Climate Change Risk for Irish Timber Power Pole Networks

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ABSTRACT:
The latest IPCC report states that warming of the climate system is unequivocal, and this warming may lead to increased risk of breakdown of infrastructure networks due to extreme weather. Before appropriate action can be taken for power infrastructure in this regard, we must first understand existing risk, and then try to predict potential climate related changes in risk. The work described in this paper examines both existing vulnerability, and potential future vulnerability, for a notional network of Irish timber power poles. These power pole networks represent important critical infrastructure assets, both nationally, and internationally. There are currently approximately two million timber power poles in service in Ireland, five million timber power poles in service in Australia, worth over $10 billion, and approximately 200 million treated power poles in service in the United States. The impacts of climate change on Irish power poles will be examined herein using a Monte-Carlo event-based sequential model, which incorporates structural reliability, deterioration, climatic effects and network maintenance. The hazards of interest are storm winds and timber decay - both of which may worsen due to a changing climate.

1. INTRODUCTION

Modern society relies on the effective functioning of critical infrastructure networks to provide public services, enhance quality of life, sustain private profits and spur economic growth (Boin and McConnell 2007). The reliance of other forms of critical infrastructure on energy infrastructure make it perhaps the most important component of our modern day critical infrastructure networks. This was illustrated in California in 2001, when power disruptions affected water supply, oil and natural gas production and transport, stressed the entire Western US power grid and idled key industries leading to billions of dollars of lost productivity. More recently, power outages resulting from the 2017 storm Ophelia in Ireland resulted in cascading failures in the wastewater treatment, water treatment and telecommunications sectors (Independent 2017). Given the particular importance of our energy infrastructure, it is vital that the energy networks we build today are capable of reliably serving our needs in the future.

We must thus examine how projected future changes in climate may impact upon our energy infrastructure. This paper uses probabilistic modelling to explore this potential climate change impact in an Irish context, considering a single aspect of the energy infrastructure, namely power distribution poles. These poles under go far less stringent design and maintenance than other aspects of power infrastructure, and consequently are perhaps the most vulnerable aspect of the network. The power pole networks themselves also constitute significant national assets across the globe, i.e. there are over two million power poles in Ireland, five million timber power poles in Australia worth over $10 billion (Crews and Horrigan 2000) and over 200 million timber power poles in the U.S. (Bolin and Smith 2011).
To date only a handful of studies have employed probabilistic methods to assess possible changes in timber power pole infrastructure performance due to climate change. Existing publications in this area are limited to the work of Bjarnadottir et al. (2013), conducted in a US context, and Ryan et al. (2016) which examines Australian power poles. The work described in this paper considers the problem in a European context, where power poles undergo different treatment type and design standards, are subject to very different environmental conditions and maintenance practices, and are likely to experience different changes in future climate.

The framework presented herein uses Monte Carlo simulation in the analysis of structural reliability of poles, allowing climate change uncertainty to be incorporated into the assessment, together with the other forms of uncertainty associated with structural reliability modelling of infrastructure elements over time. It is widely recognised that such probabilistic methods are the most appropriate tool for the representation of processes which have high levels of uncertainty (Ryan and O'Connor 2013), and examination of infrastructure networks which have high variability among network elements (Ryan et al. 2014; Vu and Stewart 2000). The probabilistic approach utilised in this study is event-based sequential modelling. Section 2 of this paper discusses the latest cliamte change projections for Ireland. The probabilistic model is discussed in detail in Section 3, before results and conclusions are discussed in Section 4 and 5, respectively.

2. PREDICTING CLIMATE CHANGE FOR IRELAND

The impact of increasing greenhouse gases and changing land use on climate change can be simulated using Global Climate Models (GCMs). However, long climate simulations using GCMs are currently feasible only with horizontal resolutions of ~50 km or coarser. Since climate fields such as precipitation, wind speed and temperature are closely correlated to the local topography, this is inadequate to simulate the detail and pattern of climate change and its effects on the future climate of Ireland. The Regional Climate Model (RCM) method dynamically downscales the coarse information provided by the global models and provides high-resolution information on a subdomain covering Ireland. The computational cost of running the RCM, for a given resolution, is considerably less than that of a global model. Consequently, the climate change predictions for Ireland used herein were based on RCMs.

