ELECTRICITY
SECTOR
CLIMATE
INFORMATION
PROJECT

ESCI Technical Report

The use of case studies of extreme/compound events in risk assessments

December 2020

Australian Government
Department of Industry, Science, Energy and Resources

CSIRO

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Australian Government
Bureau of Meteorology

Contents

Executive summary

ESCI project engagement with stakeholders, and AEMO through their ISP stakeholder engagement process, has consistently noted that extreme and compound weather events are a major concern in planning for a resilient future network.

The 2020 ISP Appendix 8 states that[1]:

> *"Energy systems face numerous challenges in a changing climate. Increasingly, energy system vulnerabilities to heightened climate impacts, particularly extreme weather, are recognised as material risks to individual assets, the integrated energy system, and society. Consumer demand for energy, and increasingly generation supply, are significantly influenced by weather, increasing the power system's climate exposure. [At the same time power system resilience] is in long-term decline … driven by numerous compounding factors:*
>
> - *Climate change is increasing the frequency and magnitude of physical weather hazards.*
> - *Cyber hazards are increasing risks to software-based system solutions.*
> - *Generation sources are increasingly located in stringy, weak parts of the system, increasing vulnerability. These generation sources are also inherently more vulnerable to extreme hazards.*
> - *System control services are increasingly complex, manual, and reactive, risking cascading system impacts.*
> - *Societal services are increasingly interconnected risking cascading societal impacts.*
> - *An increasing focus on quantitative cost benefit analysis over good design principles, that excludes mitigation for risks that are difficult to quantify and value."*

The work of the ESCI project in this area (Work Package B) sought to:

1. Establish the best climate information that can be provided on extreme and compound weather events that will threaten the electricity sector in the future.
2. Use the *ESCI Climate Risk Assessment Framework* to test whether the climate information provided by the project is in a form useable by the sector.
3. Conduct industry focus groups to explore how these findings could inform the electricity sector's climate risk decision making [2].

The project produced an initial compound event case study[3] for use in the first ESCI Workshop in May 2019. This case study was derived from historic weather events with some of the underlying climate drivers 'dialled up' to reflect expected climate change. It was used to explore system vulnerabilities, which then informed the work of the rest of the project.

The workshop and subsequent engagement identified the need for quantitative case studies (an extreme weather event presented as a data set of coincident weather variables), which include

---

[1] AEMO 2020 ISP, Appendix 8: Resilience and Climate Change

[2] ESCI Work Package B contract, Schedule 2 Clause 1.2.9 asks for "A report from these scenario exercises to the Australian Energy Market Operator and DISER, detailing how these findings could inform the electricity sector's climate risk decision making."

[3] This was described as a 'scenario' in the contract and the first workshop, but stakeholder consultation has made clear that in the electricity sector a discrete, time-bounded event is usually referred to as a 'case study'. This is the convention used throughout this report.

probability information. This information can be used by the sector to estimate the cost and consequence of extreme events as an input to investment planning decisions.

The ESCI team has demonstrated a methodology for identifying extreme and compound events in the climate projections and provided the sector with a quantitative case study of a compound weather event based on the weather 'signature' of "Black Saturday" in February 2009. This case study was used in six sector focus groups to explore:

- how decisions to support system resilience in the face of extreme events are made;
- whether the information that can be provided by climatology can be used to inform these decisions;
- what decision-making practices would need to change to use this information more effectively to support power system resilience.

The project found that current decision-making practices, guided by the RIT-T/D framework from the AER, work well for events which affect a limited geographic area and which include probability information. For widespread events, and rare extreme or compound events, the lack of probability information means that RIT-T guidelines cannot be used for investment decision-making. However, these events are expected to have significant consequences on the system and delivery of electricity and are increasing in likelihood as the climate changes.

All sector focus groups, and international best practice, indicated that having a set of case studies of compound weather events for consistent use across the sector, provided by a credible authority, is desirable. Stress-testing operational and planning decisions to increase system resilience, using these case studies, should be considered as part of electricity sector long-term planning. This set of case studies should be produced in collaboration with market bodies, and in further consultation with the sector.

Producing a suite of quantitative case studies from the climate projections is a very resource intensive exercise. The innovative approach piloted by the project has demonstrated that it can be done, however producing a suite of case studies which sample the full range of likely events and which test the full range of sector vulnerabilities, with estimates of the probability of *any* high-impact compound weather event occurring, requires a very large ensemble of climate projections and significant scientific resources. This is beyond the resources of the ESCI project but is likely to be of broad benefit to other sectors, including the emergency management sector, and should be supported by the electricity sector.

