PROBABILISTIC ANALYSIS OF CLIMATE CHANGE IMPACTS ON TIMBER POWER POLE NETWORKS

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ABSTRACT

The IPCC, a collection of 800 of the world's leading climate change scientists, state that future climate related risks to society and infrastructure are likely to change. It is therefore important for the power industry to consider the possible impacts of future climate change on infrastructure performance. However, very few studies have been published to date examining the potential impacts of climate change on power distribution poles networks, which constitute large and valuable infrastructure assets worldwide. The work presented in this paper builds on the limited research in this area by developing a framework for examination of the possible impacts of climate change on timber power pole networks. The time-dependent event-based model developed herein allows network maintenance and predicted climate change effects to be considered, while also incorporating uncertainty associated with both climate change predictions, and structural reliability modelling of infrastructure networks over time. The results of a case study which examined notional power pole networks for five Australian cities revealed that the effects of climate change on predicted power pole performance can be significant. Wind failures for the Brisbane location were predicted to increase by approximately 90% when considering a period from 2015 to 2070, under the severe climate change scenario. However, the predicted impacts are also highly regionally variable, with one location considered experiencing positive climate change impacts for a medium climate change scenario.

KEYWORDS: Climate change impacts; Timber utility poles; Structural reliability; Uncertainty; Wind vulnerability; Deterioration

1 INTRODUCTION

The latest International Panel on Climate Change Assessment Report (IPCC AR5) has stated that warming of the climate system is unequivocal, with many of the observed changes since the 1950s unprecedented over decades to millennia [1]. These observed changes in climate,

1 and perhaps more importantly projected future changes, may lead to increased risk to human
2 life and infrastructure. The Working Group II of the IPCC has identified a number of key
3 risks or “dangerous anthropogenic interfaces with the climate system’. These include risks
4 due to storm surges, inland flooding, sea level rise and systematic risks due to extreme
5 weather events leading to breakdown of infrastructure networks and critical services [2].
6 Some effects of a changing climate are already being felt by industry managers worldwide.
7 This year the UK Institute of Civil Engineers stated that Great Britain’s infrastructure is
8 beginning to struggle to cope with increasingly frequent extreme events, and warned that the
9 UK public should be primed to expect more failures in the future as climate change will make
10 it increasingly difficult to run power and transport networks in all weather conditions [3].

11
12 One of the key means of dealing with increased climate change related risks is
13 implementation of effective climate change adaptation strategies. This mode of thinking is
14 beginning to penetrate into infrastructure management and policy across the globe [2]. For
15 instance, the US military have recently announced that the Pentagon is undertaking sweeping
16 changes to operation systems and installations to adapt to climate change impacts now and in
17 the future [4]. However, in order to implement effective climate change adaptation for
18 infrastructure it is essential to first understand the nature and magnitude of predicted climate
19 change impacts on our infrastructure networks. This is not straight forward for the power
20 industry in particular for two main reasons; 1) the influence of climate change on the power
21 infrastructure performance is a relatively complex interaction of a number of different
22 climactic effects (i.e. temperature, rainfall, wind speeds etc.) manifesting in changes in
23 deterioration rates and loading conditions, and 2) there is considerable uncertainty associated
24 with future climate change projections. These issues make it difficult for power infrastructure
25 asset managers to quantify impacts, and thus ascertain if adaptation is required, and if so,
26 what adaptation strategy is most appropriate.

1 The work presented in this paper sets out a framework for assessment of climate change
2 impacts on power distribution infrastructure. The performance of notional timber power pole
3 networks under various climate change scenarios for five different regions of Australian was
4 considered over a period of over 50 years. Importantly, the framework is developed in a
5 probabilistic context. This approach, which uses Monte Carlo simulation in the assessment of
6 structural reliability of poles, allows climate change uncertainty to be incorporated into the
7 assessment, together with the other forms of uncertainty associated with structural reliability
8 modelling of infrastructure elements over time. It is widely recognised that such probabilistic
9 methods are the most appropriate tool for the representation of processes which have high
10 levels of uncertainty [5], and examination of infrastructure networks, which have high
11 variability among network elements [6, 7]. The probabilistic approach utilised in this study is
12 event-based time dependent modelling. This allows maintenance actions to be incorporated
13 into the assessment, an important consideration for realistic modelling of power pole
14 networks, as illustrated in [6].

15
16 To date, a number of studies have employed probabilistic methods to examine the existing
17 risk and vulnerability of timber power poles [6, 8-13], and indeed electrical networks as a
18 whole [14], however very few power pole studies have considered possible changes in future
19 risk due to climate change. Existing publications in this area limited to the work of
20 Bjarnadottir et al. [10]. This is somewhat surprising given the International scientific
21 community's predictions about future climate [1, 2], and the scale and value of timber power
22 pole networks worldwide. For instance, it is estimated that there are between 120 million and
23 200 million treated timber poles in service in the United States [15]. In Australia there are
24 over five million timber power poles, with a net worth of over \$10 billion [16]. The study by
25 Bjarnadottir et al. [10] examined climate change related increases in risk for timber power
26 poles in a United States context. The work in this paper builds on this existing literature in

three main ways. Firstly, the framework presented in this paper considers the impact of climate change on both wind loading and on deterioration rates. Existing studies considered climate impacts in terms of wind loading alone, but as shown in Section 5 of this paper, changes in deterioration rates constitute a major component of climate change impacts for timber power pole networks. Secondly, the case study presented in Sections 4 and 5 of this paper examine the regional variation of climate change effects for five cities in Australia. Regional variability of impacts has not been examined in the relevant power pole literature to date. However, a recent study by Wang and Wang [17] highlighted the importance of regional considerations for climate impact studies when they found the impacts of climate change on timber decay rate to vary widely across Australia. Finally, as previously mentioned the probabilistic framework herein also considers the effects of network maintenance, an important consideration when attempting to realistically model power pole vulnerability in a working power network over time [6], and something overlooked in the relevant literature to date.

