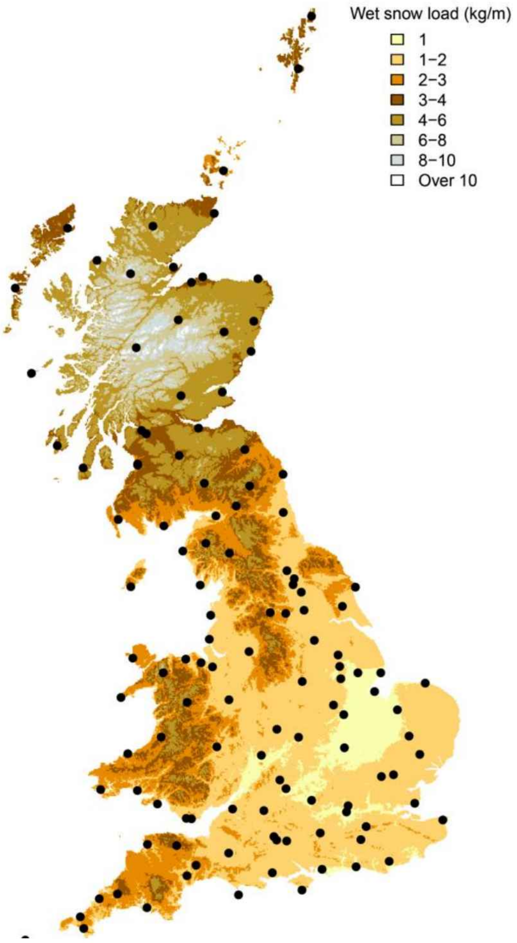

Figure 2-10: Estimated wet snow load in Britain with 50-year return period interpolated to a regular grid of 500m resolution by regression kriging.

Black dots: Locations of the weather stations used in the analysis.

2.2.2 Models based on NWP data

Instead of using weather station data as input to a wet snow accretion model, output from numerical weather prediction (NWP) models can be utilized. The disadvantage is that model data carry uncertainties and may contain biases that must be identified. Advantages include that data can be produced at high spatial and temporal resolutions, as opposed to at a limited number of observational locations at discrete times. Second, there are parameters available in the NWP model (depending on its complexity) that are normally not measured (i.e. estimates of key parameters such as wet snow content in the air W and the liquid water fraction f of wet snow). Third, there are no issues with wet snow affecting the quality of the data (in terms of measurements); and finally, such a system can be used in both forecasting mode as well as for past weather, either for single storm events or for climatological studies.

A freely available state-of-the-art NWP model is the Weather Research and Forecasting (WRF) model, currently being used for various downscaling purposes including studies of ground structural icing (e.g. Nygaard et al. 2014; Makkonen et al. 2014).

In the three dimensional grid of the WRF model, as the snowflakes begin to melt approximately as they cross the $T_w=0$ line (Figure 2-3) and pass through the melting layer, their mass is gradually transferred from a snow category to a rain category. The fall velocity of the melting snow is a function of the degree of melting. The liquid fraction of the melting snow is estimated as a bulk value for all snow and not for individual bins in the size distribution. An estimate of f is attained by the ratio of the melted mass concentration in the air (rain category) to the total mass concentration of all precipitation particles (Figure 2-11). Furthermore, the mass concentration of wet snow in the air W can be directly calculated as the sum of snow and rain (and possibly other precipitation types, depending on the complexity of the cloud microphysical scheme). Since wind velocity, temperature and air humidity are all prognostic variables easily obtained, all necessary parameters for wet snow modeling are available.

However, the non-linear nature of the fundamental equations that describe the atmospheric flow impose limitations on the ability to predict weather at a local scale. Strictly speaking, a NWP simulation is always inaccurate to some degree in predicting the state of the atmosphere both in space and time. Considering that wet snow occurs only in a very narrow temperature range, a wet snow prediction will never be more accurate than a prediction of the three dimensional structure of the meteorological fields. Under specific conditions, when a refreezing layer exists in the atmosphere, even a slight fluctuation in the temperature profile significantly affects the type of precipitation (Thériault et al. 2010).

However, the calculation of historical weather (downscaling) for the purpose of estimating weather loads does not require precise prediction in the time domain so long as the statistical distribution of the various parameters is correctly represented by the model. In Nygaard et al (2013), an ice accretion model forced by 60 years of modeled weather data was calibrated so that a 50 year wet snow load corresponded to the 50 year wet snow load based on observations in the southern region of Iceland. Such a calibrated model, that combines the output from a NWP with a model for wet snow accretion on cables, can then be used for a variety of studies and applications, such as producing a high temporal and spatial resolution dataset for historic weather and icing conditions (hindcast), studies of topographical influence on icing parameters, or downscaling climate projections for studying the effect of climate change on icing.

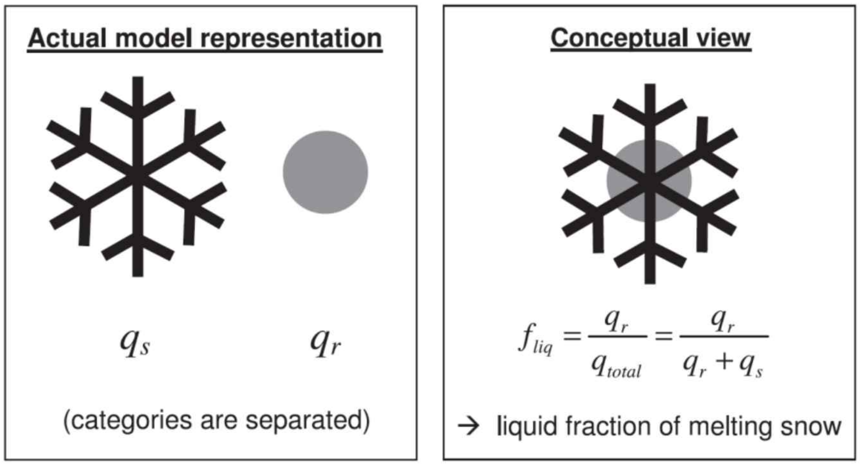

Figure 2-11: Model representation of melting snow in a microphysical scheme with two precipitation variables, snow (q_s) and rain (q_r) (Milbrandt et. Al, 2012).

Despite limitations in the ability of NWP models to precisely predict the state of the atmospheric flow in space and time, in the authors' experience, the atmospheric conditions during typical wet snow storms are generally well predicted. The reason is that wet snow usually occurs in conditions of strong synoptic forcing (e.g. related to the passage of low pressure systems); therefore, the simulation is less sensitive to small inaccuracies that under different conditions could propagate significant errors. The location of the melting layer is normally well represented in the model in typical wet snow conditions.

To illustrate, Figure 2-12 shows the results from a simulation of a recent wet snow event in Norway that caused the collapse of several towers on a 220 kV transmission line. The ice load measured on the collapsed earth wire was 15 kg/m (± 2 kg/m). The event was simulated with the WRF model at a horizontal grid resolution of 4 km, producing the necessary variables (1h data) to run the Nygaard et al (2013) wet snow accretion model. The modeled wet snow accretion was carried out for four different orientations of a horizontal conductor, indicated by the various colors in the lower panel. The actual direction of the collapsed line is close to southeast-northwest (red line), which is the worst-case line direction in this case (i.e. perpendicular to the prevailing wind direction during the storm). It is noteworthy that the incident occurred less than 2 km from a synoptic weather station; however, the data from the weather station was so severely affected by the wet snow itself that they could not be used to analyze the case.

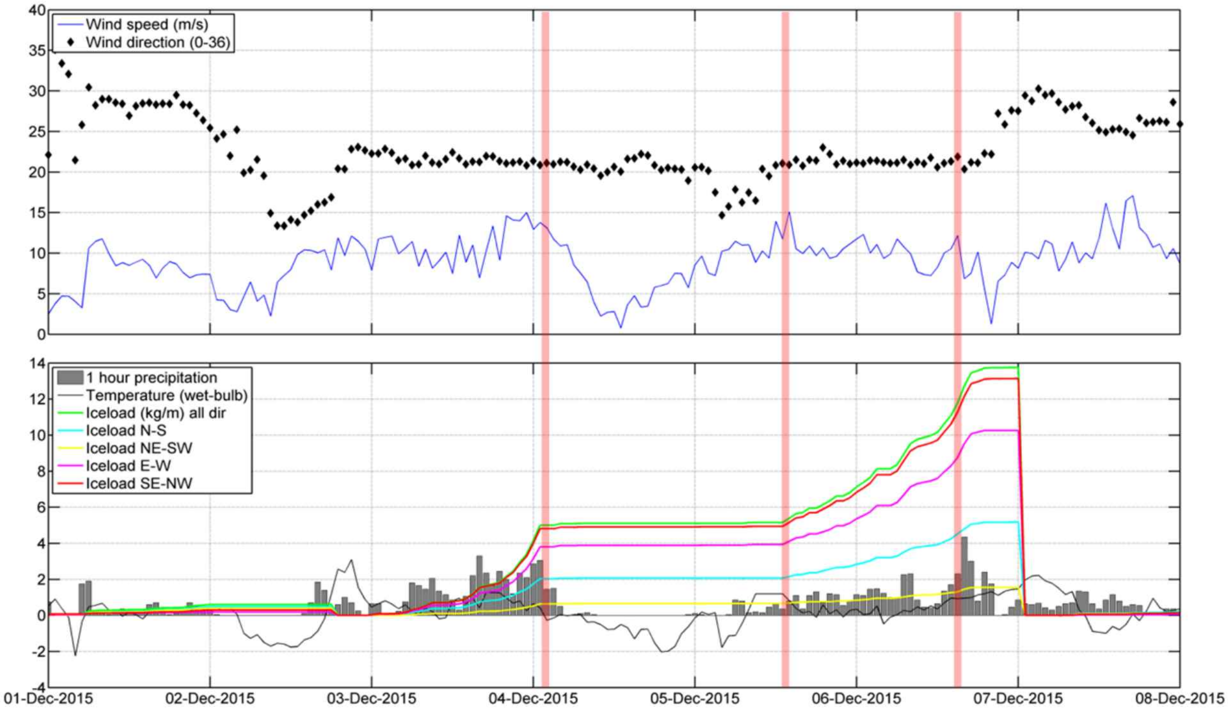

Figure 2-12: Predicted meteorological parameters from WRF and modelled ice load during a wet snow storm that caused the collapse of a 220 kV line in Norway, December 2015. The vertical red lines indicate tower failures: first a partial failure, which then led to the collapse of the line.