The qualitative (narrative) and quantitative (extracted from the climate projections) compound weather case studies developed by the project can already be used across the sector for stress-testing. A set of compound weather case studies useful for the sector could be developed by taking historical events and compounding them and/or adding a climate signal such as increased temperature. These case studies would not provide any probability information or identify events that differ from history but would significantly advance the assessment of and planning for the resilience of the electricity sector. This work is outside the scope of the current ESCI project; however the project recommends that this is considered for future work.

1. Introduction and Purpose

A changing climate with its associated impact on extreme events poses a risk to many parts of the Australian economy. By its nature, the electricity sector with a wide mix of assets, and complex interdependencies between weather and generation, transmission, distribution, and consumer behaviour, may be particularly vulnerable if future planning does not account for increasing weather extremes.

Recognising the risks, the Electricity Sector Climate Information (ESCI) project, which is a collaboration between AEMO, the Federal Government, the Bureau of Meteorology and CSIRO, was established to deliver climate information and data to assist electricity sector decision-makers manage risks to the reliability and resilience of electricity systems from extreme weather events in the context of a changing climate. It will improve the information available on likely changes to future extreme weather events such as heatwaves, high wind and maximum temperature thresholds, and consider concurrent and/or compounding weather events, to inform analysis of long-term climate risk.

The focus of this report is on how short-lived extreme events (i.e., beyond changes in the mean or average conditions) test the resilience of the electricity grid. An extreme event is not explicitly defined for the electricity sector (see Section 2.4) but focus group attendees variously considered it as beyond the 99th percentile or as an event that would historically be regarded as a 1-in-200 year occurrence. Extreme events could be rare occurrences of single phenomena (such as tornadoes or down-drafts) or single variables (such as extended heatwaves), or compound events, considered in climatology to be "two or more events occurring simultaneously, [that] can lead to high impacts, even if the two single events are not extreme per se"[4]. The project explored the question of how extreme and compound weather events may change in the future, and to what extent can credible, quantitative case studies be developed.

Through workshops and consultation with the electricity sector, the project has developed an understanding of how electricity infrastructure is vulnerable to weather and may be at risk from climate change. Based on this knowledge we identified compound weather events that would challenge known vulnerabilities of the power system and developed future examples/case studies of these events.

This report describes how the ESCI project:

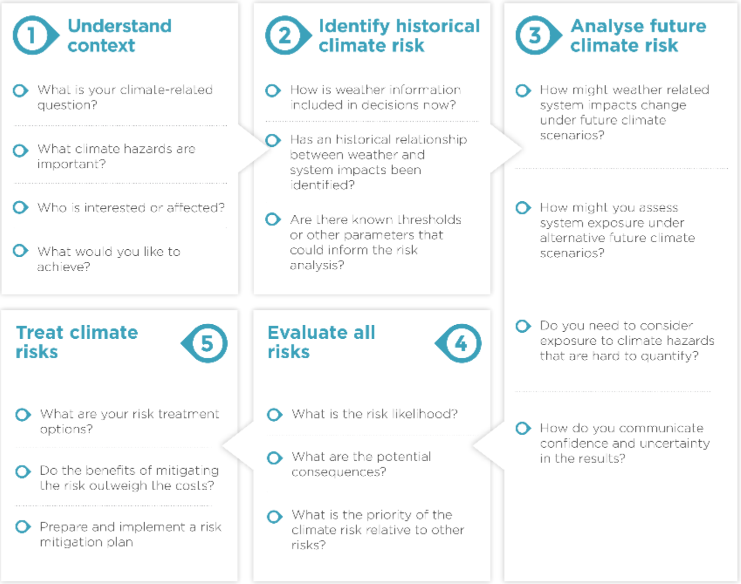
1. Established the best climate information that can be provided on extreme and compound weather events that will threaten the electricity sector in the future.
2. Used the *ESCI Climate Risk Assessment Framework* (Figure 1) to test whether the climate information provided by the project is in a form useable by the sector.
3. Conducted industry focus groups to explore how these findings could inform the electricity sector's climate risk decision making [5].

---

[4] Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Extremes (SREX), 2012 **https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf**. Defining events based on probability or return period is complicated as the climate is not stationary under climate change. Hence both of these standard metrics move with time which results in large errors in the range.