The following section of this paper presents the most up to date regional climate change predictions which will be used in the case study herein. The probabilistic framework utilised in the study is then developed in Section 3. Section 4 provides the details of the case study for climate change impacts on notional power distribution pole networks in five Australian cities. The results of this case study for three climate change scenarios are then presented in Section 5, first for a single location, followed by regional comparison of climate change impacts.

2 CLIMATE CHANGE PREDICTIONS

The case-study presented later in this paper examines climate change impacts on power distribution poles across five different Australian cities. Consequently, the most up-to-date regionally specific climate change predictions developed by the Australian Commonwealth

Scientific and Industrial Research (CSIRO) body were used in this study [18]. The five Australian cities considered were; Brisbane, Sydney, Canberra, Melbourne and Perth. Three climate change scenarios were examined for each city; a) no climate change, whereby climactic conditions remain at 1990 levels, b) the IPCC B1 (median) climate change scenario, and c) the IPCC A1FI (worst) climate change scenario. Table 1 presents the median, 10th percentile, and 90th percentile predicted changes in temperature, rainfall and wind speed for the B1 and A1FI climate change scenarios for the five Australian cities. The values represent the total change to the year 2070, relative to 1990 levels. In line with the framework set out by Stewart et al. [19, 20], truncated normal distributions were used to represent the uncertainty associated with climactic predictions, whereby the 50th, 10th and 90th percentiles provided by CSIRO [18], allow the standard deviation of two truncated normal distributions, each with a cumulative probability of 50%, to be calculated as shown Fig. 1 . In the absence of yearly data resolution for regional climate change predictions (CSIRO provide total change predictions at year 2070), a time-dependent linear change in climactic conditions for the B1 and A1FI scenarios was assumed [19, 20]. A Monte Carlo simulation approach was used to incorporate the climactic uncertainty in the probabilistic model, with one million Monte Carlo iterations carried out for each of the cities considered.

Examination of the prediction patterns in Table 1 reveals two important points. Firstly, the predicted climate change effects vary from location to location. For instance Brisbane has a predicted median wind speed increase of 6% under the A1FI (most severe) climate change scenario, while the other four cities have a predicted median reduction in wind speed under this climate change scenario. A reduction in wind speed means a reduction in structural loading, which could result in positive climate change impacts for some regions. Secondly, from, Table 1, it is noted that temperature is expected to increase and rainfall is expected to decrease (by varying amounts) for all five locations. As will be discussed in the next section,

a rise in temperature will increase deterioration rates, increasing network wind vulnerability, while a decrease in rainfall will decrease deterioration rates, decreasing network vulnerability. Thus the net impact of predicted climate change is dependent on the interactions of opposing influencing climate change effects.

The 1990 baseline temperature and rainfall levels for each location examined were obtained from the Australian Bureau of Meteorology records based on averages for a standard climactic period of 30 years i.e. 1961 to 1990. These figures are presented in Table 2. The annual weather for each year of the 2015 to 2070 monitoring period examined in the case study in Section 4 was generated in a given Monte Carlo iteration utilising these baseline values, together with the statistical parameters for climate change predictions presented in Table 1.

3 ASSESSMENT METHODOLOGY

The possible effects of climate change on power distribution infrastructure are examined in this paper using time-dependent structural reliability analysis. Importantly, this assessment method allows uncertainty and variability associated with a) climate change predictions, b) structural capacity, c) structural loading, and d) deterioration with time, to be incorporated into the analysis. The basis for the model used herein has been developed in detail in a previous paper by the authors [6], which examined the existing risk to power poles at a single location without considering climate change effects. The reader is referred to this paper [6] for detailed discussion on the model development and probabilistic model parameter selection. While this section does present the various components of the probabilistic model in brief, discussion is focused on the adjustments to the model which allow incorporation of

climate change impacts on deterioration and wind load. Sufficient detail is however provided to allow complete understanding of the methodology basis.

A structural reliability assessment requires consideration of structural resistance of the element being considered (R), and the load the element is subjected to (S). In the case of power distribution pole networks the relationship between load and resistance is time-dependent, especially when considering the possible effects of climate change over a period of 50 to 100 years. 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 ($P_f(t)$):

$$P_f(t) = P[(R(t) - S(t)) \leq 0] \quad \text{Equation 1}$$

where $R(t)$ and $S(t)$ are resistance and load effects at time t , respectively [21, 22].