As a result of the collapse, the design values for ice loads needed to be reconsidered when replacing the damaged towers. As a part of this analysis the same model was used to simulate the period between 1979 and 2015. Based on the 36 years of modeled wet snow data, an extreme value analysis (see next section) was performed to calculate the return periods for wet snow icing. The results in Table 2-1 show that an estimated 1 in 50 year wet snow load is 10.4 kg/m. This result implies that the expected return period of the wet snow load in 2015 was well above 50 years.

The dataset of the 36 years of WRF generated meteorological data is currently used to estimate design wet snow loads in the planning phase for all new transmission lines in Norway.

Table 2-1: Calculated return values for wet snow load based on 36 years of WRF generated atmospheric data as input to a wet snow accretion model.

Line direction	**Return level wet snow load (kg/m)**					
	2 yr	**3 yr**	**5 yr**	**10 yr**	**25 yr**	**50 yr**
N-S (0°)	1.6	2.0	2.5	3.5	5.3	7.2
NE-SW (45°)	0.7	0.8	1.0	1.4	2.0	2.6
E-W (90°)	1.5	1.8	2.3	3.2	5.1	7.5
SE – NW (135°)	2.4	2.9	3.6	5.0	7.6	10.4
Directional independent	2.6	3.2	4.0	5.5	8.2	11.1

2.2.3 Calculation of design loads

Estimations of probabilistic design loads have rarely been made directly based on observations of the snow on cables. This is due to the fact that such observations are too scarce for making a reliable statistical analysis, with several exceptions (e.g. Eliasson and Thorsteins 2007, Ruszczak and Tomaszewski 2015, Nikolov and Makkonen 2015). As such, the models of wet snow accumulation can be used to make load estimates by utilizing routinely observed meteorological data. This provides a means to make an extreme value analysis based on modelled wet snow events over numerous decades.

Detailed statistical analyses of wet snow events have been carried out in various parts of the world (e.g. Finland (Makkonen and Ahti 1995), Japan (Kitashima et al. 2005), Canada (Peabody et al. 2007), Germany (Makkonen and Wichura 2010), Great Britain (Nygaard et al. 2014), Italy (Lacavalla et al. 2015), Poland (Tomaszewski and Ruszczak 2013), Iceland (Nygaard et al. 2013, Eliasson et al. 2015) and France (Ducloux and Nygaard 2014)).

The statistical methods employed in these analyses have varied in detail, but essentially a theoretical extreme value distribution has been fitted to extreme data, plotted by some formula; either block maxima or peaks-over-threshold values have been used. The extreme data have been obtained in most cases by numerically harvesting and simulating wet snow events from weather data utilizing the wet snow models discussed in Section 2.2. Finally, the design load (e.g. for a 50 year return period) has been obtained through extrapolation, using a distribution function fitted to the extremes.

The statistical methodology for making the extreme value analysis should be chosen with care, since different methods produce very different values for the probabilistic design loads (Makkonen 2008). This has been demonstrated specifically for extreme wet snow loads by Makkonen and Wichura (2010). One of the various reasons for this is that wet snow events are quite rare; therefore, their distribution is not necessarily close to any asymptotic extreme value distribution, such as the Gumbel distribution. It is necessary to fit a more flexible three-parameter distribution that can give allowance for this, and provide a reasonable fit, even in absence of an exact theoretical basis. The General extreme value distribution will do this well for block maxima, and the Pareto distribution for peak-over-threshold values.

Other critical issues of the extreme value analysis include using the correct plotting formula and weighing the points optimally when making the fit (Makkonen 2008). Great care must be taken in dealing with exceptional extreme values and blocks where there has been no snow at all. An improved and objective extreme value method has recently been introduced by Makkonen and Tikanmäki (2016).

2.3 Measuring of wet snow icing

Following a significant wet snow event, measurements should be undertaken to obtain data for both modeling and statistical purposes. An unknown number of such attempts have been performed over the years. The IEC Technical Report 61774 "Overhead lines – Meteorological data for assessing climatic loads" (1997) is likely to be the first report in which several principles were recommended toward this purpose; including for various rigs and instrumentation for both manual and automatic operation.

The European COST Action 727 "Atmospheric Icing on Structures" also investigated the state of the art concerning measurements and data collection (Fikke et al., 2007).

However, it was concluded that there had been little progress within the field, especially for remote and automatic measurements; the most successful were manually inspected test spans or rigs. Test rigs were installed in significant numbers, especially in Russia, located at standard weather observation stations.

Although Iceland was not a member of Action 727, they have reported their widely used test spans for wet snow icing in Eliasson et al. (2007). This system is combined with automatic data loggers which autonomously submit data. In addition, cameras are important for observing the accretion and shedding process. This has provided valuable information to the accretion models as significant wet snow events are relatively rare, and when they occur in one country they will often affect other areas where no measuring devices are installed.

From the experience with COST Action 727 it could be argued that the Russian system is the more efficient, where relatively simple rigs or small test spans can be installed and observed in connection with existing routines.

It is strongly emphasized that measuring wet snow at a limited number of locations must be connected to modeling tools, as described above, to be useful for any statistical purpose. This is especially important to relate any measured data to the variability of wet snow icing over longer time periods.

3.0 HISTORICAL WET SNOW EVENTS

3.1 General

There are an abundance of reports on wet snow incidents on overhead power lines in the international literature, particularly in the IWAIS series and Cigré reports.

It is beyond the scope of this report to provide a comprehensive overview of such events; rather, the objective of this chapter is to provide general information on the occurrence of wet snow in various parts of the world. This information is taken primarily from the IWAIS proceedings and Cigré reports in addition to the author's own experiences. The utility survey presented in chapter 6.0 provides a selection of significant events that have affected utilities worldwide.

Wet snow accretions will occur wherever precipitation takes place with concurrent temperatures near the freezing point of water. However, as described in Section 2, the conditions for wet snow formation on power line cables are quite restricted. Thus, there can often be precipitation at near 0°C without any significant accretion on power lines, while in other cases wet snow may accrete at a rapid rate, causing overloads on the power lines. The primary determinants for this include:

- Precipitation rate
- Duration of critical temperature
- Relative air humidity
- Wind speed perpendicular to the conductors
- Joule heating of conductors

Consequently, a wet snow event seldom covers a large area. In hilly and mountainous terrain wet snow will only occur within a rather shallow layer, often not more than 50-100 m thick. Occasionally, wet snow will fall near the coast or further inland, or in valleys as well as on the tops of hills. It has been reported from Iceland and Norway that wet snow incidents may occur more often on the leeward side of gently shaped hills rather than on the windward side. This effect is not fully understood, but it is likely related to spill-over precipitation, side wind maxima and evaporative cooling at lower relative humidity (Harstveit et al. 2015).

When the critical requirements above are met however, wet snow may accrete more rapidly than for other types of atmospheric icing. This is also the reason why in many countries with power lines that have had no significant wet snow event for the past 10-20 years or more, a major wet snow incident can suddenly occur.

3.2 Examples of wet snow accretions from literature

The Cigré Technical Brochure 344 "Big storm events. What we have learned." (WG B2.06, April 2008) includes two examples of significant wet snow events, in Germany, 24-25 November 2005, and in Japan, December 1980.

3.2.1 Germany, 24-25 November 2005

In the region of Münsterland, western Germany, an area close to the Netherlands, heavy ice loads occurred on power lines on November 24-25, 2005. Five 110 kV lines owned by the large utility RWE were damaged and 83 steel lattice towers failed (see Figure 3-1). This wind and ice storm event also affected the Netherlands and Belgium.

More information can be found in Thierauf, G. (2006) and Makkonen and Wichura (2010).

Figure 3-1: Wet snow in Germany, November 2005 (from Cigré TB 344).

3.2.2 Japan

Two incidents are discussed in the literature, one in the Tohoku area in December 1980, and a second in the Niigata Kaetsu area in December 2005.

3.2.2.1 Tohoku area, December 1980

In December 1980, the Tohoku area suffered serious damage caused by heavy wet snow accretion around conductors. The heavy wet snow was the result of low atmospheric pressure with high winds and heavy snowfall, following a rapidly developed low pressure system. The diameters of the snow sleeves varied from 80 to 150 mm, and the density measured 400 kg/m3. Seventy lines were affected and 62 towers collapsed. The maximum outage power was 1.3 million kW (1.3 GW) and the longest outage duration was 1250 hours (Cigré TB 344).

Following this event, various measures were undertaken to reduce future damage:

- Increasing design load for snow accretion
- Strengthening the conductors (from HDCC to ACSR)
- Inserting additional tower steel members to resist torsional loads caused by unbalanced snow accretion between neighboring spans
- Adopting various de-icing (wet snow) measures.

The de-icing measures are discussed in Section 5.

3.2.2.2 Niigata Kaetsu area, 22 December 2005

About 650 000 households were affected in the Northern part of Niigata prefecture "under the most severe weather conditions that are rarely encountered". All outages were restored after 31 hours. The technical reasons for the outages were galloping and sea salt contaminated wet snow on the insulators.

The accumulated precipitation during the period in which wet snow occurred was expressed as "the largest values in the observation records in the past 30 years at the Niigata Meteorological Observatory". The 10 minute wind speeds ranged up to about 25 – 27 m/s at the Higashi Niigata Thermal Power B Line (Onodera et al. 2007).

Following the storm several countermeasures were introduced:

- Some long-rod insulators were replaced by cap and pin insulators due to their improved geometrics
- Rigid spacers on bundled conductor were replace by loose spacers
- Phase-to-phase spacers were adopted on single-conductor line
- The power supply to the city of Niigata was strengthened
- A lower voltage operation was implemented in accordance with the storm alarms issued by the Meteorological Agency.

3.2.3 France, 5 March 2012

The largest icing storm in the low lands of France over the past several decades occurred in the Lille area on March 5, 2012. Wet snow accumulated on the lines over 11 hours with temperatures around 0.5°C, relative humidity close to 100% and a mean wind speed of 5-10 m/s. The estimated wet snow load on the earth wires was more than double the design load, resulting in significant damage to the lattice towers and earth wires (Figure 3-2). All of the damage was found on lines oriented perpendicular to the main wind direction during the event (Pers. com. Hervé Ducloux, RTE, France).

Figure 3-2: Damage to a tower and earth wire caused by the wet snow storm in Lille, 5 March 2012 (Photos: RTE, France).

