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Cost-benefit analysis of climate change adaptation for power pole networks

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Abstract Power distribution pole networks are vulnerable to a changing climate. Climate change can increase wind speeds, and changes in rainfall and temperature can accelerate timber decay, affecting residual capacity of timber power poles. The present paper utilises advanced stochastic simulation methods to examine climate change impacts, and possible climate change adaptation strategies, for Australian power distribution networks. The assessment framework developed, which is applicable to a wide variety of infrastructure types and research areas, utilises probabilistic methods to investigate the appropriateness of climate adaptation strategies aimed at ameliorating the impact of climate change on critical infrastructure. Measures investigated include alterations to design or maintenance practices through, for example, installation of larger poles, more frequent inspections, or changes to pole replacement criteria. A cost-benefit decision analysis is developed herein using the latest AR5 climate projections, network vulnerability, adaptation measures, and cost and loss data for both direct and indirect costs. The net present value and benefit-to-cost ratio is calculated for different adaptation strategies over the life cycle of the assets up to the year 2090. An adaptation measure that allows for the installation of larger poles but less stringent pole replacement criteria has the highest net benefit—with a mean potential saving of hundreds of millions of dollars.

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1 Introduction

According to the most recent Intergovernmental Panel on Climate Change (IPCC) report, warming of the climate system is unequivocal (IPCC 2013), and this warming may lead to increased risk of breakdown of infrastructure networks due to extreme weather (IPCC 2014). The ability to implement cost-effective climate change adaptation strategies will be a key factor in determining how well our critical infrastructure copes in a changing climate. However, climate change impacts on infrastructure networks are highly complex due to (a) interactions of different climatic factors (i.e. wind, rainfall, temperature), (b) the spatially variable nature of climate, and (c) the considerable uncertainty associated with future climate projections (Ryan et al. 2016; Webb and Hennessy 2015). Consequently, detailed and robust analysis is normally required to ascertain if a given infrastructure adaptation strategy is effective for a given country, or indeed region. As stated by the IPCC, work in this area is limited to date, with 'most existing assessments of adaptation restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions' (IPCC 2014).

The work presented in this paper goes towards addressing this gap by presenting a numerical assessment of the effectiveness of climate change adaptation strategies for a critical infrastructure asset, namely, power distribution infrastructure. The assessment methodology is built upon structural reliability and probabilistic analysis, and crucially uses probability-based cost-benefit analysis to assess the effectiveness of climate adaptation strategies. Presentation of the results in this form facilitates a robust and quantitative universal metric which infrastructure asset managers, owners, and researchers across disciplines can relate to, i.e. do mean net present values (NPV) and benefit-to-cost ratios (BCR) indicate that it would be cost-efficient to implement a climate adaptation strategy. The use of probabilistic analysis allows the considerable uncertainty associated with future climate projections, and the inherent variability of assets across an infrastructure network, to be incorporated into the assessment. The approach constitutes a cross-disciplinary framework, which brings together the latest climate projections from the scientific community and established structural reliability tools from engineering research to assess and develop practical solutions to climate change. Engineering-based frameworks, like those developed herein, can play a key role in bridging gaps between the climate change scientific community and infrastructure owners and policymakers, resulting in a more sustainable and resilient critical infrastructure.

The climate adaptation analysis framework herein can be applied to any form of infrastructure network, or indeed to the assessment of climate adaptation policies for agriculture, water resource management, etc. This paper presents the framework in the context of timber power distribution pole networks in Australia. These pole networks constitute significant national assets across the globe, i.e. five million timber power poles in Australia worth over $10 billion (Crews and Horrigan 2000) and over 200 million timber power poles in the USA (Bolin and Smith 2011). Power pole failure in these critical infrastructure networks is primarily caused by a combination of timber decay and wind loading (Winkler et al. 2010). The consequences of these failures range from loss of power to business and homes, to catastrophic bushfire (wildfire) events with significant loss of life and infrastructure.

Few studies examine the possible impacts of climate change on this critical infrastructure asset using probabilistic methods. Bjarnadottir et al. (2014) and Salman et al. (2015) have used probabilistic methods to examine vulnerability and hurricane adaptation measures for power poles in the USA; however, these studies focussed on existing risk, ignoring possible impacts of climate change. Bjarnadottir et al. (2013) did consider climate change impacts, but did not examine the appropriateness of climate adaptation strategies. Ryan et al. (2014) developed vulnerability curves for timber power poles in Australia, incorporating existing and proposed network maintenance strategies over the life cycle of the network. Ryan et al. (2016) expanded this work to assess the impact of climate change on pole vulnerability for the five largest urban areas in Australia. It was found that climate change impacts on power pole networks are likely to be substantial for some locations in Australia, most notably Brisbane. For a full literature review, see Ryan et al. (2014, 2016).