For the climate change impact case study presented in this paper a failure event is defined as the bending failure of a power pole under wind loading, the most common failure mode for timber power poles [23]. Consequently, the $R(t)$ term in the limit state function in Equation 1 will be the bending resistance of a power pole in a network, incorporating deterioration and effects of climate change at a given time t . The $S(t)$ term will be the annual maximum wind load at year t , also incorporating predicted climate change impacts. The following subsection presents the model representation of time dependent resistance $R(t)$, and explains how the effects of predicted changes in temperature and rainfall are incorporated into $R(t)$ in the probabilistic framework. Section 3.2 discusses how predicted climate change effects are incorporated into the $S(t)$ model through probabilistically incorporating predicted changes in wind speed up to the year 2070. Section 3.3 presents the event-based modelling approach which allows power pole infrastructure performance of a maintained network to be examined under different climate change scenarios, using the $R(t)$ and $S(t)$ models developed.

3.1 Time Dependent Resistance

The initial bending resistance ($R(0)$) of a timber power pole at time $t = 0$ can be represented based on established bending theory as follows;

$$R(0) = f_b \cdot \pi \cdot D^3 / 32 \quad \text{Equation 2}$$

where f_b is the bending strength of the timber, and D is the ground line diameter of the distribution pole. In order to model Equation 2 probabilistically statistical parameters are required for a) the pole ground line diameter, b) the bending strength of the timber species in question, and c) the model error associated with Equation 2. These statistical parameters and the sources of the parameters are presented, together with other statistical parameters for the probabilistic event-based model, in Table 5 which appears in Section 4 of this paper. It is noted however that this initial bending resistance ($R(0)$), will tell us little about the performance of timber power poles in service, which undergo significant deterioration over their service life. Thus, for timber power pole networks, as with any infrastructure network analysis, infrastructure element deterioration must be incorporated into the probabilistic model. Timber deterioration was included herein based on the work of Wang et al. [24, 25], who developed a timber decay model based on 35 years of field data for 77 timber species. The Wang et al. model represents decay progress as an idealised bilinear relationship, characterised by a decay lag time, t_{lag} (years), and a decay rate, r (mm/yr). These r and t_{lag} values can be calculated as;

$$r = k_{wood} \cdot k_{climate} \quad \text{Equation 3}$$

$$t_{lag} = 5.5r^{-0.95} \quad \text{Equation 4}$$

where k_{wood} is the wood parameter and $k_{climate}$ is the climate parameter. The Wang et al. [25] publication provides formulas for k_{wood} which account for timber type, treatment etc. Of primary interest, however, in the context of the effects of climate change, is the $k_{climate}$ parameter. The $k_{climate}$ parameter is calculated as follows;

$$k_{climate} = f(RN)^{0.3} \cdot g(T)^{0.2} \quad \text{Equation 5}$$

$$g(T) = 0, \text{ if } T \leq 5^{\circ}\text{C} \quad \text{Equation 6}$$

$$g(T) = -1 + 0.2T, \text{ if } 5^{\circ}\text{C} < T \leq 20^{\circ}\text{C}$$

$$g(T) = -25 + 1.4T, \text{ if } T > 20^{\circ}\text{C}$$

$$f(RN) = 10 \cdot \left[1 - e^{-0.001(RN-250)} \right] \left(1 - \frac{N_{dm}}{6} \right), \text{ if } RN > 250\text{mm and } 0 \leq N_{dm} \leq 6$$

$$\text{Equation 7}$$

$$\text{Otherwise } f(RN) = 0$$

where, T is average annual temperature ($^{\circ}\text{C}$), RN is annual rainfall (mm/yr) and N_{dm} is the number of months per year where the rainfall is less than 5mm [17]. Given the influence of climactic conditions on timber decay, it is clear that if the climate changes in the future, as the IPCC predict it will, there may be significant implications for the reliability and management of timber based infrastructure assets worldwide. The uncertainty associated with the decay model was incorporated into the framework using a model error factor for decay, ME_{decay} . According to Wang et al. [24], uncertainty increases with increasing timber durability class, with class 1, 2, 3 and 4 timbers having model error Coefficient of Variation (COV) values of 0.85, 0.9, 1.1 and 1.2, respectively. Thus, depth of decay, d , at a given time, t , incorporating uncertainty and variability can be calculated as;

$$d(t) = ME_{decay} \cdot r \cdot (t - t_{lag}) = ME_{decay} \cdot r \cdot (t - 5.5 \cdot ME_{decay} \cdot r^{-0.95}) \quad \text{Equation 8}$$

The model represented by Equation 8 is, however, for a homogenous timber cross-section. As recognised by Wang et al. [25] a timber pole's cross section is far from homogenous. Instead the pole consists of zones of sapwood, heartwood (also termed outerwood), and corewood [26, 27], all of which will have different rates of deterioration and lag times [25]. Wang et al. [25] provides t_{lag} equations and values for k_{wood} for sapwood, heartwood and corewood for both internal and external decay. This information was utilised in this study to implement a multi-layer timber deterioration model to represent both internal and external decay for treated timber poles. The nature of this multi-layered model is discussed in detail in [6]. Having incorporated the predicted effects of climate change into the deterioration model on a yearly basis, and used Equation 8 within the multi-layered model framework to calculate; (i) the diameter of the internally decayed timber at time, t , $D_1(t)$, and (ii) the external diameter remaining after external decay at time t , $D_2(t)$, the following modification of Equation 2 was used to calculate the time-dependent bending resistance, $R(t)$, of a power pole.

$$R(t) = f_b \cdot \frac{\pi \cdot [D_1(t)^4 - D_2(t)^4]}{32 \cdot D_1(t)} \quad \text{Equation 9}$$

3.2 Time Dependent Wind Loading

Possible changes in wind speed are an important consideration for power distribution infrastructure as increases or decreases in annual maximum wind speed will reduce or increase the reliability performance of power pole infrastructure, respectively. The wind field for the five Australian locations considered in the case study in this paper is dominated by non-cyclonic synoptic weather systems. These non-cyclonic gust wind speeds are modelled using the Gumbel distribution, with the annual maximum non-cyclonic peak gust speed as follows [28];

$$F(v) = e^{-A} \text{ where } A = e^{-\left(\frac{v-v_g}{\sigma_g}\right)} \quad \text{Equation 10}$$

where v_g and σ_g are the location and scale parameters for the Gumbel distribution. The statistical parameters for each of the five Australian cities considered in the case study herein are presented in Table 3 [28].