3.2.4 Wet snow event in England, December 1990

In December 1990 a major storm in England occurred with significant amounts of wet snow in the Pennines (see Figure 2). Approximately 250 000 customers lost power from the failure of about 700 HV overhead line circuits and numerous low voltage networks in the area of one Distribution Network Operator (DNO). A WRF study of this event showed that the equivalent radial ice thickness (Req) was about 30 mm. According to reports from the DNOs, these results compared well with their own observations and experiences from the event, especially the areas most affected by the blizzard (Fikke et al. 2012).

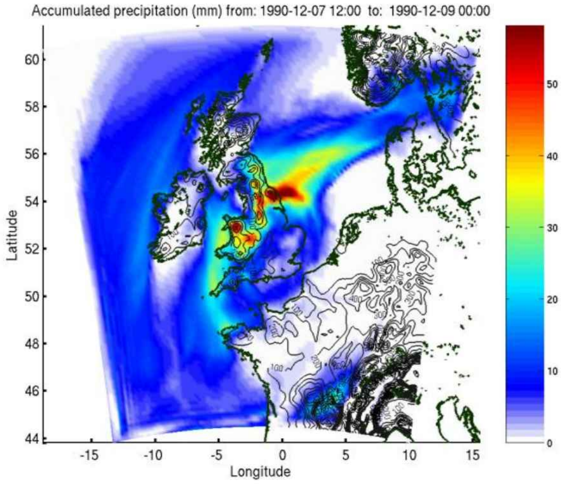

Figure 3-3: Accumulated precipitation on the British Isles over 36 hours, beginning at noon, 7 December 1990. Calculated by the WRF model (Fikke et al. 2012).

3.2.5 Wet snow events in Iceland

Over the past years, Iceland has experienced numerous wet snow events. Two relatively recent cases from 2012 are presented in Eliasson et al. (2013). On 10 September 2012 and 30 December 2012, two severe north-easterly wet-snow storms caused extreme ice loads on many transmission and distribution lines in North Iceland. The wet-snow accretion was combined with strong winds, resulting in broken wooden poles and H-frame towers. The September event was exceptional due to the extreme snowfall in early autumn. The snowfall was associated with average wind speeds in excess of 20 m/s, causing a widespread accumulation of wet snow within a certain altitude interval in North Iceland. In the latter event, heavy snowfall and gale-force winds, as well as extreme wet-snow loading, were more localized, occurring mostly in the lee of the complex orography of northwest Iceland.

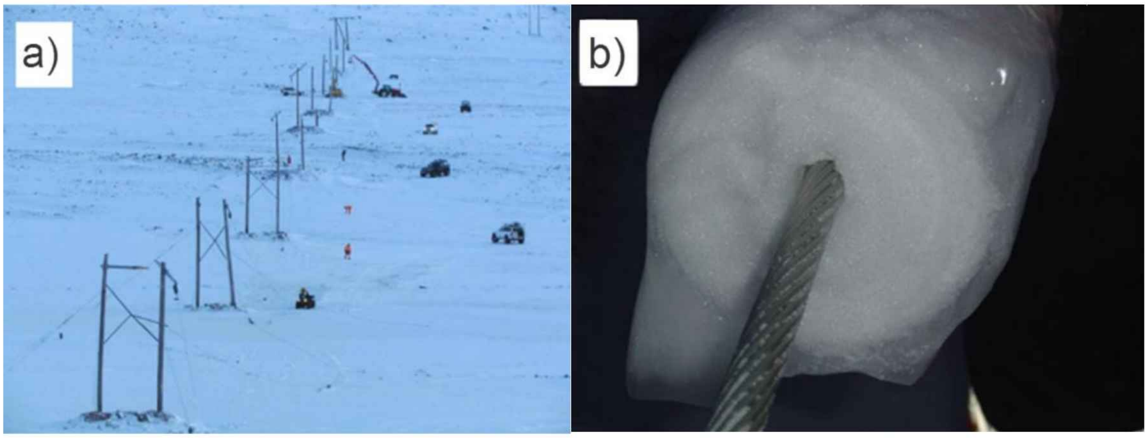

Figure 3-4: Photos from the wet-snow event of 29 December in Northwest Iceland.
a) Reparation work on faulted 66 kV OL1 at Bláfeldarhraun.
b) A wet snow sample east of Bláfeldarhraun, measuring 14 cm in diameter.

3.2.6 Norway, December 2015

In December 2015, a massive wet snow event caused the collapse of a 220 kV transmission line in Nordland County, Norway. The line was built in 1963 and no significant icing problems had been experienced prior to this event. The line was built with Curlew single phase conductors (16400 kp breaking strength) and Fe85 earth wire (11600 kp breaking strength). The vertical load caused the earth wires to break along several spans, which caused further damage to the towers, including the complete collapse of one tower. A detailed description of this event, including mitigation measures, is provided in Section 5.4.1.

3.3 Summary of the utility survey

The utility survey gathered responses concerning wet snow incidents from 13 respondents representing 11 countries. The results are listed in Table 3-1 below.

Table 3-1: List of wet snow storms based on the utility survey

Country	Events
Bulgaria	1986 - Central South Bulgaria – the most sever event ever; 2011 - NE Bulgaria; 2012/13 - 5 severe cases in the winter – the mountain Rodophes in Central South Bulgaria; 2014 - NE Bulgaria; 2015 - Rodophes in Central South Bulgaria; 2016 - NW Bulgaria.
Canada (NL Hydro)	1 recorded failure.
Canada (Altalink)	1986 - Alberta. Multiple Steel Tower and Wood pole structure failures. 2010 - Alberta. Multiple Steel Tower Failures.
Canada (Nova Scotia)	February 2004 - Tower (steel lattice) failed Halifax N3.

Country	Events
Croatia	We do not classify events in such detail; usually it is all attributed to ice.
Finland (Fingrid)	9/2014: Due to the wet snow, earth wire touched the phase conductor causing broken strands to the earth wire. Earth wire was repaired, no other actions. This occurred in East Finland. 11/2015: Altogether 5 disturbances in two lines. Nothing to be repaired. This occurred in Middle Finland.
Finland (Järvi Suomen Energia)	None at 110 kV transmission network. The following are typical examples from our 20 kV distribution network: - Ground faults and short circuits caused by trees bent by the weight of wet snow. - Broken conductor as the weight of snow stretches conductors so that a short circuit is caused.
Iceland	29.01.1966 – 80 wooden poles broken 27.10.1972 – 145 wooden poles broken 11.02.1974 – 297 wooden poles broken 02.01.1991 – 571 wooden poles broken 23.11.1992 – 176 wooden poles broken 29.01.1994 – 118 wooden poles broken 24.10.1995 – 168 wooden poles broken 10.09.2012 – 127 wooden poles broken
Ireland (ESBI)	Date Line Height a.s.l. Observed diameter 2 – 3 January 2010 - 10 kV lines in Kippure region, Wicklow ~ 300 m Max 100 mm Wet snow 31 March – 4 April 2010 - Several 11kV lines Cloughmills area 150 – 200 mm (worst affected areas) 75 - 150 mm Wet snow 13 December 2011 - 275 kV Coolkeeragh – Magherafelt (de-spacered line) 187 – 245 m ~ 150 mm Wet snow 19/20 January 2013 - 11kV to Mullaghmore 400 - 500 m Image Rime ice 22 March 2013 - 275 kV (Twin) Lisburn LV crossing 140 m ~ 150 mm* wet snow
Norway	January 1969 – Counties of Akershus and Agder January 1974 – Counties of Akershus and Agder November 1981 – County of Hordaland Winter 1992-1993 – Western and Northern Norway January 2011 – County of Sogn og Fjordane January 2012 – County of Hedmark December 2015 – County of Nordland

Country	Events
South Africa (ESKOM)	2001 - KwaZulu Natal - OPGW Failure 2008 - KwaZulu Natal - OPGW Failure 2012 - KwaZuluNatal - 22 lattice structures (KV/14) failed on 275 kV line. OPGW and Earthwire failure on 400 kV line.
Sweden (Svenska Kraftnät)	1969 Dalecarlia – altitude 540 m extreme ice and wind 1988 Dalecarlia – altitude 690 m extreme ice and wind 1988 Norbotten – altitude 375 m extreme ice 1990 Norbotten – altitude 450 m extreme ice 1996 Dalecarlia – altitude 750 m extreme ice 1996 Dalecarlia – altitude 610 m extreme ice
Switzerland (Swissgrid)	Damage of pylon cross arm about five years ago, de-icing.
USA - NYPA	Frequency is minimal and not recorded.

4.0 INDUSTRY STANDARDS

4.1 Historical review

Ice loadings have traditionally been treated individually by utilities as well as within national design codes. These are primarily based on deterministic assessments, where loadings were often combined with, or included in, the safety classifications of the line in such a way that the final reliability was found to be "acceptable". Hence, it is not possible to identify actual design values, either due to the ice loadings or to any specific type of ice.

The probabilistic concepts in overhead line design were first introduced by the IEC in report 826 "Loading and strength of overhead transmission lines," first published in 4 parts between 1985 and 1987, which was later updated and is now known as "IEC 60826". This was not a complete design code by itself, but rather a template to be followed by national regulatory bodies when developing their own codes. IEC 60826 introduced two approaches for overhead line design: one following the traditional methods, called the "deterministic approach", the other based on statistical information for both loading and strength parameters, called the "probabilistic approach". Although statistical information was initially very limited, IEC 60826 provided the theoretical procedures for including statistical information as this data became available.

By introducing the probabilistic concept, IEC 60826 also led to a new classification of atmospheric icing based the physical processes during its formation. This was necessary since the various icing types not only act differently on the overhead line conductors, but also require unique sets of data for evaluation of the load extremes.

Atmospheric icing is characterized by two main processes, *precipitation icing* and *in-cloud icing*. Each of these two primary types is again subdivided as follows (according to Cigré TB 291):

- Precipitation icing
  - Glaze due to freezing rain
  - Wet snow accretion
  - Dry snow accretion
- In-cloud icing
  - Glaze due to super cooled cloud/fog droplets
  - Hard rime
  - Soft rime

In addition to these categories, atmospheric icing includes hoar frost, which is not considered as critical to the loading but may affect electrical efficiency of the line due to the corona losses that it could generate.

Cigré TB 179 describes the density ranges and physical properties of the various forms of atmospheric icing, as shown in Table 4-1.

Table 4-1: Classification of ice types with typical density ranges (Cigré TB 179).