The work presented herein improves the state of knowledge in this area by examining a number of climate adaptation strategies through Monte Carlo event-based sequential modelling techniques and probabilistic cost-benefit analysis. Adaptation strategies may involve changes to Australian design or maintenance standards, such as installation of larger poles, more frequent inspections, or changes to pole replacement criteria. The decision analysis considers the latest AR5 climate projections, cost and loss data for power companies and users, and NPV (net benefit) decision analyses over the life cycle of the assets up to 2090. A sensitivity analysis is conducted to investigate the robustness of the results and assumptions.

2 Vulnerability assessment methodology

2.1 Climate change projections

This study uses the latest IPCC Assessment Report (AR5) climate change projections for Australia (Webb and Hennessy 2015). The focus of the analysis herein is on Brisbane, the capital city of Queensland, which is classified as a non-cyclonic wind zone by the Australian wind loading standard AS1170.2-2011 (Standards Australia/New Zealand 2011). This location was chosen based on the findings of a climate impact assessment of five Australian cities, which showed power pole networks in Brisbane to be most vulnerable to predicted climate change (Ryan et al. 2016).

In line with the large uncertainty and variability associated with long-term climate projections, climatic changes were modelled probabilistically using Monte Carlo simulation. Wind speed, rainfall, and temperature changes were considered for the no-change scenario, the Representative Concentration Pathway (RCP) 4.5 (medium) scenario, and the RCP 8.5 (severe case) scenario. For Brisbane the predicted 10th, 50th and 90th percentile changes to the year 2090 under RCP 4.5, relative to 1995 levels were; +1.2 °C +1.8 °C and +2.6 °C for temperature, -21%, -9% and +7% for rainfall, and -2.5%, +0.5% and +3.6% for wind speed, respectively. The corresponding figures for RCP 8.5 were; +2.5 °C +3.7 °C and +4.7 °C for temperature, -32%, -16% and +17% for rainfall, and -1.2%, +2.2% and +6.5% for wind speed (Webb and Hennessy 2015). In line with the framework set out by Stewart (2015) and Stewart and Deng (2015) and utilised in Ryan et al. (2015, 2016), truncated normal distributions were used to represent the uncertainty associated with climate projections provided by the Commonwealth Scientific and Industrial Research Organisation (CSIRO; Webb and Hennessy 2015). In the absence of yearly data resolution for regional climate change projections (CSIRO provide total change projections at year 2090), a time-dependent linear change in climatic conditions for the RCP 4.5 and RCP 8.5 scenarios was assumed in line with Stewart (2015) and Stewart and Deng (2015).

In accordance with the Wang et al. decay model (Wang and Wang 2012), a temperature increase will increase decay and subsequently increase vulnerability, while a rainfall reduction will reduce decay and subsequent vulnerability (Ryan et al. 2016). Intuitively, increased wind speeds will increase pole vulnerability. Thus, the net impact of predicted climate change for power pole infrastructure, and indeed many infrastructure types, is dependent on the interactions of opposing influencing climate change effects.

The 1995 baseline temperature and rainfall levels for Brisbane were obtained from the Australian Bureau of Meteorology records based on averages for a standard climatic period of 30 years. These values are 21 °C and 1247 mm/year, respectively. The annual weather for each year of the 2015 to 2090 monitoring period examined in this paper was generated in a given Monte Carlo iteration utilising these baseline values, together with the statistical parameters for climate change projections discussed previously.

2.2 Network details

This study considers a notional network of one million CCA (copper chrome arsenate)-treated timber power distribution poles in Brisbane (see supplementary material Sect. A1 for the layout of a typical Australian power pole). This number of poles was selected based on the number of Monte Carlo iterations required to ensure stabilisation of the model results. It is also noted, however, that the Brisbane and Queensland regions of Australia have an estimated 1.2 million timber power poles (Francis and Norton 2006). The simulation period for the notional network of one million new poles is 2015 to 2090. The poles considered were designed and sized in accordance with existing Australian practices and standards (Standards Australia/New Zealand 2010, 2011). The timber type modelled was spotted gum (*Corymbia citriodora*, *C. henryi*, and *C. maculate*), the most common pole type used for treated poles in Queensland and in Australia in general (Francis and Norton 2006). Pole inspections were based on current guidelines in Australian Standards (Standards Australia/New Zealand 2013), and existing pole inspection and network maintenance practice in the Australian power industry. Inspection intervals were set at 5 years, with first inspection at 20 years (Standards Australia/New Zealand 2013). A power pole in the network is replaced due to (i) wind failure—extreme wind event causes pole to fail (break) at ground level, or (ii) condemning failure—if an inspection reveals that the pole moment capacity was less than 50% of the original pole moment capacity, the pole fails the inspection and is condemned, and subsequently replaced. A brief overview of the stochastic wind field modelling, the multi-layer timber deterioration model, and the probabilistic parameter selection is described in the following section. For more details on these aspects of the model, see the supplementary material associated with this paper or Ryan et al. (2014, 2016).