These location and scale parameters were developed by Wang et al. [28] based on data recorded from 1939 to 2007. Thus, this wind field does not account for the possible future reductions or increases in wind field magnitude due to climate change. A modification to Equation 10 has been suggested by Stewart [29] to allow climate change related effects to be incorporated into the Gumbel distribution under the assumption that the relationship between mean wind speed (averaged over 10 minutes), and peak gust wind speed is constant (i.e. the proportionality constant between gust wind and mean wind speeds is one). Equation 10 thus becomes;

$$F(v) = e^{-A} \text{ where } A = e^{-\frac{\left(\frac{v}{1 + \frac{\gamma_{mean}(t)}{100}}\right)^{-v_g}}{\sigma_g}} \quad \text{Equation 11}$$

where $\gamma_{mean}(t)$ represents the time-dependent percentage change in gust wind speed for a given Monte Carlo simulation. The Wang et al. [28] statistical parameters for the Gumbel distribution are assumed to reflect pre-climate change wind speeds.

Having established an expression which probabilistically represents the time-dependent wind speed incorporating climate change, the work of Henderson and Ginger [30] was used to calculate the time-dependent wind load $S(t)$ as follows;

$$S(t) = B \cdot v(t)^2 \quad \text{Equation 12}$$

where

$$B = ME_w \cdot A \cdot (C \cdot E^2 \cdot D_w^2 \cdot G \cdot \rho/2) \quad \text{Equation 13}$$

The terms in the brackets in Equation 13 are related to the nominal values given in the Australian wind loading standards [31] where; C is the quasi-steady pressure coefficient related to the C_d parameter in AS/NZS 1170.2, E is the velocity height multiplier that accounts for exposure and height related to $M_{z,cat}$ in AS/NZS 1170.2, D_w is the wind directional effects related to M_d in AS/NZS 1170.2, G is a factor that accounts for gusting effects and is related to K_a and K_l in AS/NZS 1170.2 and ME_w is the model error for the wind load model. The term $v(t)$ in Equation 12 is the time dependent 3-second gust wind speed. This model allows uncertainty and variability to be incorporated into predictions for the wind load on the power poles, conductors etc. for a given wind speed v , at a given time t . Details of the statistical properties used for the variables in Equation 13 are provided in later in this paper in Section 4 Table 5.

3.3 Event-Based Modelling Approach

A time-dependent event-based modelling approach was utilised to allow probabilistic assessment of power pole network performance over time, incorporating both maintenance and climate change effects. The nature of this modelling approach is described in detail in [6]. To summarise, the time-dependent aspect of the model relates to the fact that each Monte Carlo simulation runs on a year-by-year basis from 2015 to the year 2070. Each yearly step includes; calculation of $R(t)$ and $S(t)$ accounting for climate change effects on deterioration and wind load, in addition to simulation of network maintenance if appropriate. This time-dependent modelling approach simulates the actual stochastic behaviour of the system over time, thus creating “an artificial history” of infrastructure network performance. It is also referred to as a sequential modelling approach in the literature [32, 33]. The event-based

aspect of the probabilistic model refers to the fact that the occurrence of certain events over the monitoring 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 the pole fails, 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. This new pole is of the same timber type as the original pole but is assigned new properties generated from the appropriate distributions i.e. new pole diameter, new pole bending strength, new sapwood depth etc. The process of deterioration then restarts for this new pole, and the sequential Monte Carlo process continues for the iteration in question up to the year 2070. This time-dependent event-based modelling approach means that, in effect, each Monte Carlo iteration represents one pole location in a network of poles, whereby if this pole fails at a given location it must be replaced to prevent power supply interruption.

4 CASE STUDY – AUSTRALIAN TIMBER POLES IN FIVE CITIES

The aim of this case study was to determine the likely climate change impacts on a notional network of one million newly installed CCA (Copper Chrome Arsenate) treated timber power distribution poles, for the period 2015 to 2070, across five Australian cities. It was not intended to attempt to simulate existing power pole networks, each of which comprise of an unknown mix of treated and untreated poles of various unknown ages, designed using older allowable stress design methods [34] or the current AS/NZS standards. Attempting to represent such a network would detract from the case study aim of assessing climate change impacts on poles designed and maintained to current standards.