Ice and snow type	Density (kg/m³)	Description
Glaze ice	700-900	Pure solid ice, occasional icicles underneath the wires. Density may vary with the content of air bubbles. Very strong adhesion and difficult to knock off.
Hard rime	300-700	Homogenous structure with inclusions of air bubbles. Pennant shaped against the wind on stiff objects, more or less circular on flexible cables. Strong adhesion and more or less difficult to knock off, even with a hammer.
Soft rime	150-300	Granular structure, "feather-like" or "cauliflower-like". Pennant shaped on flexible wires. Can be removed by hand.
Wet snow	100-850	Various shapes and structures are possible, mainly dependent on wind speed and torsional stiffness of the conductor. When the temperature is close to zero it may have a high content of liquid water, slide to the bottom side of the object and slip off easily. If the temperature drops after the accretion, the adhesion strength may be very strong.
Dry snow	50-100	Very light pack of regular snow. Various shapes and structures are possible, very easy to remove by shaking the wires.
Hoar frost	<100	Crystal structure (needle like). Low adhesion, can be blown off by wind.

Ice loadings on electric overhead lines have been calculated using two different methods:

- As equivalent radial ice thickness
- As unit loading, or ice mass per unit length, kg/m.

In the first case, the ice density (900 kg/m^3) is normally used to calculate the loading, while the cross section area is given directly for calculating the wind force in combination with the wind. The radial ice thickness method is adequate for areas where glaze ice from freezing rain prevails.

In the second case, the loading is given directly, but the cross section must be calculated according to the prevailing density for the local ice formation. In this case, the radial ice thickness (based on the density of 900 kg/m^3) has little physical meaning. Nevertheless, the radial ice concept is widely used in such areas. This is due to the fact that many countries have copied other design codes without adapting them to local climatic conditions and prevailing icing types. This is the likely reason that few countries take wet snow explicitly into account in their design codes, even though wet snow is the main source of ice loading on power lines.

Figure 4-1 shows the relation between radial thickness and loadings for various ice densities. The graph is intended to provide a quick conversion between these variables.

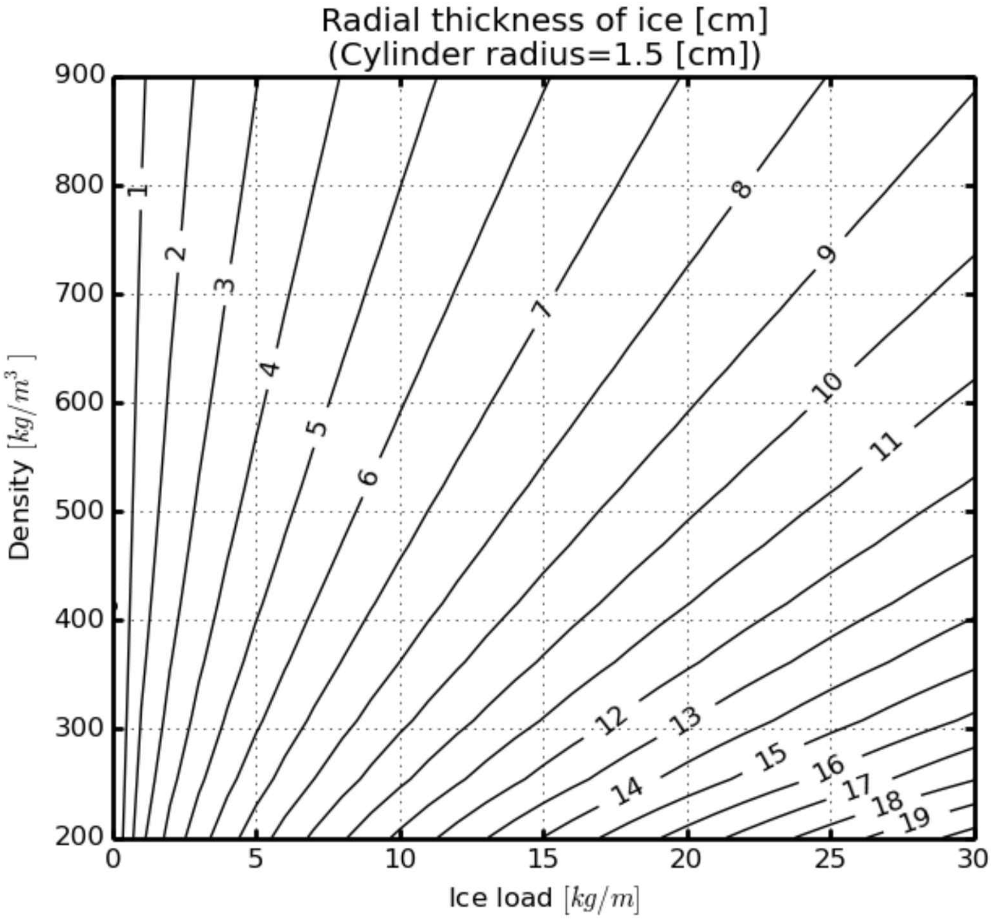

Figure 4-1: The relation between radial thickness (cm), loadings (kgm^{-1}) and densities kgm^{-3} for a conductor with a 3 cm diameter.

The answers in the Appendix, Questionnaire Part A must be interpreted with this in mind. However, it is also important to realize that although wet snow is not specifically mentioned in the National code, it is more or less self-evident that wet snow is the most significant icing case in the lowlands of most countries where freezing rain is not prevailing. Freezing rain is the typical icing type in countries where cold air can be trapped near the ground over large areas, such as in Russia, Canada, in large parts of the US and several areas of Europe. In most other countries, including Japan, New Zealand, South Africa and most of Europe, wet snow is the dominating load case, especially in the lowlands.

In rare cases, as has occurred in Alaska and parts of Japan, dry snow may accrete on power line conductors in such significant amounts that it influences the design loads of electrical overhead power lines. The load case to consider in the case of dry snow accretion is only the vertical load. Horizontal loads due to wind on iced conductors are not relevant for dry snow due to the weak adhesive and cohesive forces of the accreted snow.

4.2 Wet snow as treated in design codes and standards

This section does not provide a comprehensive overview of international practises concerning ice loadings from wet snow; rather, several examples from relevant countries are presented as a general reference. The following information is primarily based upon international collaborations with Cigré and IWAIS.

4.2.1 Canada and USA

Canada and the US are generally not exposed to severe wet snow accretions in most areas; however, these countries are dominated by freezing rain that can create devastating loads (e.g. the January 1998 Quebec ice storm). Freezing rain is a typical inland phenomenon where cold air accumulates over the Great Plains or drains down along valleys (e.g. St. Lawrence valley). Therefore, the design codes in these countries have been developed according to this type of icing.

Wet snow will nevertheless also appear in these countries, presumably with higher frequencies of occurrence in the western areas where on-shore winds transport higher humidity and where near zero temperatures occur during winter.

For the sake of comparison, part of a study by Rezaei et al. (2011) is detailed below. This shows how the factors for different return periods vary between the ASCE, CSA and CENELEC (EN 50341-1). The conductor diameter is 30 mm and the reference ice thickness is 19 mm in all cases (for Boston). Figure 4-2 shows how the vertical ice loads vary between the three standards. It is clear that the CSA and CENELEC (EN) standards are based on similar principles for extreme value distributions for return periods other than the common reference period of 50 years, while ASCE has a more conservative calculation model for return periods greater than 50 years.

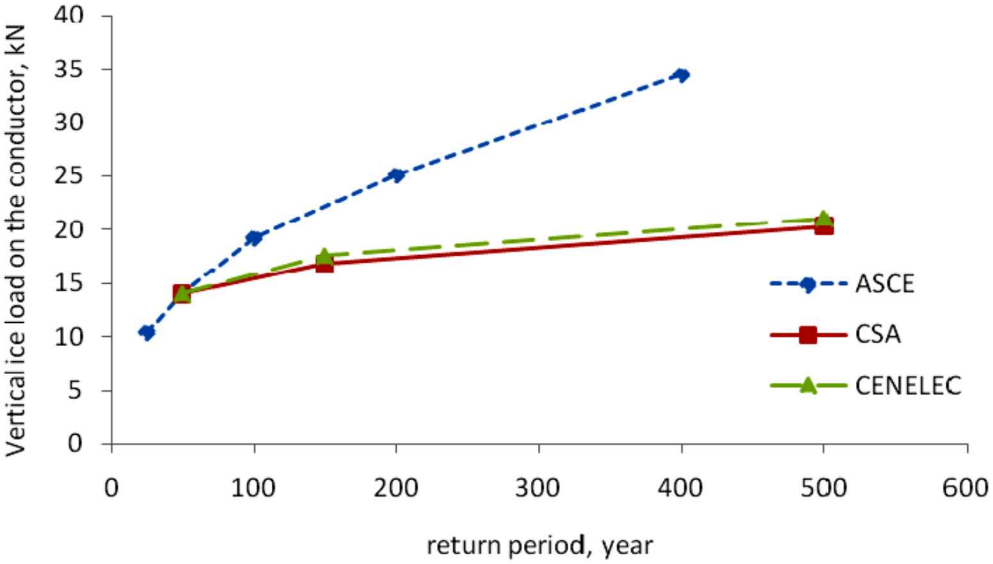

Figure 4-2: Comparison of conversion of vertical ice loads (kN) on conductors between selected return periods according to different codes (ASCR, CSA and CENELEC (EN 50341-1)).

Parameters used include wind span: 450 m, weight span: 540 m, effective height above ground: 25 m, conductor diameter: 30 mm, coincident temperatures: 15ºC for wind loads and -5ºC for ice loads.

4.2.2 New Zealand

Although no responses were provided in the utility survey from utilities in Australia or New Zealand, it is relevant to include an example of the principles of overhead line design from New Zealand since many countries in northern Europe have a similar topography and climate.

Standard AS NZS 7000-2010 Appendix EE "Snow and ice loads (informative)" describes atmospheric icing as a phenomenon which should be accounted for above 800 m.a.s.l. in Australia and in some areas in New Zealand.

For Australia, the design values for icing are given as radial ice thicknesses with the density of the ice set to 900 kg/m^3, while for New Zealand, the radial ice thicknesses are given for 400 and 700 kg/m^3 in AS NZS 7000-2010. The TSO (Transpower) specifies further details in Transpower TP.DL 12.01. "Transmission line loadings code," Issue 3, 2011.