2.3 Probabilistic modelling of power pole vulnerability

The performance of the power distribution infrastructure is modelled using a sequential event-based probabilistic model which considers (a) structural reliability, (b) infrastructure element deterioration, (c) network maintenance, (d) climate change effects, and (e) the uncertainty and variability associated with each of these aspects of the model.

The power pole failure limit state is defined as the bending failure of a power pole under wind loading, the most common failure mode for timber power poles (Winkler et al. 2010). In calculating the probability of wind failure, the structural reliability analysis considers the time-varying wind load the element is subjected to, $S(t)$, and the time-dependent bending resistance $R(t)$ of a power pole in a network at a given time t, taking into account deterioration and the effect of climate change on both deterioration and wind load. The effects of deterioration on timber poles are modelled based on the work of Wang et al. (2008a, 2008b). The implementation of this model for timber power poles is discussed in detail in Sect. A3 of this paper's supplementary material, and in Ryan et al. (2014). The predicted future changes in annual rainfall and temperature, discussed in the previous section, are incorporated into the model to account for climate change impacts on timber deterioration rates. The time-dependent wind speed is modelled using the Gumbel distribution (Stewart 2015; Wang et al. 2013), with future predicted change in wind speeds incorporated. The work of Henderson and Ginger (2007) is utilised to calculate the time-dependent wind load $S(t)$ on a power pole, as described in more detail in Sect. A4 of the supplementary material, and in Ryan et al. (2014, 2016).

Sequential event-based modelling techniques were employed in order to incorporate the time-dependent changes in load and resistance, and the effects of infrastructure-network maintenance, into the model. The role of both sequential modelling and event-based modelling techniques in accurately representing the time-dependent vulnerability of the power pole network is described in Sect. A2 of the supplementary material. This section explains how each Monte Carlo simulation is used to effectively represent a pole location in a notional power pole network. The reader is referred to the supplementary material Sect. A5, or Ryan et al. (2014, 2016), for the statistical characteristics of each of the model variables and for details on the selection of these variables.

3 Cost-benefit analysis

Stewart (2006) proposed that the total life cycle cost (LCC) of an asset can be described as

$$\mathrm{LCC}(T) = C_D + C_C + C_{IN}(T) + E_{damage}(T) \tag{1}$$

where C_D is the design cost, C_C is the construction cost (materials and labour), $C_{IN}(T)$ is the cost of inspections during the service life T, and $E_{\mathrm{damage}}(T)$ is the expected cost of repair or loss during service life T.

The expected cost of repair and loss can be described as a present value:

$$E_{damage}(T) = \sum_{j=1}^{DS} \sum_{i=1}^{T} P_{f,i} \frac{C_{damage}}{(1+r)^i} \tag{2}$$

where $P_{f,i}$ is the probability of damage in year i; C_{damage} is the cost of repair, pole replacement, and loss; r is the discount rate; and DS is the number of different damage states. In the present case, there are two damage states, namely, power pole condemnings and power pole wind failures. The probabilities used in the estimation of E_{damage} are calculated using Monte Carlo simulation techniques.

The aim of the current study is to compare the effect of adaptation strategies on LCC over the period 2015 to 2090. The initial design cost is assumed to be equal for all cases analysed. Thus, in accordance with Eq. 1, the economic performance is determined by the cost of initial pole construction, inspection costs, and the expected damage costs, all of which are impacted by the cost of adaptation-strategy implementation, and the effectiveness of the adaptation strategy. The 'benefit' of an adaptation measure is the reduction in damage costs related to the adaptation strategy, and the 'cost' is the extra costs associated with implementation of the adaptation strategy. The NPV of an adaptation strategy is

$$\mathrm{NPV}(t) = \mathrm{LCC}_{\mathrm{BAU}}(t) - \mathrm{LCC}_{adaptation}(t) \tag{3}$$

where $\mathrm{LCC}_{\mathrm{BAU}}(t)$ and $\mathrm{LCC}_{\mathrm{adaptation}}(t)$ are the life cycle costs for 'business as usual' (BAU, i.e. existing practice) and each adaptation measure, respectively, discounted to the present value.

The BCR of an adaptation strategy is also examined herein, whereby

$$\mathrm{BCR} = \frac{Benefit_{adaptation}}{Cost_{adaptation}} \tag{4}$$

The benefit is defined as the reduced losses due to reductions in pole condemnings, number of inspections, or pole wind failures, when compared to the BAU case. Similarly, the costs associated with the implementation of an adaptation strategy can range from additional construction cost to additional wind failure and condemning costs, and to additional inspection costs, depending on the nature of the adaptation measure employed. A NPV greater than 0, and a BCR value greater than 1, indicates that an adaptation measure is cost-effective.

It is noted that there is some debate about appropriate discount rates (r) for climate change considerations (Dasgupta 2008). In line with the work of Stewart (2015), a discount rate of 4% was utilised herein; however, the sensitivity of the analysis to the discount rate value is further explored in Sect. 7.