The projections of future precipitation, temperature and wind speed used were obtained from Nolan et al., (2014, 2015 & 2017) for locations corresponding to Dublin (on Ireland's east coast) and Cork (south). The climate projections were generated using the COSMO-CLM (v4.0 & 5.0) and WRF (v3.6) RCMs. Projections for the future Irish climate were generated based on two Representative Concentration Pathways (RCP4.5 and RCP8.5) by downscaling five CMIP5 global datasets, namely: HadGEM2-ES GCM, EC-Earth GCM, CNRM-CM5 GCM, MIROC5 GCM, and the MPI-ESM-LR Earth System Model. For the current study, 4km and 6km grid spacing RCM data was considered. This relatively high-resolution data allowed for sharper estimates of the regional variations of climate projections. Data from two time-slices, 1981–2000 (the control) and 2041–2060, were used for analysis of projected changes in the mid-21st-century Irish climate. The historical period was compared with the corresponding future period for all simulations within the same RCM-GCM group. This results in future anomalies for each model run; that is, the difference between future and past.

A total of 24 RCP 4.5 and 24 RCP 8.5 ensemble comparisons were generated. This ensemble was then used to develop statistical parameters for the projected changes in temperature, rainfall and wind speeds for RCP 4.5 and RCP 8.5. These statistical parameters, given in Table 1 below for Dublin and Cork, were utilised in the probabilistic framework herein to help incorporate the considerable uncertainty associated with projected climate change.

Table 1. Predicted Changes for Cork and Dublin to 2050

Parameter	RCP 4.5			RCP 8.5		
	10th P[1]	50th P	90th P	10th P	50th P	90th P
Dublin						
Temperature (°C)	+0.9	+1.1	+1.5	+1.2	+1.5	+1.9
Rainfall (%)	-14,0	-6.1	+3,0	-13.7	-7.1	+6.1
Wind speed (%)	-16.0	-1.0	+14.3	-15.9	-0.2	+15.0
Cork						
Temperature (°C)	+0.9	+1.1	+1.5	+1.1	+1.5	+1.9
Rainfall (%)	-15.9	-8.3	+5.0	-15.4	-7.2	+5.0
Wind speed (%)	-14.8	-0.8	+17.9	-15.3	+1.2	+17.3

[1] P = Percentile

3. PROBABILISTIC METHODOLOGY

Sequential event-based Monte Carlo simulation is used herein to represent the Irish timber power pole network. The basis for this model was developed over two previous publications by the authors, which examined Australian power poles (Ryan et al. 2014; Ryan et al. 2016). The reader is referred to these papers for detailed discussion on the fundamentals of the model development. This section will provide a very brief overview of the model, with a focus on adaptations required to realistically represent Irish-European networks, such as loading models, deterioration mechanisms etc.

The core of the probabilistic model is based on the time dependent structural reliability. The objective of structural reliability analysis is to evaluate the probability of occurrence of a given failure event at a given time through calculation of the failure probability ($P_f(t)$):

$$P_f(t) = P\left[\left(R(t) - S(t)\right) \leq 0\right] \quad (1)$$

where *R(t)* and *S(t)* are resistance and load effects at time *t*, respectively (Stewart and Val 1999). The *R(t)* term in the limit state function in Equation 1 will be the bending resistance of a power pole incorporating deterioration, while the *S(t)* term will be the annual maximum wind load. The impact of climate change on both *S(t)* and *R(t)* is also incorporated into the model. The bending failure limit state was selected based on the most common failure mode of timber power poles (Winkler et al. 2010).