For each of the five locations considered one million Monte Carlo simulations were carried out using the time-dependent event-based framework presented in the previous section. This number of Monte Carlo simulations was selected to ensure the statistical stability of the model output. To facilitate fair comparison between locations, both the new 2015 poles, and replacement poles, were designed for each location in accordance with existing standards (AS/NZS 1170.2:2011 [31] and AS/NZS 7000:2010 [35]), for the typical Australian power distribution pole layout presented in Fig. 2. It is noted that possible future developments in pole technology for replacement poles installed up to 2070 were not incorporated in the model. The pole design procedure is presented in [6]. Having obtained the design diameter for each location, the appropriate sizing grade was selected based on the manufactures sizing grades used in each Australian city. These sizing grades, which result in uniform distributions of pole diameter for each location, are presented in Table 4. Spotted Gum (*corymbia citriodora*, *corymbia henryi* & *corymbia maculate*) is the most common timber species used for treated poles in Brisbane, Sydney, Canberra and Melbourne [36, 37], and thus was utilised in the design and modelling for these locations. This hardwood timber is classified as a strength group 2 timber [38] and a durability class 2 timber in ground contact conditions [39]. The majority of newly installed poles used in Western Australia, however, are CCA treated Radiata Pine, and thus this pole type was used in the design and modelling for Perth. This softwood timber is classified as strength group 6 [38], with a durability class of 4 in ground contact conditions [39]. In order to implement the multilayer decay model for Spotted Gum and for Radiata Pine the depths of sapwood, corewood and heartwood needed to be defined. This was done for Spotted Gum in accordance with the procedure described in [6]. The same procedure was utilised for the Radiata Pine, with the exception that the heartwood and corewood for Radiata Pine was together assumed to account for 10 growth rings, while the corewood was assumed to consist of the first 3-5 growth rings, in accordance with the

findings of Harris and Crown for plantation grown Radiata Pine [40]. The sapwood depth for the two timber types was in accordance with the findings of [41] as shown in Table 5.

For this case study inspection of the poles was carried out based on current guidelines in Australian Standards [42], and existing pole inspection and maintenance replacement practice employed in the Australian power industry. Inspection intervals were set at 5 years, with first inspection at 20 years [42]. This maintenance procedure was also used for replaced poles, which are not inspected for the first 20 years after installation, and are then inspected on the first inspection year after the 20 year period. In accordance with common industry practice in Australia, inspection failure, or pole condemning criteria, was set at 50% of original pole capacity based on loss of section modulus (Z), meaning if inspection revealed that the pole moment capacity was less than 50% of the original pole moment capacity the pole failed the inspection and was condemned. In reality, some Australian utility companies have slightly different condemning criteria and inspection intervals, however, the values used herein are representative of the typical Australian network. It is also noted that the effects of individual pole reinforcement programs and cascading pole failures are not considered in this comparative study. It is planned to investigate both cascading failures and the effects of individual pole maintenance practices in future studies. The remainder of the statistical characteristics of the model parameters used for the probabilistic assessment presented in Table 5.

5 RESULTS – IMPACT OF CLIMATE CHANGE

This section presents the impacts of climate change on power pole network performance over the monitoring period of 2015 to 2070 through examination of; a) the numbers of poles being condemned over this period, and b) the number of poles failing under wind loading over this

period. The climate change impact results for Brisbane are presented first to facilitate discussion of the nature of the model output. Brisbane was selected as it was found herein to experience the largest climate change impacts of the five cities considered. Having presented this discussion in the context of a single location, the climate change impacts for the five Australian cities are compared and discussed to illustrate the regional variability of climate change effects.

5.1 Climate Change Impacts for Brisbane

Fig. 3 presents the annual failure rate for the no climate change scenario. As can be seen from the plot there are very few wind failures in the network in the first 15 years. This is due to the low level of pole deterioration in the early years after installation of the notional network of 1 million new poles. After the 15 year point in Fig. 3 there is a steep rise in wind failure rates to 20 years, followed by a rise and fall in wind failure rates every five years. This five year cycle of rising and falling wind failures is caused by the network maintenance inspection intervals. As mentioned in the previous section, inspections occur at the end of every fifth year. These inspections lead to the replacement of the most decayed poles, which are most vulnerable to wind failure. Thus, in the year following the inspection the network is most resilient to wind failure and the failure rates are low, while just before the inspection the wind vulnerability of the network is at its highest. It is noted that the average annual wind failure rate over the 56 year period from 2015 to 2070 is 0.014%, this is in the region of pole failure rates experienced in industry in Australia, approximated to be in the range of 0.01% to 0.04% [6]. Although obtaining a failure rate of the same order of magnitude as that experienced in industry is positive from a modelling perspective, it is again highlighted that the aim of the case study was not to represent the existing networks, which are made up of different types and age poles designed in accordance with a range of different standards [34, 35]. The case

study herein was instead designed to examine notional pole networks which would be put in place if installed in 2015.

Fig. 4 shows the cumulative wind failures for the network of one million poles for each of the three climate change scenarios. The cumulative failure line for each climate scenario is obtained by calculating a running total of wind failures from year 2015 to 2070, i.e. adding the failures occurring across the network of one million poles for each year up to year 2070. As can be seen from the figure the IPCC BI (median) and A1FI (worst) climate change scenarios have a substantial impact on the number of power pole wind failures. The total cumulative wind failures from 2015 to 2070 for the no change, B1 and A1FI climate change scenarios are approximately 7,700, 12,300 and 15,100, respectively. The resulting average annual wind failure rates are 0.014%, 0.022% and 0.027%, respectively, meaning the B1 and A1FI climate change scenarios lead to a predicted increase in annual wind failure rates of 60% and 96%, when compared to the no climate change scenario. An increase of annual failure rate of this magnitude could have considerable societal impact when one considers the consequences of power pole failure, which ranges from loss of power to homes and business, to loss of property and life due to wildfires [6, 45].