4 Costs

The probabilistic analysis incorporates a number of different costs associated with the operation of a power distribution network as follows:

- Cost of newly installed pole at 2015 — C_C
- Cost of pole inspections — C_{IN}
- Cost of pole replacement — C_{replace}
- C_{damage}Loss of sale of electricity during power outage arising from pole wind failure — C_{sales}
- User costs associated with pole wind failure — C_{user}
- Safety cost associated with pole wind failure — C_{safety}

Hence, total damage cost at time of pole wind failure is $C_{\mathrm{damage}} = C_{\mathrm{replace}} + C_{\mathrm{sales}} + C_{\mathrm{user}} + C_{\mathrm{safety}}$, while the damage cost associated with pole inspection failure (pole condemning) is simply C_{replace}, as it assumed that the other cost implications arising from scheduled replacements are negligible (i.e. minimal or no power interruption).

Following consultation with Australian power pole suppliers, the cost of a new pole (C_c), designed in accordance with existing Australian standards, was taken as \$561, while the cost of a pole one size grade larger was taken as \$715 (i.e. cost of \$154 associated with increasing pole ground-line diameter size by one sizing grade). Information on inspection and pole replacement costs were obtained from the Australian Energy Regulator (AER) Regulatory Information Notices (RIN) (AER 2015). This is publically available data which each power company in Australia is obliged to submit to the AER each year. Mean inspection costs per pole across four Australian power companies in New South Wales and Queensland range between \$23 and \$104. This inspection cost (C_{IN}) is modelled herein as a uniform distribution with a range of \$25 to \$125.

Again, considering the AER RIN data for utility companies in New South Wales and Queensland, the mean pole replacement costs (C_{replace}) across both failed and condemned poles was found to be between \$5300 and \$10,400. This pole replacement cost is modelled in this analysis as a uniform distribution with a range of \$3500 to \$15,000.

Calculation of the cost to the power company of power (C_{sales}) unsupplied during an outage requires (a) the rate charged for a unit of electricity and (b) the loss of electricity supplied per pole wind failure, termed Lost Load (LL). Again, it is noted that scheduled pole replacements arising from pole condemnings are assumed to result in minimal or no power service interruption, i.e. $C_{\mathrm{sales}} = 0$. The rate the power company charges customers per kilowatt-hour supplied fluctuates over time in Australia and differs for off-peak and on-peak times. A general power charge rate per kilowatt-hour supplied is \$0.30/kWh (AEMO 2015). The LL (lost electricity load per pole wind failure) can be obtained as

$$\mathrm{LL} = \mathrm{OD}[N_{\mathrm{res}}R_{\mathrm{res}} + N_{business}R_{business}] \tag{5}$$

where OD is the power outage duration resulting from the pole failure, N_{res} and N_{business} are the number of residential and business customers affected by the outage, respectively; and R_{res} and R_{business} are the power consumption rates for residential and business customers, respectively. Information on the average duration of power outages (OD) is obtained from the AER RIN data (AER 2015). The average power outage duration across Queensland's two primary power companies for 'unplanned outages' was found to be 380 min. It is likely that power outage duration specific to pole failures will be longer than this mean figure; however, in the absence of outage duration data specific to pole failures, an OD value of 380 min is used in the analysis.

According to the AER RIN data, the average number of customers affected by a given 'unplanned outage' for Queensland's two primary power companies is 95 (AER 2015). The Australian network comprises 88% residential customers and 12% business customers (ESSA 2015). Incorporating the proportional breakdown of the national network, this translates to $N_{\mathrm{res}} = 83.6$ and $N_{\mathrm{business}} = 11.4$ customers. According to the Energy Supply Association of Australia (ESSA), the average hourly power consumption rate for residential and business customers is $R_{\mathrm{res}} = 0.67$ kWh/h/customer and $R_{\mathrm{business}} = 13.21$ kWh/h/customer (ESSA 2015). This calculation assumes a constant power usage over the entire year, disregarding the effect of peak hours. This is deemed an acceptable approximation herein, as a power pole is equally likely to fail in or out of peak hours.

The above costs affect the utility company operating the network directly, while the C_{user} cost is borne by the power user. This user cost is the product of LL per pole failure expressed in kilowatt-hours (discussed above), and Value of Lost Load (VoLL), described as the average cost to consumers per unit of unserved electricity due to outages, expressed as dollars per kilowatt-hour (\$/kWh) (Stoft 2002). The inelastic nature of electricity demand leads to high losses of consumer surplus during outage, meaning VoLL tends to be considerably higher than the actual cost of electricity (Praktiknjo et al. 2011). In a comprehensive study of German residential customers, Praktiknjo et al. (2011) estimated the VoLL to be \$23.57/kWh, with a coefficient of variation (COV) of 1.22. This mean value is similar to the Value of Customer

Reliability (VCR) of \$25.95/kWh, published by the Australian Energy Market Operator (AEMO) (AEMO 2014). It is noted that the VCR metric used by the AEMO, described as the estimated dollar value that customers place on reliable supply of electricity, is similar to the VoLL metric.