The sequential event-based modelling approach used herein allows power pole network performance over time to be assessed, considering both maintenance and climate change effects. The uncertainty and variability associated with a) climate change predictions, b) structural capacity, c) structural loading, and d) deterioration with time are incorporated in the analysis. The sequential aspect of the model relates to the fact that each Monte Carlo iteration runs on a year-by-year basis from the year 2018 to 2050. This time-dependent modelling approach simulates the actual stochastic behaviour of the system over time, thus creating “an artificial history” of infrastructure network performance. The event-based aspect of the probabilistic model refers to the fact that the occurrence of certain events over the simulation period can influence the course of a given sequential Monte Carlo simulation. The two key events which can occur are a) violation of the limit state, whereby the annual wind load exceeds the deteriorated pole capacity, and b) the condemning of a pole as a result of the network inspections and maintenance programme. Upon occurrence of a wind failure or the condemning of a pole, the pole in question is replaced by a new pole in the Monte Carlo simulation.

It is noted at this point that network inspection and maintenance procedures were modelled in line with common industry practice in Ireland, as will be discussed in Section 4. The modelling of the *S(t)* and *R(t)* terms in an Irish context now discussed in Sections 3.1 and 3.2.

3.1. Time Dependent Wind Loading

There are a number of steps involved in modelling the time-dependent wind loading. Firstly, the wind field parameters, which reflect wind speeds under existing conditions must be established. The predicted future changes in this wind field must then be incorporated. This can be done using the wind speeds predictions presented in Section 2. Having developed characteristics for existing and future wind speeds, the wind load resulting from a given wind speed must be modelled.

Parameters for the existing wind field were derived from wind speed data recorded by the Irish meteorological institute, Met Éireann. Met Eireann provides downloadable data on maximum monthly gust wind speeds for previous decades, facilitating computation of the annual maximum gust wind speeds. However, the computation of the wind actions on structures using Eurocode 1 (Eurocode-1 2013) requires the use of the maximum 10-minute mean wind speed, denoted $V_{b,max}$. The maximum mean 10-minute wind speed was obtained by dividing the annual maximum gust wind speed by the 10-minute gust ratio-R_{10} developed by Logue (Logue 1989). The Gumbel distribution, given by Equation 2 below, was then fitted to the past wind field data for Dublin and Cork to obtained statistical parameters for the existing wind field $V_{b,max}$ for each location.

$$F(v) = e^{-A} \text{ where } A = e^{-\left(\frac{v - v_g}{\sigma_g}\right)} \tag{2}$$

where v_g and σ_g are the location and scale parameters for the Gumbel distribution. The 98th percentile from the distributions developed compared well with the 1-in-50 year wind speeds in the Irish national annex map for basic wind speed, with differences of less than 5% (Eurocode-1 2013).

The probabilistic parameters for the wind field developed above do not account for the possible future reductions or increases in wind field magnitude due to climate change. A modification to Equation 2 has been suggested by Stewart (2015) to allow climate change related effects to be incorporated into the Gumbel distribution in Equation 2 thus becomes;

$$F(v) = e^{-A} \text{ where}$$
$$A = e^{-\frac{\left(\frac{v}{1+\frac{\gamma_{mean}(t)}{100}}\right) - v_g}{\sigma_g}} \tag{3}$$

where $\gamma_{mean}(t)$ represents the time-dependent percentage change in wind speed for a given Monte Carlo simulation.

Having established an expression which probabilistically represents the time-dependent wind speed incorporating climate change, the Eurocode wind loading equation for annual maximum wind load W_{max} was used to calculate the time-dependent wind load *S(t)* as follows (Eurocode-1 2013);

$$W_{max} = \frac{1}{2}\rho . C_s C_d . C_a . C_g . C_r^2 . V_{b,max}^2 \tag{4}$$

where ρ is the density of air, C_sC_d is the structural factor, C_r is the roughness factor, C_a is the shape factor and C_g is the gust factor. Details of the equation and the various parameters can be found in the Eurocode 1 (Eurocode-1 2013). The air density, ρ, is considered deterministic since its scatter is small at large wind speeds (Kasperski 2009). However, the C-factors are affected by aleatory and epistemic uncertainties and thus were modeled probabilistically. The statistical parameters used for the C-factors herein were adopted from the work of the Joint Committee on Structural Safety (JCSS 2001).