[5] ESCI Work Package B contract, Schedule 2 Clause 1.2.9 asks for "A report from these scenario exercises to the Australian Energy Market Operator and DISER, detailing how these findings could inform the electricity sector's climate risk decision making."

Figure 1: The ESCI climate risk assessment framework



Focus groups on this topic were organised by role as follows:

- Network regulatory economists and policy analysts.
- Network engineers and planners.
- AEMO engineers and planners.
- ESCI Reference Group (cross-sector).
- Consumers and consumer representatives.
- Generator proponents, insurance representatives and finance companies.

Summaries of the key ideas and discussion from each focus group can be found in Attachment A.

2. Understand context

2.1. Expected Increases In extreme weather

Extreme events have always been part of Australia's variable climate, however, climate change is expected to amplify many of the historical drivers of extreme weather events resulting in changes that will produce "significant property, personal and economic damage and hardship."[6]

Australia's climate is historically naturally highly variable, characterised by coherent rainfall variability with long dry periods and periods of widespread heavy rainfall (see Figure 2). This variability is driven by underlying, global-scale, weather phenomena, in particular, the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM)[7]. These three global

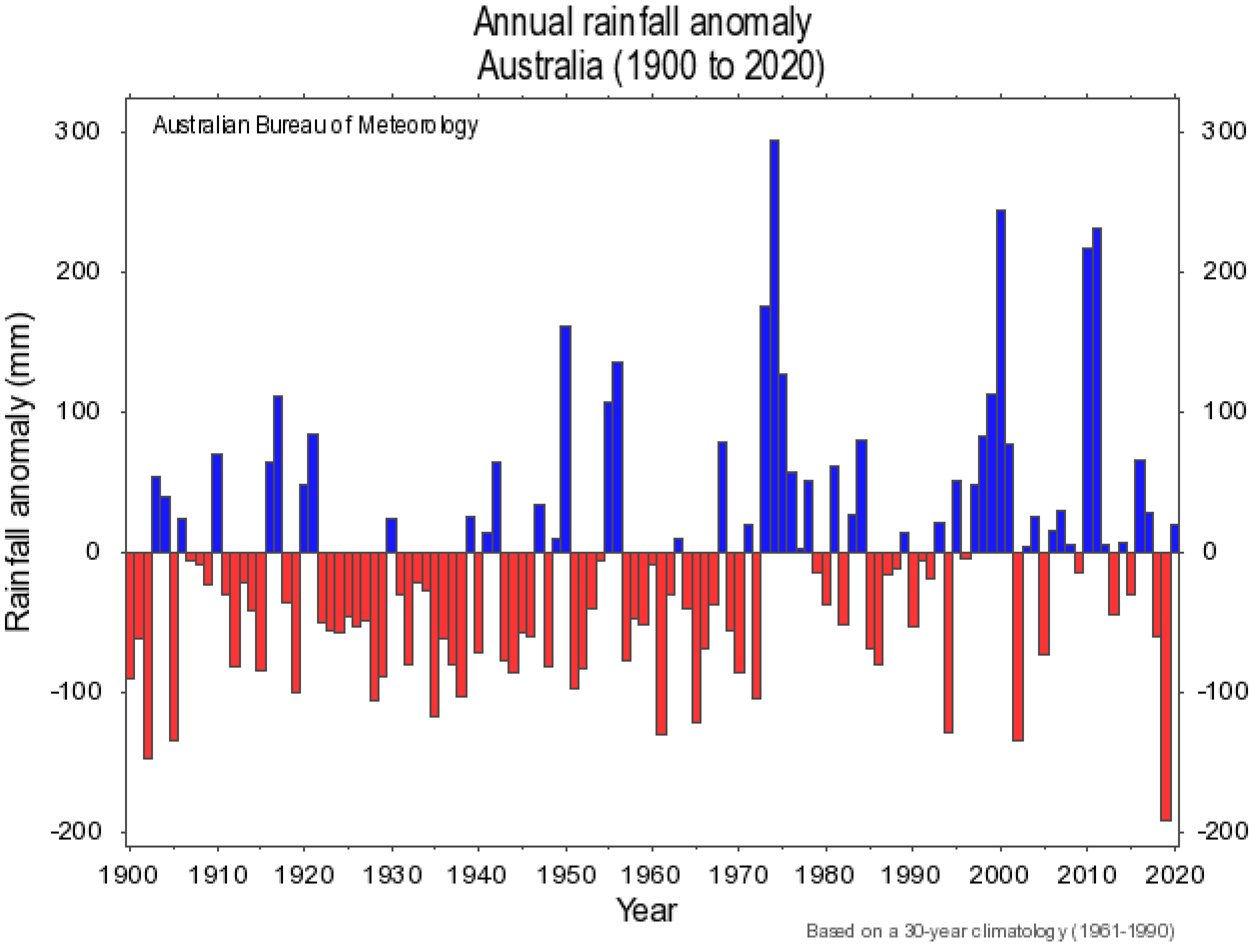
---

[6] Buckley, B., Chan, P., Leplastrier, M., Dyer, A., *Severe Weather in a changing climate*, IAG/NCAR report 011119.

[7] See ESCI Webinar ***The influence of climate change on the Australian Bushfire Season*** for more explanation of how the underlying phenomena affect weather extremes.

climate phenomena fall into or out of phase, leading to large rainfall and temperature variability. Climate change adds strong trends in both temperature and rainfall (Figure 3, for example) as well as unpredictable changes in the underlying drivers; for example, climate modelling provides evidence for a doubling in the occurrences of extreme El Nino events in the future[8] and a near doubling of the frequency of category 4 and 5 storms in the Atlantic Ocean by the end of the 21st century[9].

Figure 2: Australian rainfall anomalies since 1900 (Source: BOM)



A recent report from the United Nations Office for Disaster Risk Reduction highlighted that between 1980 and 1999, 4,212 disasters were linked to natural hazards worldwide resulting in approximately US$1.63 trillion in economic losses, but that in the following twenty years this number nearly doubled with 7,348 major recorded disaster events between 2000 to 2019 resulting in approximately US$2.97 trillion in global economic losses[10]