Given the similarity between the Praktiknjo et al. (2011) and the AEMO (2014) findings and the importance of considering the high variability and uncertainty associated with VoLL (Praktiknjo et al. 2011), the mean and COV VoLL values developed by Praktiknjo et al. (2011) are used in the Monte Carlo simulation herein for Australian residential customers. The Praktiknjo et al. (2011) study did not, however, consider business customers. Consequently, the mean user cost developed by the AEMO across four Australian business-customer sectors is used in this analysis (\$54.12/kWh). The AEMO did not publish statistical parameters for user costs. Consequently, the user cost COV for business customers was assumed to be the same as the residential customers, at 1.22. Both user costs are modelled with a lognormal distribution.

In accordance with the findings of Praktiknjo et al. (2011), the influence of outage duration on user outage cost for residential customers is

$$d = 1 - 0.21\ln(\mathrm{OD}) \tag{6}$$

where d is the factor for the influence of outage duration and OD is the outage duration in hours. In the present case, since OD = 380 min, $d = 0.63$. For business customers, $d_{\mathrm{business}} = 1.0$. This is due to the fact that the initial period of a power interruption is more costly than the later periods of interruption for residential customers, who tend to adapt to power interruptions over a number of hours; however, each minute of power interruption is more likely to represent a loss of earnings for business customers.

The final cost to be discussed is the safety cost (C_{safety}), borne by the power company due to power pole failure. This is the cost associated with high consequence, low probability events, such as bushfires or wildfires, death or injury to people or livestock due to downed power lines, etc. Given the rare nature of these events, little probabilistic cost data is available either in an Australian context or in an international context. Consequently, this cost is not considered in the main body of the results in the next section, but instead is dealt with using the sensitivity analysis in Sect. 7.

5 Adaptation strategies

The five adaptation strategies and the BAU strategy investigated in this study are as follows:

- Business as usual (BAU): Pole diameter design is in accordance with AS/NZS standards; inspection intervals are set at 5 years; and pole condemning criteria are set at 50% of original pole capacity.
- Adaptation strategy 1: Same as BAU, with the exception that the pole condemning criterion is increased from 50 to 55% of original pole capacity. This means that poles are replaced at an earlier stage of deterioration, reducing the vulnerability of the network to power pole wind failures.
- Adaptation strategy 2: Same as BAU, with the exception that pole inspection intervals are reduced from 5 to 4 years. Poles are thus inspected more frequently, meaning severely

deteriorated poles are more likely to be removed before wind failure occurs, increasing the overall resilience of the network.

- Adaptation strategy 3: Same as BAU, with the exception that both original poles and replacement poles used are one size grade larger than required under existing Australian design procedures. Practical implementation for this strategy would mean that power companies only install larger poles in their network from this point in time onwards.
- Adaptation strategy 4: As with strategy 3, both original poles and replacement poles are one size grade larger than required under current Australian design procedures; however, the pole condemning criterion is lowered from 50 to 45%. Thus, this adaptation strategy balances measures to increase and decrease vulnerability, respectively, in an attempt to optimise the cost-benefit result.
- Adaptation strategy 5: This strategy combines poles one size grade larger than required under AS/NZS design procedure, with an increase in inspection intervals from 5 to 6 years. Again, this dual approach seeks to increase network resilience to climate change through increased pole size, while reducing network-operating costs by increasing inspection intervals.

6 Results

6.1 Climate impact results

Climate change impacts were examined in terms of total pole wind failures, and total poles condemned, for the BAU case (i.e. no adaptation) for the notional network of one million poles in Brisbane over the 2015 to 2090 period. The analysis indicates that climate change increases pole condemnings from approximately 760,000 under no climate change to 809,000 (6% increase) under RCP 4.5, and 846,000 (11% increase) under RCP 8.5. The pole wind failures were found to increase from 13,600 under no climate change to 16,000 (18% increase) under RCP 4.5, and 18,700 (37% increase) under RCP 8.5. These sizable predicted climate impacts, combined with the consequences of failure associated with these critical infrastructure elements, highlight the need to investigate the cost-effectiveness of climate change adaptation strategies.

6.2 Climate adaptation results

The effectiveness and cost-benefit outcomes for the five climate adaptation strategies under the RCP 4.5 and RCP 8.5 trajectory scenarios for Brisbane are presented in Table 1, for the period 2015 to 2090. The effectiveness of each adaptation strategy is presented in terms of its ability to reduce pole condemnings and pole wind failures to pre-climate-change levels. These metrics are independent of cost and are expressed as a percentage of condemning rates and pole wind failure rates, occurring under the adaptation strategy and RCP scenario, as a percentage of those occurring for the BAU approach under pre-climate-change conditions. For instance, BAU under RCP 8.5 reads as 137% in Table 1, reflecting the fact that the impacts of RCP 8.5 increases wind failures by 37% as discussed in Sect. 6.1. Looking at adaptation strategy 1 in Table 1, this strategy reduces wind failures under RCP 8.5 to 105% of those experienced under pre-climate-change conditions (a 32% reduction compared to BAU).The cost-benefit results for each adaptation strategy are expressed in terms of mean NPV and mean BCR. These results