3.2. Time Dependent Resistance

The time dependent resistance of the power pole is modelled in this study based on Equation 5 below:

$$R_b(t) = f_b \frac{\pi}{32} \frac{D_1(t)^4 - D_2(t)^4}{D_1(t)} \tag{5}$$

where f_b is the bending strength of the timber, $D_1(t)$ is the outer pole diameter incorporating external decay, $D_2(t)$ is the diameter of internally decayed wood. The values for $D_1(t)$ and $D_2(t)$ were calculated based on a comprehensive decay model developed by Wang et al. (2008). This model takes account of timber type, pole treatment type, the multi-layered aspect of timber poles and model error as discussed in detail in (Ryan et al. 2014; Ryan et al. 2016). Importantly in the context of this study the model also considers climate through a $k_{climate}$ parameter. This parameter value is determined based on annual average temperature and yearly rainfall at the location considered. As shown by Wang and Wang (2012) the influence of climate change predictions on this parameter can significantly affect the rate of timber deterioration. The predicted changes in temperature and rainfall to 2050 for Ireland were incorporated into the calculation of the $k_{climate}$ parameter herein. This allowed the effects of predicted climate change on deterioration, and the resulting time dependent resistance ($R(t)$), to be considered in the analysis.

4. IRISH CASE-STUDY DETAILS

The Irish power distribution network comprises of 2.1 million timber power poles and 150,000km of overhead lines. The network is operated by the Irish Electricity Supply Board (ESB). A typical set-up for an Irish power pole is provided in Figure 1. The most common timber type used for these poles in Ireland is Scots pine (pinus sylvestris). The poles were assumed to be creosote treated in line with common practice in Ireland. For the pole setup in Figure 1, the ESB utilize a pole ground line diameter sizing grade of between 236mm to 295mm i.e. pole ground line diameter uniformly distributed from 236mm to 295mm. Between 2016 and 2017 the ESB have undertaken a substantial pole testing regime, whereby in the region of 700 scots pine poles have undergone full scale destructive testing. The findings of this study were used to develop statistical properties used in the modelling herein for parameters such as bending strength, f_b, sapwood depth, creosote treatment retention, timber air dry density etc. Inspection intervals in the model were set at 12 years in line with common historical practice in Ireland. Inspection failure, or pole condemning criteria, was set at 75% of original pole capacity based on loss of section modulus (Z), meaning if inspection revealed that the pole moment capacity was less than 75% of the original pole moment capacity the pole failed the inspection and was condemned and subsequently replaced. This 75% pole condemning criteria is in line with values used in Ireland for the pole set-up show in Figure 1.