Robert Lake, of Groundline Engineering, NZ, states that one reason for the lack of responses to the questionnaire from utilities in Australia and New Zealand is "not for a lack of wanting to help, but a lack of issues with snow and ice". Furthermore he adds:

In Australia, there have been individual spans affected by ice loading in the Alps, but no cascade or structure failure events, so this type of loading is only applied in a small number of locations, and is almost an aside for completeness.

In NZ, I am not aware of any structure failures, but there have been a few earth wire peaks bent as a result of unbalanced tensions and/or ice un-loading. The main reason that we investigated snow/ice loading recently was that the standard developers had gone to a very conservative level and this loading was starting to govern structure designs. So we reviewed the situation to bring the loading back in to line with historical experience.

It is assumed that similar statements apply to many of the utilities that did not respond to the survey.

4.2.3 Russia

A Cigré working document from 2004, "Increasing requirements to assessments of climatic loads under OHL designing in Russian power utilities," L. Timashova, V. Lugovoy, S. Chereshnyuk and V. Shkaptsov (B2-04(WG16)37), discusses the revision of ice loadings on power networks in Russia (valid from 1 October 2003). In Russia, ice loadings are given as an equivalent radial ice thickness; however, according to Cigré TB 645 "Meteorological data for assessing climatic loads on overhead lines" (January 2016), for all measurements of ice loadings the type of ice is recorded and included in the database.

4.2.4 Europe

The fundamental concepts from IEC 60826 concerning ice loadings are incorporated in the "Main body" of the European standard code, EN 50341-1:2012 "Overhead lines exceeding AC 1 kV, Part 1: General requirements – Common specifications," as prepared by CENELEC body CLC/TC11. The drag coefficients and ice densities are given for various ice types, as shown in Table 4-2.

Table 4-2: Drag coefficient C_d and ice density ϱI (kg/m3) for four ice types (After EN 50431-1:2012)

Ice type	Wet snow	Glaze ice	Soft rime ice	Hard rime ice
C_d	1.0	1.0	1.2	1.1
ϱ_I	500	900	300	700

However, the main body of EN 50341-1 is not compulsory for all member countries of CENELEC. Each country can specify their own practice in separate "National Normative Aspects" (NNA), giving so-called A-deviations (dependent upon national laws or regulations that cannot be altered at the time of preparation of the standard) "Special national conditions" (snc) (e.g. due to climatic conditions) and "National complements" (NCPT) reflecting alternative national practices (it is anticipated that NTCPs will be gradually reduced in the future).

For the purpose of this report a comprehensive survey of the various NNAs for European countries was not undertaken, however, Iceland, France, Germany, the UK, Ireland and Norway are all countries where the main principles of such icing types are implemented in their respective NNAs.

An example of the specification of the regional design values for ice loads is provided for Norway in Table 4-3. In this case, ice loads are provided for 16 areas representing the majority of the power lines built in the country. Also note that some recommendations consider a combination of wind and ice; these loads represent wet snow only. In areas or altitudes where rime ice is expected, it is recommended that a meteorologist is consulted.

Table 4-3: Design loads for 16 areas in Norway. The values represent a 50 year return period for wet snow (Table 4.5.1/NO.1 in EN 50341-1)

No	Region	Height above sea level (m)	Design ice load (N/m) 50 year return period
1	Main areas of the South East region*	0 - 200	30
2	Main areas of the South East region*	200 - 400	40
3	Main areas of the South East region	400 - 600	50
4	Østfold and Vestfold	0 - 200	20
5	Telemark and Agder	0 - 200	35
6	Telemark and Agder	200 - 400	50
7	The coast Rogaland – Stad	0 - 200	35
8	Fjordane Rogaland – Stad	0 - 400	40
9	The coast Stad – Namdalen	0 - 200	40
10	The fjords Stad – Namdalen	0 - 400	40
11	The coast Namdalen – Lofoten	0 - 200	40
12	The inland of Nordland	0 - 200	30
13	The coast Vesterålen – Nordkapp	0 - 100	35
14	The inland Troms - Vest-Finnmark	0 - 200	30
15	The coast of Aust-Finnmark	0 - 100	30
16	The inland of Aust-Finnmark	0 - 200	20

*Except areas mentioned in no 3 and 4.

NOTE: In areas 1, 2, 4 and 5, combined ice and wind loads may be replaced by applying V_{500} on ice free conductors. For insulated overhead cables other return periods may be applied.

In areas 3 and 6-16, combined ice and wind loads shall be applied. This may be deviated from on the advice of a meteorologist.

4.3 Concurrent ice loadings and perpendicular wind speeds

Most standards have separate rules for the horizontal forces on power line conductors due to the perpendicular winds on ice covered conductors.

Ideally, the combined action from concurrent winds on ice covered conductors should be calculated from wind speeds occurring during icing events. This has normally been unachievable, such that alternative methods are applied.

EN 50341 and IEC 60826 describe two options for calculating a combined loading for wind and ice:

- An extreme (or low probability) ice load, I_T combined with a high probability wind velocity, V_{IH} (often selected as the wind speed with a return period of 3 years).
- A nominal (or high probability) ice load, I_3 (often selected as the ice load with a return period of 3 years) combined with a low probability wind velocity, V_{IL}.

EN 50341-1 suggests a reduction factor on wind speed in combination with ice covered conductors. This is based on the fact that ice loadings remain for only a short and limited time on the conductors, therefore there is a low probability that seasonal extreme winds will occur simultaneously with high ice loads on the conductors. This factor will also vary with the icing type; for instance, wet snow in temperate countries will remain for only a short time on the conductors and will also shed more easily with a moderate wind. In regions where sub-freezing temperatures are dominating throughout the winter season it is reasonable that wet snow accretions will have a higher adhesion force to the conductor and also remain for a longer time. A similar consideration may also apply for glaze.

For the case of a moderate ice load (e.g. 3 year return period) in combination with an extreme wind load (e.g. 50 years return period); the reduction factors include wind at 0.7 in combination with wet snow at 0.85 with rime ice.

Some countries (e.g. Norway) apply project specific reduction factors if sufficient data is available. For instance, ice in mountains may remain on conductors for weeks and even months, and therefore the reduction factor must be specified according to the local conditions. Calculating these reduction factors requires sufficiently long time series of meteorological and icing data, either obtained from observations or from model generated hindcast archives.

5.0 MITIGATION METHODS

5.1 General

Due to the socio-economic effects resulting from the outages of electric power supply in connection with severe ice accretions on electric overhead lines, there have been many attempts to develop and test various methods and devices for both preventing ice formation on the conductors and removing ice from the lines whenever excess loads are threatening the safe operation of the line. Such methods can be either mechanical or electrical.

However, the most significant "lessons learned" on mitigation measures can be taken from the historical evolution and experiences related to design standards and codes, the selection of line routes, and the design practices of overhead lines over most of the past 50-60 years or more. This evolution is mainly based on the historical failures of overhead lines, in addition to an increased knowledge of the physical processes behind the formation of various types of ice accretion, topographical influence and improved methods for ice load assessments. The static and dynamic effects that the ice loadings have on the structural responses and behavior of towers, masts and conductors are also taken into account.

It is the impression of the authors that there is no conclusive evidence from the experiences with the explicit systems installed on overhead line conductors that can support a recommendation concerning this issue. This includes the application of Joule heating to conductors by lowering the line voltage.

In this section, historical experiences as well as methods and devices are summarized from the literature. Comments from the authors are also provided when relevant.

5.2 Mitigation in the pre-construction phase

5.2.1 Design codes and standards

The development of IEC TR 60826 "Loading and strength of overhead transmission lines" during the late 1980s and early 1990s introduced a new and reliability based philosophy for overhead line design. It incorporated general experiences from the operation of overhead lines as well as their characteristic failures over the previous decades. Accordingly, IEC 60826 introduced some new aspects in overhead line design that must be considered as fundamental mitigation methods for preventing a large number of traditional failures in conventional lines.

Examples of the mitigation countermeasures introduced in IEC 60826 include:

- Introduction of a reliability based design with respect to both the strength of line components and the probability distribution of extreme weather loadings
- Separate analyses of tension, longitudinal and transverse bending forces on singular towers
- Insertion of tension towers in long and straight sections of a line in order to reduce cascading failures
- Acceptance of the various types of atmospheric icing (freezing rain, wet snow and rime ice) and their individual physical properties
- A physically based accretion model for ice build-up with respect to conductor diameter

It is the strong belief of the authors that these countermeasures have reduced the failure rate of overhead lines significantly (e.g. the experiences from the January 1998 ice storm in Canada).

5.2.2 Line planning and routing

Another important lesson learned over the history of overhead line planning is the selection of line routes. It has been recognized that the local exposure and shielding effects are highly important for wind exposure as well as for the accretion of ice. These may also be different for the various icing types (rime ice, wet snow and freezing rain) (see Cigré TB 291).

5.2.3 Load assessments

Finally, the scientific developments concerning the analyses of the atmospheric conditions for assessing the conditions for and quantification of loadings from wet snow and in-cloud icing are emphasized (see Cigré TB 645).

5.3 Mitigation methods for lines in operation

A good overview of the current mitigation methods for icing on overhead lines is described in Cigré TB 438. This Technical Brochure classifies the anti-icing and de-icing methods as follows:

- Passive methods
    a. Coatings and devices
- Active methods
    a. Mechanical methods for ice removal
    b. Thermal methods (melting of ice on conductors)

A brief overview is provided in the following subsections.

5.3.1 Passive methods

Three strategies are used to prevent ice accretion on conductors:

1. Weakening the adhesion strength
2. Preventing the freezing of supercooled water droplets on impact
3. Using a combination of specific devices for limiting the impact of ice overloads on conductors

The first two strategies are defined as anti-icing and are not considered relevant for this report since they require special design considerations for the material and surfaces of the conductors. Therefore, several device strategies (method iii) are discussed below.

5.3.1.1 Counterweights

It is well known that the accretion rate of ice, including wet snow, on overhead line conductors is a function of the torsional stiffness of the conductors themselves. The easier they are to rotate, the higher the ice accretion rate will be and the more rapid a cylindrical ice sleeve will grow. Hence, a single conductor line will accumulate more ice than a sub-conductor in a bundle. In this case, the ice will accrete only on the windward side and prevent the build-up of the more efficient circular shape.

Comment: This method should be efficient for both rime icing and wet snow; however, there have been experiences in which this method enhanced galloping of the conductors. It seems that this method has not obtained a wide application. It should not be used in areas where rime ice or freezing rain dominates due to the increased risk of galloping.