Table 1 Climate adaptation strategy results for Brisbane under RCP 4.5 and RCP 8.5 scenarios

Adaptation	RCP 4.5				RCP 8.5			
	Effectiveness		Cost-benefit		Effectiveness		Cost-benefit	
	Percent of condemning failures	Percent of wind failures	Mean NPV ($/pole)	Mean BCR	Percent of condemning failures	Percent of wind failures	Mean NPV ($/pole)	Mean BCR
BAU (i.e. climate change impacts)	106	118	–	–	111	137	–	–
Strat. 1—CC 55%	116	88	−102	0.47	121	105	−99	0.66
Strat. 2—insp 4 years	109	83	−30	0.81	114	98	−25	0.87
Strat. 3—LP	93	40	163	1.13	98	46	184	1.18
Strat. 4—LP and CC 45%	83	69	241	1.79	87	82	272	1.87
Strat. 5—LP and insp 6 years	92	69	164	1.39	97	82	193	1.44

Strat. adaptation strategy, *CC* condemning criteria, *LP* larger poles, *insp* inspection interval

indicate whether or not a climate adaptation strategy is cost-effective. Thus, a negative NPV and a BCR less than 1.0 indicate that the investment required to implement the strategy outweighs its financial benefit, when costs are discounted to present value. The BAU case is also shown in the table for comparative purposes.

Examination of the results for adaptation strategies 1, 2, and 3 provides insight into the individual effect of changes in condemning criteria, inspection intervals, or pole design procedure, respectively. As can be seen from Table 1, increasing the condemning criterion to 55% is effective in reducing the number of pole failures to almost-no-climate-change levels (137 to 105% for RCP 8.5); however, this occurs at the expense of a significant increase in the numbers of poles condemned and replaced. Due to the relatively rare nature of power pole wind failures, replacement due to pole condemning is in the region of 50 times more likely to occur over the modelling period. Consequently, while the increase in condemning criteria to 55% was found to significantly reduce pole wind failures, the significant increase in pole replacements due to condemning meant the adaptation strategy was highly cost-ineffective, with the lowest mean NPV, and smallest mean BCR, of the five climate adaptation strategies considered.

Reduction in inspection intervals from 5 to 4 years was found to be a more effective measure. This strategy reduced pole wind failures below pre-climate-change rates for both RCP scenarios. This came at a cost of a 9 and 14% increase in the annual pole condemning rates for RCP 4.5 and RCP 8.5, respectively, and the cost associated with a greater number of inspections over the 76-year network monitoring period. These costs resulted in a negative cost-benefit result. By contrast, increasing the pole dimensions by one size grade was found to have a highly positive cost-benefit outcome, while also being highly effective in reducing climate change impacts. Failure rates are less than half those experienced under the no-climate-change condition for both RCP scenarios, while the mean NPV is $184 per pole for RCP 8.5, equating to a saving of $2.4 million per year over the BAU approach for the notional network of Brisbane poles.

Strategy 4 illustrates how combined adjustments to design procedure and pole condemning criteria can be used to optimise climate change adaptation. This adaptation strategy, which combines the use of larger poles with less stringent pole condemning criteria, is the best-performing adaptation strategy. The BCR metric under RCP 8.5 indicates that for each \$1 of investment, \$1.87 of benefit is obtained; while the NPV indicates a mean saving of \$272 million dollars to 2090 for a network of one million Brisbane poles. Finally, adaptation strategy 5, which combines larger poles with longer inspection intervals, can be seen from Table 1 to be the second-best adaptation strategy, with a BCR of approximately 1.4. It is noted, however, that this adaptation strategy may be easier to implement from a practical perspective, and thus, may be more favourable for power companies. It is noted that the safety cost is assumed to be zero in the above analysis, given the uncertainty associated with this cost. As shown in the sensitivity study in the next section, incorporation of the safety cost in the assessment increases the cost-benefit performance of the climate adaptation strategies. Overall, it was also found that cost-benefit results were not hugely sensitive to the climate change scenarios considered. In fact, climate adaptation strategy 4 was found to exhibit a strongly positive cost-benefit outcome for the 'no climate change' scenario, with a mean BCR of 1.73 and a mean NPV of \$223 per pole, representing a win-win adaptation strategy.