The observed increase in wind failure rates is due to a combination of increased decay rates and increased wind speed for Brisbane. As shown in Table 1, the wind speed and temperature are predicted to increase in Brisbane under the B1 and A1FI climate change scenarios, while annual rainfall is expected to reduce. For Brisbane the increase in temperature and reduction in rainfall results in a net increase in decay rates. This is not the case for all locations considered herein, as will be discussed in Section 5.2. The impact of decay alone on power pole network performance can be observed in Fig 4, which shows the predicted cumulative condemned poles for the period 2015 to 2070 for the three climate change scenarios. These

1 pole condemning rates are not sensitive to changes in wind speed, but rather are a function of
2 decay rates and network inspections and maintenance. The B1 and A1FI climate change
3 scenarios once again have a significant negative impact on pole condemning rates. The
4 cumulative poles condemned for the network of one million poles for the no change, B1 and
5 A1FI climate change scenarios are 388,000, 458,000 and 479,000, respectively, meaning the
6 B1 and A1FI scenarios result in an 18% and 23% increase in the number of condemned
7 poles, respectively. As the predicted level of climate change increases from the B1 scenario
8 to A1FI scenario, the magnitude of annual temperature increase becomes greater, as does the
9 magnitude of rainfall decrease. Thus the difference in predicted impact between the B1 and
10 A1FI scenarios is smaller for pole condemning than was observed for wind failures in Fig. 5.
11 The stepped nature of the cumulative lines in Fig. 5 is as a result of inspections occurring at 5
12 year intervals.

13
14 Fig. 6 depicts the climate change impacts for Brisbane in a different form, through
15 presentation of the number of poles condemned per pole location from 2015 to 2070, for each
16 climate change scenario i.e. a histogram of the number of poles condemned over the 2015 to
17 2070 period per sequential Monte Carlo simulation. As can be seen from Fig. 6, the
18 probability that a given pole does not need to be replaced due to being condemned over the
19 2015 to 2070 period reduces from the no change scenario (65%), to the B1 scenario (59%)
20 and the A1FI scenario (57%), while the probability of both one pole and two poles being
21 condemned over the monitoring period increases from the no change scenario, to the B1
22 scenario to A1FI scenario.

23
24 Fig. 7 presents the histogram of the number of wind failures per pole location from 2015 to
25 2070, for the three climate change scenarios. As one would expect the probability of wind
26 failure of a given pole is very low, meaning the probability of zero wind failures occurring

from 2015 to 2070 is approximately 99.4%, 99.1% and 98.9% for the no change, B1 and A1FI scenarios, respectively. Fig. 7, which is plotted at a probability of occurrence scale of 0% to 2%, again shows the notable impact of projected climate change on predicted wind failure rates for Brisbane. Comparing the no change and A1FI scenario, the probability of a given pole failing once from 2015 to 2070 increases from 0.40% to 0.78%, while the probability of a given pole failing twice over the monitoring period increases from 0.18% to 0.32%. Finally it is noted that, although there are high levels of uncertainty and variability associated with the input parameters of the event based model (as shown in Tables 1, 3, 4 and 5), the actual variability of the model output is relatively small, as depicted in the histograms shown in Figs 6 and 7.

5.2 Climate Change Impacts for Five Australian Cities

Fig. 8 presents the predicted impact of the three climate change scenarios on the average annual pole condemning rates for the five Australian cities. Fig. 9 presents the percentage increase in pole condemning rates for the climate change scenarios, for each of the locations i.e. increase relative to “no change”, or baseline condemning rates for each location. As can be seen from Fig. 8, the predicted climate change impact is largest for Brisbane, with Sydney also experiencing a notable proportional increase in pole condemning rates due to climate change. The A1FI climate scenario for Sydney results in an increase in average annual condemning rates over the monitoring period of approximately 0.06%, representing an 8% increase in pole condemning rates when compared to the Sydney “no change” scenario. In contrast to Brisbane and Sydney, Melbourne actually experiences a slight reduction in annual pole condemning rates for both the B1 and A1FI climate change scenarios, while the climate change impacts for Canberra were relatively small.

Insight into the nature of the regional variability of climate change impacts can be obtained by comparing the findings for Sydney and Canberra, which exhibit very different results for the A1FI climate change scenario, despite having almost identical predicted changes in temperature and rainfall for this scenario (see Table 1). This is due to the influence of the cities' baseline 1990 temperature and rainfall levels on probabilistically modelled timber deterioration in accordance with the Wang et al. [25] timber decay model. Firstly, considering temperature, it can be noted from Equation 6 that the relationship between temperature and decay rate in Wang et al.'s model is bi-modal, with a greater increase in decay rate for unit change in temperature after the 20°C point. Thus, 1°C increase in temperature in a location with a baseline annual average temperature of 22°C will have a greater influence on decay than a 1°C change in temperature at a location with an annual average temperature of 16°C. As shown in Table 2, Sydney is much closer to the critical 20°C mark than Canberra, with baseline temperatures of 18.2°C and 13.6°C in the two cities, respectively. Thus, with Sydney and Canberra both having a median climate change related temperature increase of 3.0°C, the temperature change has a higher influence on decay rates for Sydney than for Canberra. This is also a key contributing factor in Brisbane's high predicted climate change impacts, as Brisbane has a baseline temperature of 21°C.