5.3.1.2 Snow rings around the conductor

Several decades ago, Japanese utilities introduced plastic rings or twisted (plastic) cables onto the conductors. The intention was that wet snow would slide along the inclined conductor and break off when it met the obstacle on the conductor surface. These rings remain installed on several lines in Japan.

Comment: This method requires that the snow sleeve is wet enough to slide (low adhesion forces). This requirement is probably not met in most wet snow cases around the world.

5.3.1.3 Other methods

Excess loads due to ice will increase the sag of conductors. In order to avoid the clashing of conductors, especially on multi-circuit lines with a vertical configuration, the middle cross arm is often longer than the others; thus, there is less chance for clashing both when a conductor has a higher overload than the one below, and also in cases with a sudden shedding of ice.

Vertical interphase spacers (insulated) are also often applied to prevent the clashing of conductors in a vertical configuration.

Comment: In a horizontal configuration, the upper ground wire may sag between the phase conductors below and also blow to the sides in a moderate wind. When this occurs, the ground wire is often buried in the ground or removed.

5.3.2 Active methods

5.3.2.1 Mechanical methods for removing ice

Several methods for removing ice from the conductors have been utilized in various countries, including:

- Scraping machine, called a "Remotely Operated Vehicle" (ROV). This was developed by IREQ following the January 1998 ice storm in eastern Canada and the northeastern states of the US.
- Scraping rope. This has been used in several countries, but has been phased out due to the risk of flashover along the rope.
- Shock wave methods. Different methods were tested for creating a shock wave along the conductors to break off the ice; for instance, a "hammer hook" to hang on the conductor.

- Use of a helicopter. Helicopters have been used to remove ice in two ways. First, blowing the low density ice (wet snow) off the conductors by flying close to the line. Second, suspending a vibrating device underneath the helicopter that is hooked on the conductor (tested in Norway). This method is dependent upon weather conditions for safe operation.

5.3.2.2 Joule heating

When voltage is lowered the current will automatically increase in order to transmit the same amount of power. This has been used in many countries, including the US (New England, 1920) and Canada, and remains in use in Russia and some eastern European countries. This method requires special arrangements at both ends of the line, and can only be used on lines that are not too long for the required melting power. It is less efficient on bundled conductors due to the required amount of melting power for these lines.

Further details, including theoretical foundations and references, can be found in TB 438.

5.4 Recent field experiences

5.4.1 Norway

As previously mentioned, a wet snow event in December 2015 caused the collapse of a 220 kV transmission line in Norway. The line was built in 1963 and icing had not caused any significant problems until December 2015. The line was built with Curlew single phase conductors (16400 kp breaking strength) and Fe85 earth wire (11600 kp breaking strength).

Figure 5-1 shows a map of the affected sections. The main failure occurred near an 800 m long span crossing lake Røssoga. A list of the affected spans and towers is provided in Table 5-1, which shows that both towers on each side of the 800 m long span had broken tops, likely caused by the breaking of the earth wire. The damages escalated further to the east, with broken earth wires between tower 95 and 96, and tower 96 completely collapsed. A few intermediate failures were registered during the first two days of the storm (4-5 December), probably caused by the broken earth wire west of tower 95. The permanent outage of the line on 6 December was likely caused by the collapse of tower 96 (Figure 5-2, left). It was further noted in the analysis from the TSO that a large number of tension towers on each side of the lake may have saved the towers further away from cascading failures.

A cylindrical wet snow sleeve with a diameter of 12-14 cm was measured on the earth wire just after the collapse. The density of the accumulated ice was exceptionally high (near glaze ice), which corresponds to an ice load of about 13 kg/m. Figure 5-2, shows the remaining ice on the collapsed earth wire 3 days after the event. Near tower 95, the snow sleeve had a diameter of 15-20 cm.

Figure 5-1: Line route map showing the sections affected by the wet snow icing.

Table 5-1: List of affected towers/spans.

Tower number	Tower type	Span length	Damage	Tower type after restoration
92	Tension	163 m	-	Tension
93	Suspension	800 m	Broken tower top, broken earth wire	Tension
94	Suspension	315 m	Broken tower top	Suspension
95	Tension	269 m	Both earth wires broken on one side and one on the other side	Suspension
96	Suspension	273 m	Collapsed tower	Tension
97	Tension	230 m	-	Tension

Figure 5-2: Left: Collapsed tower number 96. Right: Remaining ice on the broken earth wire, three days after the incident.

5.4.1.1 Mitigation measures

The original ice loading taken into account in the design of the line was 4 kg/m (50 year return period). The design load was estimated based on general weather data as well as qualitative evaluations carried out by experienced meteorologists at that time. Note that the value of 4 kg/m at 385 m above sea level corresponds well to the reference value of 3 kg/m (applied 0-200 m above sea level) found in line 12 of Table 4-3.

The failures experienced can be clearly explained by the weight of the ice alone, which probably exceeded the design load by a factor of three. The wind during the event was moderate and only about 25 % of the design wind speed. Though differences exist between the current standards and those applied in the 1960s in terms of taking ice loads into account (different load cases etc.), the obvious reason for failure in this case was that the design ice load was significantly exceeded during the storm.

Before restoring and strengthening the line, two main questions needed to be answered. What is the probability for the occurrence of a similar wet snow load in the future (i.e. what is the actual return period of the 2015 wet snow storm)? And secondly, what is the proper ice load to use in the design of the new line sections?

To answer these questions, a detailed meteorological analysis was performed by specialized meteorologists. The analysis is briefly discussed in section 2.2.2 with results of a simulation of the event shown in Figure 2-12. Based on 36 years of modeled wet snow data, a 1 in 50 year wet snow load of 10.4 kg/m was calculated. The result implies that the estimated return period of the wet snow load in 2015 was well above 50 years. The report concluded that this particular line section was especially exposed to wet snow icing due to the local topographical features as well as the orientation of the line route being perpendicular to the main icing wind direction.

During 2016 and 2017, the TSO will restore the affected sections according to current design standards, with a new design ice load of 13 kg/m (150 years return period). The new design has several important structural implications, including:

- More robust towers, normally used for 420 kV lines
- Rearranged positioning and number of tension towers (Table 5-1)
- New earth wire from tower 93 to tower 96, with a 33 % increased breaking strength (Trima 412,58 mm^2)
- New phase conductors from tower 93 to tower 96 with 49 % increased breaking strength (Lunde, single conductor,791,38 mm^2)

5.4.2 Experiences from Iceland

The extensive icing database of Landsnet, the Icelandic TSO, is based on a large dataset of reports of failures and problems due to icing on overhead lines, including on older telephone wires (Figure 5-3). The database has been used to identify problem zones in the net and prioritize work pertaining to the mitigation of icing problems (Figure 5-4).

An efficient method of mitigation depends on the fact that wet-snow accretion is strongly dependent on the actual line orientation with respect to the angle of attack of the wind. The most efficient accretion occurs when the wind blows perpendicular to the conductors, while the efficiency is quickly reduced with a larger angle of attack. This fact has been used by Icelandic line operators when rebuilding damaged lines, in particular for frequently exposed parts of the distribution system.

Another effective method of mitigation is to replace overhead lines with underground cables, which is a method that has been actively employed in Iceland. Prioritization has been based on the aforementioned database as well as rebuilding following severe icing events; for example, the severe event on 10-11 September 2012 (Elíasson et al., 2013) in which a northeasterly storm caused extreme snow accretion, in combination with strong winds, on many distribution and transmission lines for large parts of northern Iceland. The damage was extensive with outage/blackouts in many regions. During the rebuilding phase, a large part of the system was replaced with underground cables. Prior severe wet-snow storms in the region were characterized by a slightly different wind direction and had caused extensive damage to other parts of the net. Underground cables were also used to replace damaged lines at this time, however the different wind direction explains why parts of grid were not as severely affected by these earlier storms.

At the time of the design of most existing and older lines, a specific and detailed analysis of the icing climate was not possible. New designs take into account data from the icing database, extensive observations from a network of icing test spans (initiated in the 1970s) as well as a detailed analysis of icing simulations. This has significantly reduced the frequency and severity of problems related to wet-snow icing on new and rebuilt lines.

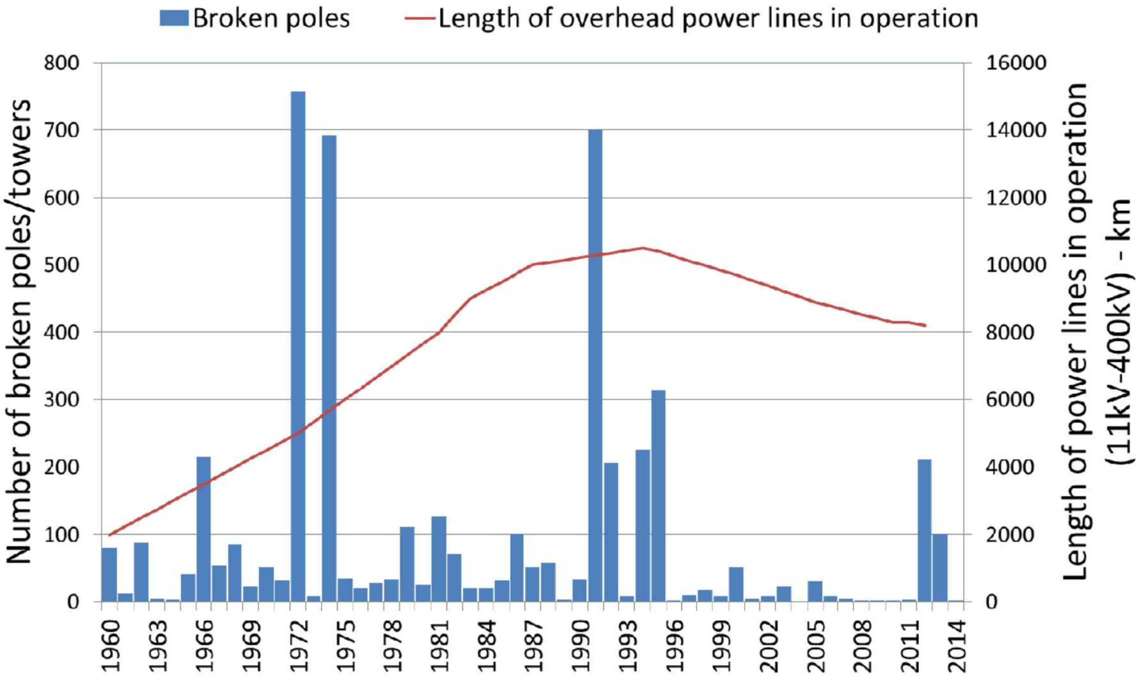

Figure 5-3: Number of broken poles registered in the database since 1960.
Most failures are due to wet snow icing on 11-33 kV lines (source: utility survey response from Landsnet, Iceland).