While Table 1 provides insight into the performance of each adaptation strategy, it does not provide information on the uncertainty or variation associated with the cost-benefit performance. The nature of this variation or uncertainty is not straightforward. It is strongly influenced by high-consequence, rare events, i.e. the wind failure of a power pole, which has an annual probability of occurrence in the region of 0.02%. Figure 1 illustrates the nature of cost-benefit performance variation across the power pole network using histograms of NPV for climate adaptation strategy 4 under RCP 8.5. The one million Monte Carlo simulations produce one million NPVs based on the LCC of adaptation strategy vs the LCC of the BAU strategy. Figure 1a illustrates the range of NPVs across the one million iterations, which ranges from −\$230,000 to \$630,000, with the majority of values having a NPV in the region of \$0. Examination of the histogram on a smaller *x*-scale from −\$1000 to \$1000 in Fig. 1b provides further insight. For approximately 40% of all iterations (380,000) the NPV is equal to −\$154. This NPV arises in a given Monte Carlo iteration when there is no difference between the BAU case and the adaptation case in terms of wind failures and pole condemnings over the monitoring period. When this occurs, the initial investment of \$154 to increase pole size is not offset by any improvement in pole performance over the monitoring period.

However, when considering an infrastructure network, the effectiveness of an adaption strategy from infrastructure element to infrastructure element is not of primary concern. What is of greater concern is the average performance across the entire network, represented by the mean NPV. This means NPV is strongly influenced by the tails of the NPV distribution, which represent high-consequence rare events, i.e. wind failure of power poles, with associated costs. The lower and upper tails of the NPV distribution are presented in Fig. 1c, d, respectively, which shows NPV ranges from −\$100,000 to −\$700,000, and \$100,000 to \$700,000, respectively. As can be seen from the comparison of the lower and upper tails, the implementation of adaptation strategy 4 is far more likely to result in a significant saving than a significant loss. This is a key factor in the positive mean NPV result for adaptation strategy 4.

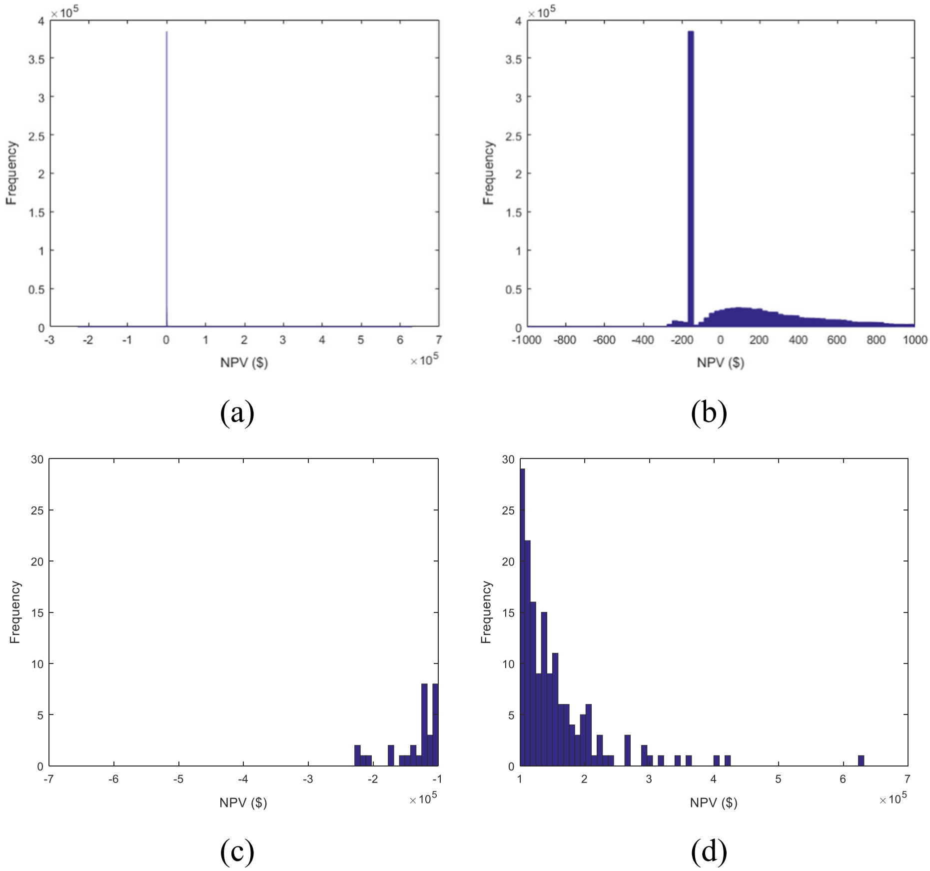

Fig. 1 Histograms of NPVs for adaptation strategy 4 under RCP 8.5, with (a) showing the entire range of NPVs, (b) showing NPVs from −$1000 to $1000, and (c) and (d) showing the lower and upper tails of the NPV histogram, respectively

The 10th percentile, mean, and 90th percentile NPVs under RCP 8.5 for the five adaptation strategies are as follows: strategy 1, 10th = −$437, mean = −$99, 90th = $0; strategy 2, 10th = −$245, mean = −$25, 90th = $41; strategy 3, 10th = −$176, mean = $184, 90th = $461; strategy 4, 10th = −$154, mean = $272, 90th = $739; strategy 5, 10th = −$139, mean = $193, 90th = $467.