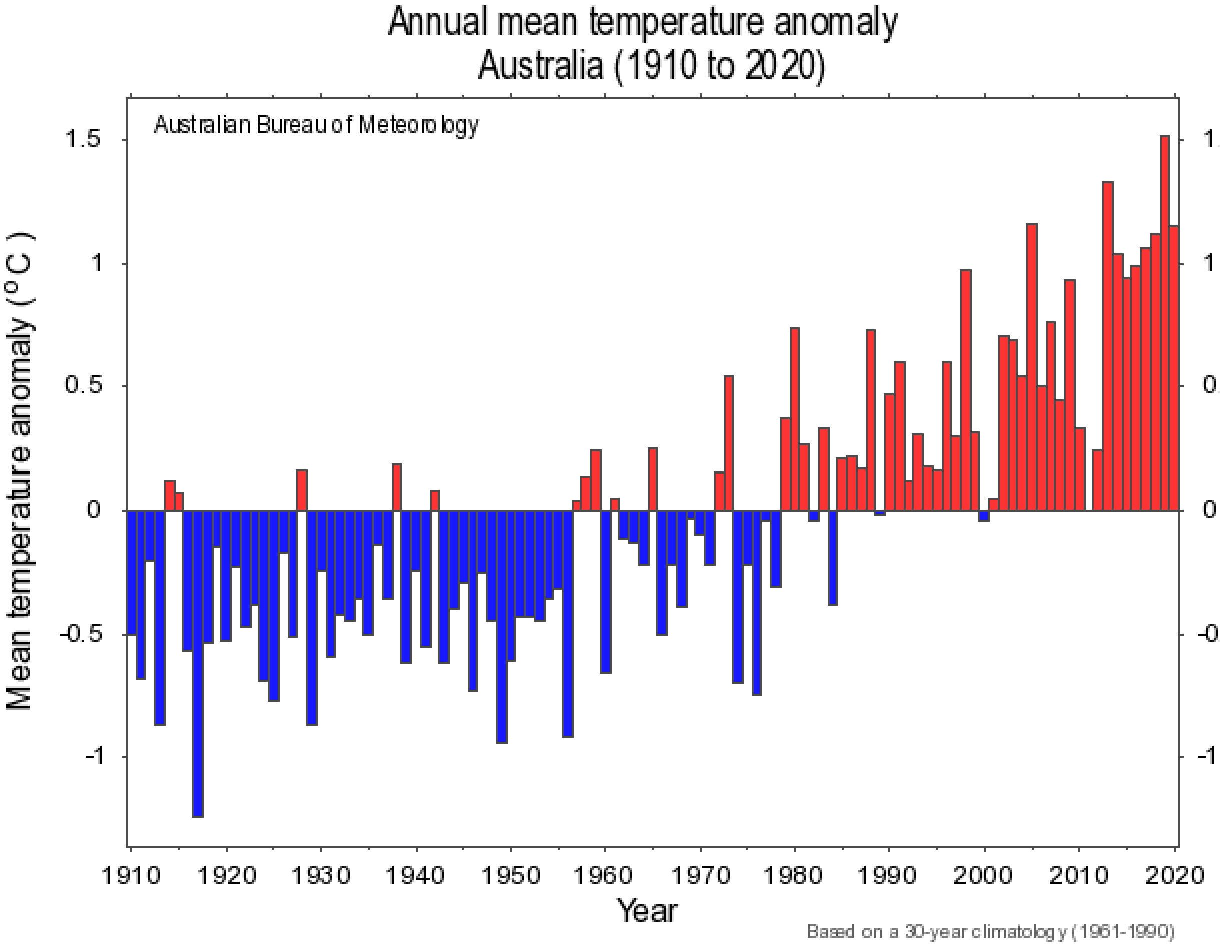
---

[8] Cai, W., Borlace, S., Lengaigne, M. *et al.* Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Clim Change* **4,** 111–116 (2014). https://doi.org/10.1038/nclimate2100.

[9] Bender, M.A., Knutson, T.R., et al. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes**.** *Science* 22 Jan 2010: Vol. 327, Issue 5964, pp. 454-458 DOI: 10.1126/science.1180568

[10] UNDRR, The human cost of disasters: an overview of the last 20 years (2000-2019), Published October 2020, **https://www.undrr.org/publication/human-cost-disasters-overview-last-20-years-2000-2019**

Figure 3: Frequency count of the national daily mean temperature (continental average) reaching the 99th percentile (relative to the month) each year (Source: BOM[11])



The predicted increase in the frequency and severity of extreme weather events will challenge Australia's electricity infrastructure, in particular[12]:

- Increased frequency of large-scale heatwaves and record-high temperature
- Longer fire season with more extreme fire danger days
- Reduced average rainfall, particularly during the cooler months of the year with an increase in heavy rainfall
- Increased frequency of coastal storm surge inundation as sea levels continue to rise
- Possible reduction in the total number of tropical cyclones but an increase in the proportion of high-intensity storms.

---

[11] http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries

[12] See for example: **http://www.bom.gov.au/climate/extremes/** and **http://nespclimate.com.au/new-information-on-extreme-weather-and-natural-hazards-in-our-changing-climate/**

The vulnerability of Australia's electricity infrastructure to severe weather highlights the inadequacy of current decision-making approaches to using the science of extreme climate events, and there is a need for a changed approach to transforming meteorological information into actionable decisions[13].

2.2. Vulnerability of the electricity system to extreme and compound events