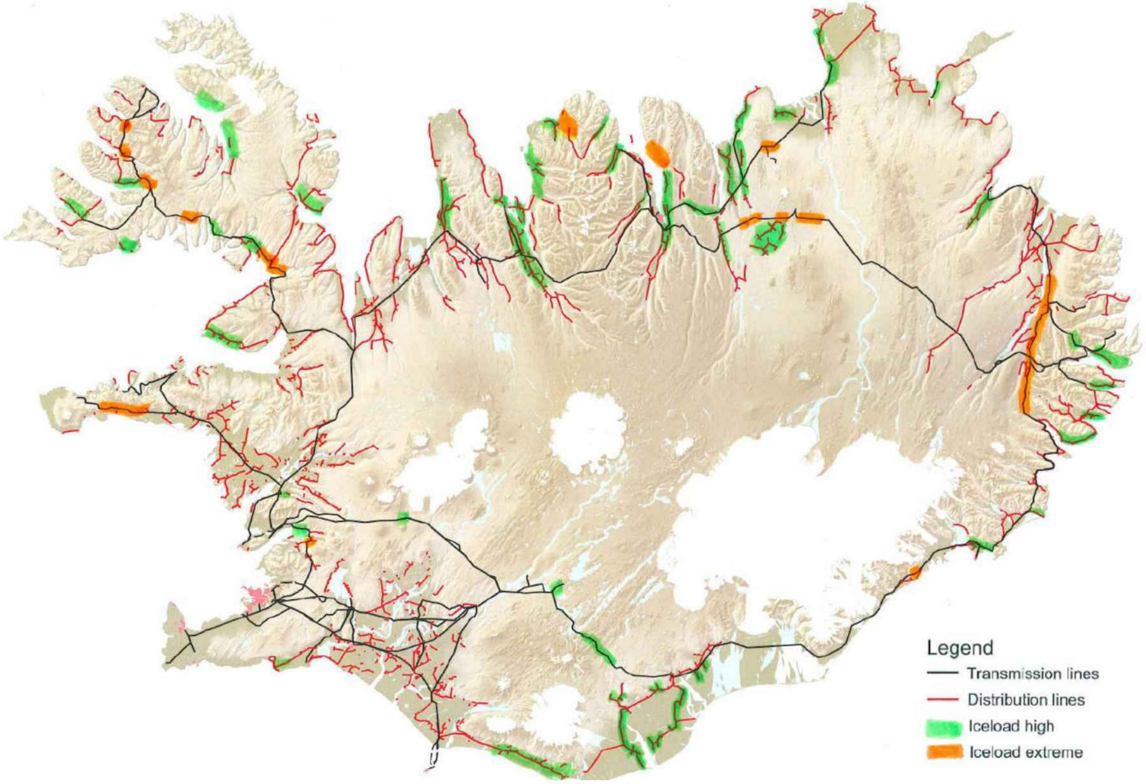

Figure 5-4: Power lines where high and extreme wet snow accretion has been observed (Source: utility survey response from Landsnet, Iceland).

5.5 A concluding comment

From the literature the authors have found no reliable method for preventing icing on overhead line conductors or for removing such ice after its formation. The most effective mitigation method seems to be designing the line according to the expected loading for the area. This includes configuring to the local topography, prevailing exposure and wind direction.

6.0 UTILITY SURVEY

6.1 Introduction

A questionnaire was distributed to a large number of international utilities in order to obtain a global perspective on the occurrence of wet snow accretion on electric overhead line conductors, and to identify variations in design codes and practices for wet snow load assessments. The survey is broken into six parts:

1. Part A: Wet snow loadings as treated in design codes, standards and operational experience
2. Part B: Occurrence of wet snow
3. Part C: Collection of specific data for wet snow load assessments
4. Part D: Restoration measures
5. Part E: Electrical failures due to wet snow
6. Part F: Wet snow Removal

The complete questionnaire is shown in **Appendix A.**

6.2 Responding utilities

The survey was submitted to 32 recipients, primarily utilities in the US and Canada, but also to other countries including Ghana, Israel and New Zealand. In addition, the questionnaire was sent to specific contact persons in more than 30 countries (22 European countries and 8 representing South America, Africa, Oceania and Asia) including China, Russia and Japan.

The questionnaire was responded to by 20 individual utilities representing 13 different countries. These are listed in Table 6.1.

Table 6.1: List of respondents

	Country	Utility	Comment
1	Bosnia		
2	Bulgaria		
3	Canada	Altalink	
4		NL Hydro	
5		Nova Scotia	
6	Croatia		
7	Finland	Fingrtid (TSO)	
8		Järvi Suomen Energia	
9		Loiste Sähköverkko	
10	Iceland		
11	Ireland	ESBI	

	Country	Utility	Comment
12	Norway		
13	Poland		
14	South Africa	ESKOM	
15	Sweden		
16	Switzerland		
17	US	USA - BPA	
18		Duke Energy	
19		NYPA	
20		Entergy	

6.3 Main conclusions

Individual responses are provided in Annex A.

The general conclusion from the survey is that most utilities do not distinguish amongst individual icing types. The main reason for this is that for a specific utility (region) or country there is usually only one dominating type of ice, whether this is wet snow or freezing rain. However, in areas where freezing rain dominates, wet snow may also occur but is often less significant and therefore not specifically noted.

Another important issue regarding wet snow is that accretions occur only when the atmospheric conditions are quite restricted, as described in Section 2. Since these restrictions seldom remain for long, the resulting wet snow accretion is often low. However, in rare cases (generally), the physical requirements for wet snow may remain for a longer period of time where the accretion may grow rapidly to significant values. This is often the case for countries such as Japan, Iceland, Norway and various countries in central Europe.

An important observation is that electric overhead lines in countries where precipitation occurs near 0°C may be at risk of severe wet snow events at some point in time.

In addition to the specific responses to the questionnaire, supplementary information is included below based on available literature, including from Cigré reports and IWAIS proceedings.

The general responses are summarized in the following 6 tables. Where the total number of answers is lower than 20, some responses were blank or were answered with N/A, N/R or "No data". Some respondents answered positively for two or more options.

Part A: Wet Snow Loadings as Treated in Design Codes, Standards and Operational Experience				
Are wet snow loads explicitly taken into account in your design practice?	Yes: 11	No: 8		Comments: Most utilities do not distinguish wet snow from other types of ice loadings. However, wherever wet snow dominates, this is causing their main load.
At which level are wet snow loads incorporated in the design codes: a) International (e.g. IEC, CENELEC,) b) National regulations and/or codes c) Company practice	a): 5	b): 11	c): 5	Some utilities apply a combination of two or all three of these options.
Are regional design values for wet snow load specified in your region/country?	Yes: 8	No: 8		One utility specifies wet snow loadings individually for each line or line section. One utility may change with a revision of NNA.
Are these loadings connected to any measurements, icing models and statistical distribution (probabilistic approach), or fixed according to traditional "best practice" (deterministic approach)?	Probabilistic: 6	Deterministic: 6		
Are wet snow loadings considered less dominant with respect to other types of icing?	Yes: 4	No: 8	Variable: 2	

Part B: Occurrence of Wet Snow				
How often, annually, is snow accretion on power lines observed in your region/country?	< 1: 3	1 – 10: 8	> 10: 2	

Part B: Occurrence of Wet Snow				
How often, annually, are mechanical overloads due to wet snow observed?	< 1: 8	1 – 10: 4	> 10: 2	
How often do failures or damages due to wet snow occur?	0: 5	<1: 6	1-10: 5	Nova Scotia responds: "N/A" and "Usually heavy wet snow loads have led to catastrophic failure"
What is the structural type and voltage level of overhead lines exposed to overloads?	Poles (<50 kV): 6	Steel (lattice) (> 50 kV): 15		
Are observations, overloads or failures due to wet snow limited to certain regions, locations or certain types of terrain?	High ground, inland	Limited: 7	Everywhere : 7	
If possible please give a list of the 5-10 most important wet snow events, including year and location:	13 respondents reported 1 – 10 events. See Appendix A for further details.			

Part C: Collection of Specific Data for Wet Snow Load Assessments				
Are specific data and information on wet snow loadings collected in your country/region?	Yes: 5	No: 9	Occasional: 2	
Measurements on dedicated rigs	Yes: 1+ 1(?)	No: 12		
Observations on overhead lines		Yes: 12 (mostly occasional)	No: 5	
Mechanical failure analyses	Yes: 10	No: 6		
Wet snow loadings maps based on Icing models/weather data	Yes: 9	No: 8		
Are wet snow loads analyzed in combination with concurrent wind speed and direction?	Yes. 8	No: 8	Uncertain: 1	
Other	None			

Part D: Restoration Measures				
Indicate main restoration measures after damages due to wet snow overloads:				
Re-built as before	Yes: 9	No: 4	Variable: 2	
Strengthening of structures	Yes: 6	No: 4	Variable: 2	
Change of structure types	Yes: 6	No: 3	Variable: 3	
Removal of ground wires	Yes: 2	No: 7	Variable: 2	
Rerouting of the line	Yes: 1	No: 9	Variable: 3	
Re-analyzes of weather data	Yes: 6	No: 7	Variable: 2	
Other	None			

Part E: Electrical Failures due to Wet Snow				
Have you had electrical failures due to wet snow? In case of "yes" please specify:	Yes: 9	Possibly: 6		See further comments in Appendix A
Was it on-line insulation?	Yes: 7	No 3		See comments from Finland in Appendix A
Was it in substations?	Yes: 4	No: 5		
Was it in combination with sea salt pollution?	Yes: 3	No: 7		
Was it in combination with industrial pollution?	Yes: 1	No: 8	Uncertain: 1	
Specify countermeasures	Longer chains: 1	Water wash: 1	Various: 2	

Part F: Wet Snow Removal				
Do you apply any method for ice removal? In case of YES please specify:	Yes: 11	No: 5		Answers include: rope, impact, or possibly other mechanical option.
Mechanical removal of snow/ice	Yes: 10	No: 2		Use of rope or helicopter.
Electrical (Joule heating)	Yes: 1	No: 11		
Do you consider ice-phobic coatings?	Yes: 1	No: 12		
Other	None			

7.0 CONCLUSIONS AND RECOMMENDATIONS

A detailed literature review on the physical phenomenon of "wet snow icing" is conducted and presented in Section 2. While aspects of the literature review are devoted to understanding wet snow icing and its relation to meteorological conditions, important methods are described for taking wet snow icing into account in the design of transmission lines.