7 Sensitivity study

7.1 Effect of monitoring period on cost-benefit performance

The results presented in the previous section are for a monitoring period which runs from the year 2015 to 2090. The sensitivity of the cost-benefit results to the monitoring period selected is illustrated in Fig. 2. This figure shows the mean NPV for adaptation strategy 4 under RCP 8.5, when the monitoring period starts in year 2015 and ends in years 2030, 2045, 2060, 2075, and 2090. This plot effectively provides information on the likely payback period for the

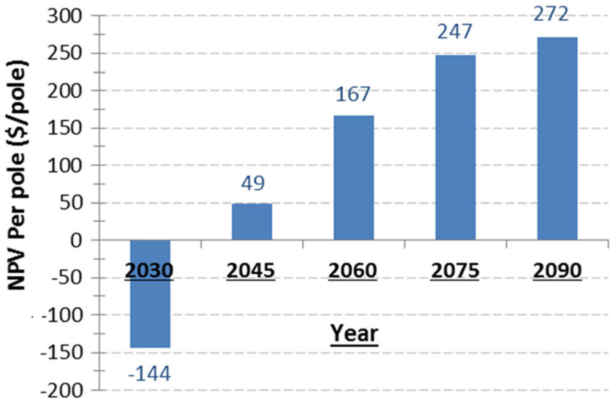

Fig. 2 Sensitivity of NPV to end of monitoring period selected for adaptation strategy 4 under the RCP 8.5 scenario

climate adaptation strategy, which involves an initial investment of $154 per pole at t = 0 years. As can be seen from Fig. 2, adaptation strategy 4 has a strongly negative cost-benefit result at the year 2030. This is due to the fact that the network is just 16 years old at this point, meaning few poles have failed and no poles have been replaced for either the BAU case or the adaptation strategy 4 case. However, by the year 2045 adaptation strategy 4 has a modestly positive NPV. This NPV of the adaptation per pole continues to grow with time, as the poles in the network continue to age and are thus more likely to fail and require replacement. It is noted, however, that benefits realised later will have diminished effect on the NPV as a result of future costs and benefits being discounted in accordance with Eq. 2.

7.2 Discount rate

The effect of discount rate on mean NPV and BCR was investigated for climate adaptation strategy 2 (inspection interval = 4 years), and adaptation strategy 4 (larger poles, condemning criteria = 45%) for the RCP 8.5 scenario. Discount rates of 1%, 2%, 4%, 6% and 8% were examined. An increase in discount rate will mean less value is placed on costs and benefits which occur later in the monitoring period. Changing the discount rate had a notable effect for strategy 4. The mean NPV and BCR at the discount rate of 1% were $1175 and $4.21, respectively, while the corresponding values at the discount rate of 8% were −$22 and $0.62, respectively. This effect is primarily due to the fact that adaptation strategy 4 requires an investment of $154 at year 1, and the benefits of this strategy for a given pole (given Monte Carlo simulation) are not generally felt until later in the monitoring period, if at all. Nonetheless, adaptation strategy 4 still has a positive cost-benefit outcome at a discount rate of 6%. Discount rate was found to have only minor impacts on adaptation strategy 2. This strategy's performance improved with increasing discount rate, but was still only borderline cost-effective at the discount rate of 8%.

7.3 Safety cost

As discussed in Section 4, there is little or no data available to provide a precise estimation of safety cost for power pole wind failure (C_{safety}). Industry experience indicates that this cost may be in the region of $20,000 to $60,000, with a large COV in the region of 1. This information was used for the sensitivity analysis with mean safety costs per pole wind failure of $0, $10,000, $20,000, $60,000, and $90,000 explored, modelled as lognormal distributions with a COV of 1.0. The sensitivity analysis was conducted for adaptation strategy 4 under RCP 8.5. The mean NPV and mean BCR increased with increasing safety cost, from $290 and 1.88 at $10,000 to $440 and 2.07 at $90,000, respectively. Given the sensitivity of the analysis to this safety cost, further collaboration with the power industry is required to put procedures in place to better quantify the magnitude of safety cost.

8 Conclusions

A probabilistic framework was developed to quantify the cost-effectiveness of climate adaptation strategies for critical infrastructure. Five adaptation strategies for power pole networks were considered, incorporating a range of adjustments to current practice in design and network maintenance. It was found that the impacts of climate change could be substantially reduced by nearly all adaptation strategies. However, it is more challenging to develop cost-effective climate adaptation strategies. An adaptation measure that allows for the installation of larger poles, but with less stringent pole replacement criteria, was found to have the highest net benefit. This adaptation strategy substantially reduced power distribution infrastructure operation costs across a range of climate change scenarios. The sensitivity analysis highlighted the importance of monitoring (or payback) period and discount rate in the analysis and indicated that further effort should be made to attempt to ascertain the probabilistic parameters for the safety cost arising from power pole failures. The probabilistic cost-benefit analysis framework employed herein could be used to explore climate adaptation feasibility for a range of research areas.

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