ESCI project consultation identified the key vulnerabilities of the power system to extreme weather events, including:

1. Physical damage to critical infrastructure, both generation and transmission/distribution assets, affecting supply.
2. Loss of supply due to the indirect impact of weather on generation – e.g., reduced solar generation because of bushfire smoke and high temperatures, reduced wind output due to high winds and/or high temperature, reduced output of thermal coal plants due to ineffective cooling.
3. Increase in customer demand across the National Electricity Market (NEM) due to extreme temperatures, particularly when heatwave conditions affect large areas.
4. De-rating of transmission and distribution lines because of smoke and high wind.
5. Shorter windows of opportunity for maintenance on network assets due to a longer bushfire season.
6. Additional demands on personnel: in support of the emergency services; due to system restoration or local generation needs; as a result of poor communications in an emergency; stress due to extended working periods.

While individual events or localised weather extremes pose local or asset-specific risks, compound events in which multiple adverse impacts occur concurrently or in quick succession pose challenges to whole-of-system resilience. Widespread exposure to extreme weather hazards can result in electricity system failures as well as health hazards, and compounding failure of other systems, such as telecommunications systems[14].

Examples of compound extreme events affecting the NEM include:

- A heatwave in February 2009 was followed by the devastating 'Black Saturday' bushfires in Victoria.
- A multiple tornadic storm event in September 2016 led to the loss of power for 850,000 customers ('Black System').
- A high pressure system over the Tasman Sea, combined with an approaching cold front, resulted in north to northwest winds and very hot humid conditions across southeast Australia[15]. This led to thunderstorms in January 2020 that created severe convective downbursts which damaged transmission towers causing the islanding of South Australia.