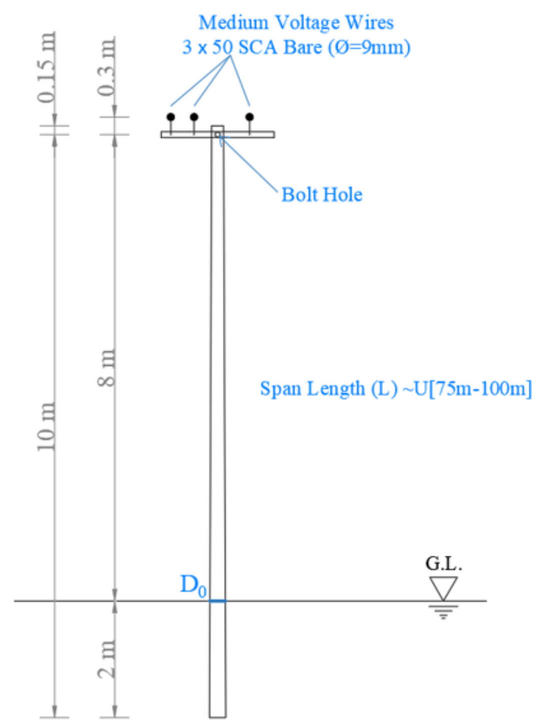

Figure 1. Typical Irish power pole loading set-up

5. EXISITNG VULNERABILITY

Figure 2 presents a wind vulnerability curve for Dublin. This curve was developed based on existing environmental conditions and does not incorporate the impact of climate change on pole deterioration. The curves show the probability of failure of a pole in the simulated Irish network across a range of wind speeds. The curve was generated for a 20 year old network, meaning it represents the network vulnerability eight years after the first inspection. As can be seen from the plot, the first non-zero values of failure probability start at around 22m/s. Probability of failure remains very low until about 40m/s. The mean annual maximum wind speed for Dublin is 21.8m/s, with a CoV of 12% (Gumbel distribution). Consequently, the key wind speed range in the vulnerability curve is 22m/s to 40m/s. As expected, probabilities of failure in this region are very low indicating a functioning network i.e. if probability of failure was 10% for a probable storm event, we would expect 10% of the Dublin's poles to fail during this storm. This would be an unacceptably high proration.

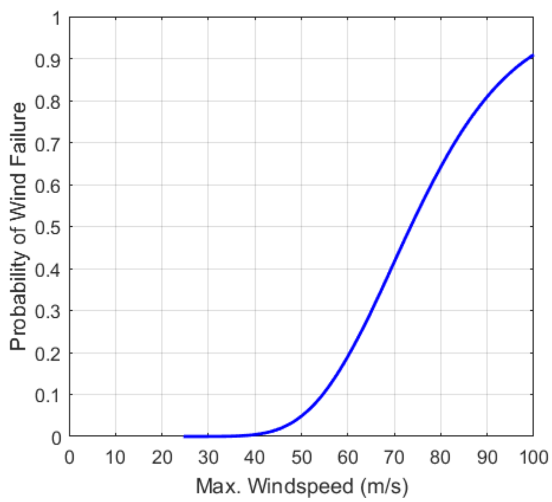

Figure 2. Vulnerability curves for a 20 year old notional network in the Dublin region.

6. CLIMATE CHANGE IMPACTS

Figure 3 presents some preliminary results for the cumulative power pole failures due to wind loading over the period of 2018 to 2050, for notional networks of one million poles in Cork and in Dublin. Results for the 'no change', RCP 4.5 and RCP 8.5 climate change scenarios are presented. Firstly, considering the nature of the output, it is noted the number of failures is influenced heavily by both the age of the poles, and the network maintenance interventions. In the initial 15 years the network experiences few wind failures. This is due to the fact that the poles are relatively new, and have thus undergone little deterioration. There is however a steep increase in wind failures between 2025 and 2041. The year 2041 is an inspection year. At this point the network is inspected and the most vulnerable poles are removed (i.e. poles with > 25% loss in section modulus). The effectiveness of the network maintenance can be seen in the following years, with the pole failure rate dropping considerably, before rising again as the poles continue to deteriorate on a yearly basis.

In terms of the network performance under existing conditions, it can be seen that Cork experiences substantially more power pole wind failures than Dublin. Pole condemnings are also higher in Cork. This is primarily due to the fact that Cork experiences a higher annual rainfall than Dublin (1244mm vs 747mm), which results in higher decay rates in accordance with the Wang et al. deterioration model (Wang et al. 2008). It is noted that that industry quoted pole condemning rates in a given inspection year in Ireland are approximately 2% to 3%. While the notional network modelled herein does not attempt to mimic a real aged network, it is worth observing that pole condemning rates for the inspection at 24 years in the simulation were 1% for Cork and 0.7% for Dublin. This would indicate the model is performing well with realistic output, especially given that the notional network herein is relatively young (i.e. 33 years old). Industry information was not available for pole wind failures in Ireland at the time of writing.