Given the somewhat complex nature of the $f(RN)$ expression in Equation 6, the relationship between rainfall and decay rate is plotted in Fig. 10. This figure illustrates how decay rate can be highly sensitive to a location's baseline rainfall levels. As can be seen in the plot, once annual rainfall drops below approximately 600mm, the decay rate begins to drastically reduce. Again, referring to Table 2 it is noted that Canberra has a baseline annual rainfall of 607mm, while Sydney's baseline annual rainfall is 1302mm. This results in a greater reduction in decay rates due to annual rainfall change for Canberra than for Sydney, despite

1 both locations experiencing nearly identical predicted climate change related reductions in
2 rainfall.

3
4 Finally in the context of Fig. 8 and Fig. 9, it is noted that the Perth pole network experiences
5 a low annual condemning rate for the three climate change scenarios. This was due to the
6 influence of pole timber species utilised, with the Radiata Pine poles resulting in far less
7 poles condemned than the Spotted Gum poles over the 56 year monitoring period for a given
8 location. As shown in Fig. 9 however, the small increases in pole condemning rates due to the
9 A1FI climate change scenario represent a notable proportional increase in condemning rates,
10 with a 17% increase observed when compared to the no change scenario.

11
12 Fig. 11 shows the average annual wind failure rates for the three climate change scenarios for
13 each of the five Australian locations, with Fig. 12 showing the percentage change in annual
14 wind failure rates for the B1 and A1FI climate change scenarios for each location. Brisbane
15 can be seen to experience the most severe increase in annual wind failures, which is due to
16 the fact that Brisbane is the only one of the five cities examined to experience a median
17 increase in wind speed (Table 1). Sydney also experiences a notable increase in average
18 annual wind failure rates for the A1FI scenario, with a rise of 0.055%, representing a 21%
19 increase in the average annual wind failure rates when compared to “no climate change”
20 scenario. This is primarily related to increased decay and increased variability in wind speed
21 caused by climate change uncertainty. Canberra experiences a small increase in average
22 annual wind failure rates, but a significant proportional increase in wind failure rates. This is
23 due to the fact that Canberra city experiences low wind failures for the “no change” scenario
24 as median wind speed for this location is approximately 20m/s, 9m/s less than Sydney (see
25 Table 3), despite both locations having the same wind speed classification from a design
26 perspective [31]. It is also interesting to note that Melbourne experiences a decrease in wind

failures for the B1 climate change scenario, and only a very slight increase in wind failures for the A1FI climate change scenario.

Overall, the results for the five Australian cities examined herein illustrate the regional nature of climate change impacts for timber power distribution infrastructure. In addition to the interaction between three climactic change parameters (temperature, rainfall and wind speed), predicted climate change impacts are also influenced by a regions baseline climactic conditions, type of timber used in a region, and the uncertainty associated with climate change predictions, something that can only be captured in a probabilistic assessment. This complex regionally variable nature of impact emphasises the need for detailed regional specific probabilistic analysis before effective climate adaptation strategies can be put in place, with neither impacts, nor regional effects intuitive i.e. Sydney experiences an increase in predicted wind failures despite a median reduction in wind speed, and Canberra and Sydney experience very different condemning rate impacts, despite having almost identical climate change predictions. Thus, Sydney and Canberra are likely to require different adaptation strategies, while the analysis indicates the implementation of an adaptation strategy for Melbourne based on perhaps a national assessment would have been a waste of finances. Future work will investigate the appropriateness of regionally specific climate change adaptation strategies, examined through a probability-based cost-benefit analysis, considering both direct and indirect costs.

6 CONCLUSION

The probabilistic methodology developed in this paper has allowed the climate change impacts for idealised power distribution pole networks to be assessed incorporating pole inspections, subsequent network maintenance and climate change effects on both wind speeds

and deterioration over time. The case study examined herein indicates that climate change impacts on power pole networks are likely to be substantial for some locations in Australia, with Brisbane experiencing a projected 23% increase in pole condemning rates, and a 96% increase in wind failure rates over the period 2015 to 2070. Such increases could have substantial societal impacts when one considers the consequences of power pole failures, which range from interruption of power for businesses and homes, to loss of life due to wildfires. It is noted however that the predicted impacts of climate change were found to be highly regionally variable. For instance Melbourne showed slightly positive climate change impacts under the B1 (medium) climate change scenario. The regional analysis also highlighted the fact that climate change impacts for given climactic projections are not intuitive, with impacts depending on opposing interactions of temperature, rainfall and wind, the baseline climactic conditions in a region, and the nature of the uncertainty associated with future climactic predictions. This emphasises the need for region-specific, probability-based climate change impact analyses before attempting to implement climate adaptation strategies for power infrastructure. Future work is required in order to explore the suitability of various climate adaptation strategies. Such strategies should be examined in a probabilistic cost-benefit assessment, considering both direct and indirect costs.