- Compared to other icing types, wet snow has a lower adhesive force and will more easily shed from torsional rigid cables. Thus, wet snow icing is primarily a problem on single phase conductors and overhead earth wires. It may also occur on bundled conductors, but to a lesser extent.
- Wet snow icing on transmission lines only occurs in a very narrow range of atmospheric conditions, including a combined range of temperature, relative humidity, wind speed and precipitation rate, along with its profile in the atmosphere. Thus, wet snow icing may be infrequent in many regions, such that it is nonexistent for many years or even decades. However, over the expected life time of a transmission line, the probability of a severe wet snow event remains significant and must be considered in its design.
- The density of accumulated wet snow may vary within a wide range, depending upon meteorological conditions. Therefore, a fixed ice density of 900 kg/m^3, which is used in many standards for calculating wind pressure on iced conductors, is not applicable for wet snow icing. Density in the range of 500 – 700 kg/m^3 is more accurate for wet snow icing. A site specific value can be calculated from meteorological data.
- Joule heating may be effective during the early stage of an icing event in preventing or delaying icing. However, as soon as a cylindrical wet snow sleeve has been formed around the conductor, Joule heating is less efficient as a mitigation method.

Section 2 also deals with several issues related to the modeling of wet snow icing based on meteorological data.

- Aspects of the wet snow accretion mechanisms are complex, such that practical models require a combination of theory and empirical relations. Therefore, a variety of models and parameter settings have been proposed in the literature. Based on a review of the literature, the most recently published papers on the respective subject are recommended (e.g. Ducloux and Nygaard, 2014).
- When using weather station data as input to wet snow icing models, care should be taken regarding the quality of meteorological measurements during wet snow storms since the wet snow itself could affect instrumentation (e.g. under-catch (underestimation) of precipitation amounts and slowdown of wind anemometers). These effects could cause an underestimation of the modeled wet snow loads if not properly taken into account.
- Numerical weather prediction (NWP) models show promise for predicting the necessary meteorological data to model wet snow icing. However, these methods are at a very early stage of development, and the use of such models should be carried out in collaboration with NWP experts.
- Regional or national maps of wet snow occurrence and its extreme value distribution can be made based on a dense network of weather stations and/or hindcast archives from NWP model simulations. Mapping of wet snow icing should be carried out in all regions where it may occur and affect the reliability of power lines.

Severe events of wet snow are reported for all continents in the northern hemisphere; several cases have also been registered in New Zealand and South Africa. Section 3 describes wet snow storms of significance that have been recorded throughout history. A wet snow storm in Germany and some neighboring countries in 2005 was the most severe wet snow storm in terms of total damage and economic consequence. This case clearly illustrates that wet snow icing can suddenly strike a region where past experiences has been limited.

Wet snow loads are mentioned as one possible icing type to consider in international standards, such as IEC 60826 or CENELEC (EN 50341-1). Several European countries treat wet snow specifically in their "National Normative Annex (NNA)," included in EN 50341-1. Wet snow loads are considered differently amongst utilities, varying from country to country. In some wet snow prone regions, a map or tabulated reference values of characteristic wet snow loads are provided according to area and altitude, while in other regions wet snow load is indirectly taken into account through infrastructure design.

From the author's point of view, it is necessary to treat the load case of wet snow according to the climatic conditions of the specific region or country simply because wet snow may vary by an order of magnitude in density, while its frequency, magnitude and duration is highly variable between different climatic zones. This also affects a combined load case with extreme wind and the specific reduction factors that should be applied.

A review of mitigation methods is presented Section 5. Regarding the reviewed literature, no fully reliable method for preventing icing on overhead line conductors or for removing formed ice was found. The most effective mitigation method seems to be designing the line according to the expected loadings in the area. This includes determining the configuration and taking into account the topography and the prevailing exposure and wind direction. In critical situations, de-icing measures such as joule heating or mechanical ice removal are actively used in various countries.

In case of failure or collapse due to wet snow, it is important to review designs for wet snow loadings in the restoration process. Analyses of design loads should take local conditions into account, including prevailing wind direction during icing and its normal component to the transmission line. If there is a lack of reliable and representative weather station data, studies using NWP models must be considered.

The general conclusion from the utility survey is that most utilities do not distinguish individual icing types. The main reason for this is that for a specific utility (region) or country there is only one dominant type of ice, whether it is wet snow or freezing rain. In areas where freezing rain dominates, wet snow may certainly occur as well; however, since it is often less significant than freezing rain it is typically not taken into account.

Considering the literature review and responses to the utility survey, several observations and recommendations can be concluded:

- Since wet snow, freezing rain and rime ice result from different physical processes, their statistical properties accordingly differ. Extreme values must therefore be calculated individually for each process.
- Where occurrence is rare, it is generally very difficult to collect data from wet snow icing events.

- Measurements of wet snow icing can be performed where icing is frequent, preferably through the use of test spans instrumented with load cells and data loggers. Heated web-cameras should be included to improve data during the ice shedding process.
- The greatest potential for improving the data collection of local wet snow icing conditions is through combining a measurement campaign with a model study such that a wet snow accretion model is coupled to an NWP model. Long time-series of gridded weather data (re-analyses) are publicly available and can be used for further downscaling to a local level.
- Reliable extreme value calculations can be performed in all types of terrain with such models.

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APPENDIX A. QUESTIONNAIRE FOR REVIEW OF EXPERIENCE, OCCURRENCE, DESIGN PRACTICES AND MITIGATION METHODS RELATED TO WET-SNOW ACCRETION ON OVERHEAD POWER LINES

This survey has been prepared for the use in the CEATI Project TODEM 33101 "State of the Art report on Designing Transmission Lines for Wet Snow Accumulation". The Survey will be used in order to gather data needed to comply with the scope of the project. Answers to all provided questions are greatly appreciated, and will assist in improving the reliability of overhead line networks.

Introduction

Atmospheric icing is a general term for several types of ice accretions as described in more details in for instance Cigré Technical Brochure 291 "Guidelines for meteorological icing models, statistical methods and topographical effects (Cigré, 2006), and ISO 12494 "Atmospheric icing" (ISO, 2001). Most relevant types for electrical power overhead lines are in-cloud icing (rime icing), freezing rain (glaze ice) and wet snow.

This questionnaire deals with wet snow accretion only, which occurs more or less frequently on power lines in such areas of the world where precipitation occurs in combination with air temperature between 0 and + 2 °C, roughly. An example of a wet snow sleeve on an electric conductor is shown in Figure A-1.

Figure A-1: Wet snow event in Northern Ireland, December 2011. (Source: BBC news)

Electrical overhead power lines in all countries, where cold climate prevails during winter, are usually designed to withstand ice loadings of various types. The loads themselves can be assessed differently according to the icing type, using the available data and icing modeling. The purpose of this questionnaire is to collect information on how the design loads, as given in various standards and codes, are specified by the utilities with respect to wet snow, and what are the operational experiences when such loadings occur. The results of the survey will be analyzed and the summary of the findings will be shared with the respondents.

Your response will be greatly appreciated. Complete answers to all questions will be valuable in the analysis of the results, even in the cases where previous reports from individual utilities already exist. In such a case, please refer to the previous report, for example Cigré and/or IEEE reports.

This questionnaire is prepared for wet snow loadings on electric overhead power lines, in order to identify variations in design codes and practices for such load assessments.

This Survey is broken into six parts:

- Part A: Wet snow loadings as treated in design codes, standards and operational experience
- Part B: Occurrence of wet snow
- Part C: Collection of specific data for wet snow load assessments
- Part D: Restoration measures
- Part E: Electrical failures due to wet snow
- Part F: Wet snow Removal

For the purposes of this Survey, the following definitions apply:

N/A = Information is NOT AVAILABLE (assumed default for items left blank)
N/R = Item is NOT RELEVANT or NOT APPLICABLE (give reasons)

N/D = Not disclosed (confidential)

If your answer to one or several questions depends on the type of network (transmission vs. distribution) please specify for both types in your response.

Name of utility:

PART A: Standards and Codes	Response	Additional Comments
Are wet snow loads explicitly taken into account in your design practice?		
At which level are wet snow loads incorporated in the design codes: a) International (e.g. IEC, CENELEC, ..) b) National regulations and/or codes c) Company practice		
Are regional design values for wet snow load specified in your region/country?		
Are these loadings connected to any measurements, icing models and statistical distribution (probabilistic approach), or fixed according to traditional "best practice" (deterministic approach)?		
Are wet snow loadings considered less dominant with respect to other types of icing?		

PART B: Occurrence of wet snow	**Response**	**Additional Comments**
How often, annually, is snow accretion on power lines observed in your region/country?		
How often, annually, are mechanical overloads due to wet snow observed?		
How often do failures or damages due to wet snow occur?		
What is the structural type and voltage level of overhead lines exposed to overloads?		
Are observations, overloads or failures due to wet snow limited to certain regions, locations or certain types of terrain?		
If possible please give a list of the 5-10 most important wet snow events, including year and location:		

PART C: Collection of Data	Response	Additional Comments
Are specific data and information on wet snow loadings collected in your country/region?		
Measurements on dedicated rigs		
Observations on overhead lines		
Mechanical failure analyses		
Wet snow loadings maps based on Icing models/weather data		
Are wet snow loads analyzed in combination with concurrent wind speed and direction?		
Other		

PART D: Restoration Measures	Response	Additional Comments
Indicate main restoration measures after damages due to wet snow overloads:		
Re-built as before		
Strengthening of structures		
Change of structure types		
Removal of ground wires		
Rerouting of the line		
Re-analyzes of weather data		
Other		

PART E: Electrical Failures due to Wet Snow	Response	Additional Comments
Have you had electrical failures due to wet snow? In case of "yes" please specify:		
Was it on-line insulation?		
Was it in substations?		
Was it in combination with sea salt pollution?		
Was it in combination with industrial pollution?		
Specify countermeasures		

PART F: Removal of Wet Snow	Response	Additional Comments
Do you apply any method for ice removal? In case of YES please specify:		
Mechanical removal of snow/ice		
Electrical (Joule heating)		
Do you consider ice-phobic coatings?		
Other		

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