From Figure 3 and Table 2, the predicted impact of climate change on power pole wind failures is shown to be around 20% and 30% in Dublin and Cork, respectively. This relative increase is very significant in the context of the consequences of power pole wind failures, which range from loss of power to business and homes, to catastrophic wildfire events with significant loss of life and infrastructure. Intuitively, one can expect impacts to increase from RCP 4.5 to RCP 8.5, however the impact is a complicated interaction between temperature, rainfall and wind speed, and their associated uncertainties. The region's baseline climatic conditions will also have an effect i.e. a region's pre-climate change temperature, rainfall and wind speed as shown in Ryan et al. (2016).

The impact of climate change on pole condemnings is somewhat lower, with an increase of between 4% and 8% predicted, depending on location and climate change scenario. An increase of comdeminigs of up to 8% could result in a significant increase in operating costs for a power pole network stakeholder. Further work is currently being carried by the authors to investigate if implementation of a climate adaptation strategy would be practical. This will be examined using probabilistic cost-benefit analysis in accordance with a framework developed by (Ryan and Stewart 2017).

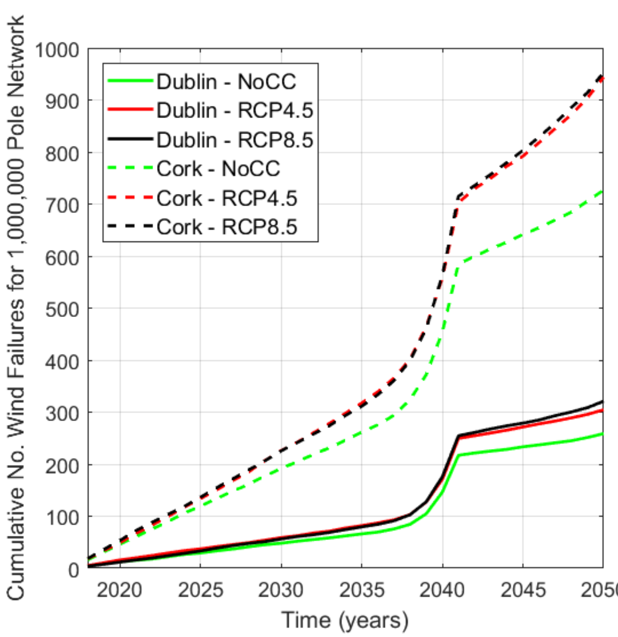

Figure 3. Cumulative power pole failures from 2018 to 2050 for network of one million power poles (NoCC = No Climate Change)

Table 2. Impacts of climate change scenarios on power pole wind failures and condemning rates

Location	No Climate Change	RCP 4.5	RCP 8.5
	Total Wind Failures		
Dublin	259 -	305 (+18%)	321 (+24%)
Cork	727	944 (+30%)	953 (+31%)
	Total Poles Condemned		
Dublin	7,094 -	7,402 (+4%)	7,662 (+8%)
Cork	10,045 -	10,610 (+6%)	10,808 (+8%)

7. CONCLUSIONS

A probabilistic event-based sequential model has been developed herein for Ireland to facilitate insight into the existing and future vulnerability of power pole networks to extreme weather events and decay. A case-study has also been presented, which utilised the model to assess existing vulnerability the possible climate change impacts for two regions in Ireland. The results indicated that power pole wind failures could increase by up to 31% in Ireland by 2050. Pole condemnings and subsequent pole replacements could increase by up to 8% by 2050. These impacts could have a large financial and societal impact, given the consequences of power pole failure, which range from loss of power, to loss of life. As part of ongoing research into this topic, the authors investigating if climate change adaptation measures are required, and if so can cost-effective measures be developed. Impacts with longer timelines are also being investigated, as the 2050 time horizon used herein is relatively short in the context of critical infrastructure life spans.

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