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- 20

Table 1. Statistical parameters for climate change predictions for five Australian locations

Parameter	B1 10 th P	B1 50 th P	B1 90 th P	A1FI 10 th P	A1FI 50 th P	A1FI 90 th P
Brisbane						
Temperature (°C)	+ 1.1	+ 1.6	+ 2.3	+ 2.1	+ 3.1	4.4
Rainfall (%)	- 18	- 5	+ 9	-33	-9	17
Wind speed (%)	- 1	+ 3	+ 10	-2	+6	19
Sydney						
Temperature (°C)	+ 1.1	+ 1.6	+ 2.2	+ 2.1	+ 3.0	+ 4.3
Rainfall (%)	- 14	- 4	+ 5	- 25	- 8	+ 10
Wind speed (%)	- 8	0	+ 6	- 15	- 1	+ 12
Canberra						
Temperature (°C)	+ 1.1	+ 1.6	+ 2.2	+ 2.1	+ 3.0	+ 4.2
Rainfall (%)	- 14	- 5	+ 4	- 26	- 9	+ 8
Wind speed (%)	- 10	- 1	+ 7	- 20	- 2	+ 13
Melbourne						
Temperature (°C)	+ 1.0	+ 1.4	+ 2.0	+ 1.9	+ 2.8	+ 3.8
Rainfall (%)	- 14	- 6	+ 1	- 25	- 11	+ 3
Wind speed (%)	- 9	- 1	+ 6	- 18	- 1	+ 12
Perth						
Temperature (°C)	+ 1.0	+ 1.4	+ 2.0	+ 1.9	+ 2.7	+ 3.8
Rainfall (%)	- 21	- 11	+ 1	- 37	- 19	+ 2
Wind speed (%)	- 5	0	+ 4	- 9	- 1	+ 7

Table 2. Baseline 1990 temperature and rainfall data for five cities (obtained from 1961 to 1990 climactic period)

Cities	Annual Average Temperature (°C)	Annual Rainfall (mm)
Brisbane	21.0	1247
Sydney	18.2	1302
Canberra	13.6	607
Melbourne	15.5	638
Perth	19.0	819

Table 3. Statistical parameters for annual maximum non-cyclonic peak gust speed

Location	v_g	σ_g
Brisbane	24.276	3.208
Sydney	29.289	2.572
Canberra	20.076	2.104
Melbourne	25.803	1.825
Perth	29.043	2.780

Table 4. Statistical parameters for pole diameters for each of the five cities

Property	Units	Distribution	Mean	Source
Pole diameter - Brisbane	mm	Uniform (250 - 295)	273	Design and sizing grade
Pole diameter – Sydney & Canberra	mm	Uniform (242 - 294)	268	Design and sizing grade
Pole diameter – Melbourne	mm	Uniform (245 - 290)	268	Design and sizing grade
Pole diameter - Perth	mm	Uniform (304 - 348)	355	Design and sizing grade

Table 5. Statistical parameters for probabilistic model

Property	Units	Distribution	Mean	COV	Source
f_b Spotted Gum	MPa	Normal	104.1	0.14	[43]
f_b Radiata Pine	MPa	Normal	43.0	0.10	[44]
Radiata Pine corewood depth	Growth rings	Uniform (3-5)	4	–	[40]
Spotted Gum corewood depth	Growth rings	Uniform (5-10)	7.5	–	[6]
Spotted Gum sapwood depth	mm	Uniform (25 – 50)	37.5	–	[41]
Radiata Pine sapwood depth	mm	Deterministic	100	0	[41]
ME_{decay}^a Spotted Gum (D.C. 2)	-	Lognormal	1.00	0.92	[24]
ME_{decay}^a Radiata Pine (D.C. 4)	-	Lognormal	1.00	1.20	[24]
HV and LV wire diameter	mm	Normal	13.5	0.06	Fig 2 & [10]
Street lighting wire	mm	Normal	9.0	0.06	Fig. 2 & [10]
Pole height	m	Normal	10.7	0.03	[10, 16]
High voltage wire height	m	Normal	10.95	0.03	
Low voltage cables height	m	Normal	9.5	0.03	[10, 16]
Communication wire height	m	Normal	8.1	0.03	
ME_w	-	Lognormal	1.00	0.05	[30]
ρ_{air}	kg/m ³	Lognormal	1.2	0.02	[30]
$M_{z,cat}$	-	Lognormal	0.95	0.10	[30, 35]
C_d pole	-	Lognormal	1.2	0.05	[6, 35]
C_d wires	-	Lognormal	1.0	0.05	[6, 35]
G (poles)	-	Normal	0.96	0.11	[10]
G (wires)	-	Normal	0.81	0.11	[10]

^a ME_{decay} distribution truncated at 10.0

Fig. 1. Truncated probability distribution of change of wind speed to year 2070 [20]

Fig. 2. Distribution pole layout

Fig. 3. Brisbane annual wind failure rates for the “no climate change” scenario

Fig. 4. Cumulative wind failures for the three climate change scenarios per network of one million poles

Fig. 5. Cumulative poles condemned for the three climate change scenarios per network of one million poles in Brisbane

Fig. 6. Probability of number of poles condemned per pole location from 2015 to 2070 for the three climate change scenarios in Brisbane

Fig. 7. Probability of number of wind failures per pole location from 2015 to 2070 for the three climate change scenarios in Brisbane

Fig. 8. Annual pole condemning rates for three climate change scenarios for the five locations

Fig. 9. Percentage change in annual pole condemning rates due to climate change for five locations

Fig. 10. Relationship between decay rate and rainfall with average annual temperature set at 15°C

Fig. 11. Annual pole wind failure rates for three climate change scenarios for the five locations

Fig. 12. Percentage change in annual pole wind failure rates due to climate change for five cities