---

[13] Troccoli, A. (Ed.) Weather and Climate Service for the Energy Industry (2018) DOI 10.1007/978-3-319-68418-5

[14] Cainey, J.M., 2019, *Resilience and Reliability for Electricity Networks*. The Royal Society of Victoria, 131, 44-52, 10.1071/RS19005.

[15] https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/preliminary-report-31-jan-2020.pdf?la=en

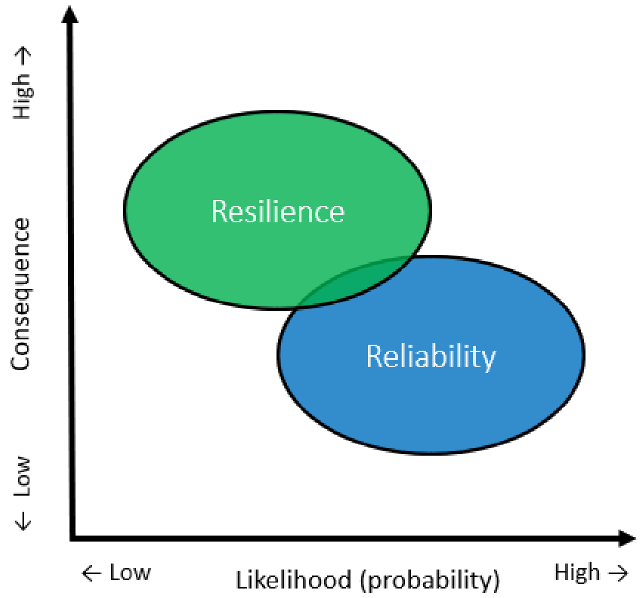
The consideration of possible changes to the severity or frequency of compound and extreme weather events as a result of climate change was identified by decision-makers in the electricity sector as a priority climate information gap, and critical to long-term system resilience.

2.3. Increasing the resilience of the electricity system:

Planning for the energy sector is guided by the **National Electricity Objectives** of efficient investment in, operation and use of, electricity services with respect to: price, quality, safety and reliability. This requires cost-benefit analysis to ensure that decisions are affordable, credible and likely to deliver net benefits to consumers.

Disasters occur when the impacts of extreme natural events ("natural hazards") exceed the capacity of local systems to cope. Evaluating resilience for the power system requires a different approach from evaluating reliability (see Figure 4). Reliability is highly measurable based on known parameters and the actual and simulated performance of the power system. Resilience is nearly impossible to measure with leading indicators and requires a design-centred approach to understanding exposure.

Figure 4: High Impact Low Probability (HILP) events test system resilience[16]*.*



High Impact Low Probability events are increasing in likelihood and magnitude:

- Climate change is increasing the frequency and magnitude of weather hazards
- Cyber hazards are increasing risks
- ... and then there are exceptional events such as a pandemic

Energy system resilience is in decline:

- Generation sources are increasingly located in stringy, weak parts of the system
- These generation sources are inherently more vulnerable to extreme hazards
- System control services are increasingly complex, manual and reactive
- Societal services are increasingly interconnected

Resilience metrics are generally based on the performance of power systems and the consequence of outages, as opposed to relying on attributes of power systems[17]. AEMO has adopted the ***CIGRE*** definition of resilience as "*the ability to limit the extent, severity, and duration of system degradation following an extreme event.*"[18] This definition emphasises that, in contrast to reliability, resilience is achieved through "a set of key actionable measures to be taken before (*anticipation and preparation*),

---

[16] Source of text: AEMO 2020 ISP, Appendix 8.

[17] Sandia Report SAND217-1493 February 2017, *Resilience Metrics for the Electric Power System: A Performance-Based Approach*

[18] E-cigre.org, WG C4.47 ***Defining Power System Resilience***, RP_306_1 2019

during (*absorption)* and after (*sustainment of critical system operations, rapid recovery and adaptation)* the event". This definition focuses on the performance of the system and is appropriate to AEMO as the market operator with primary responsibility for managing the electricity system and market across Australia.

In some contrast, the **Sendai Framework for Disaster Risk Reduction**[19], used for emergency management[20] may be more appropriate for compound events by taking a societal focus: "*the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions*". This definition is consistent with the feedback from the focus groups (see Attachment A) which emphasised the need to include consumer risk appetite when designing risk mitigating solutions to major compound events.

Consumer groups observed that appropriate system adaptation for resilience could include the adaptation occurring outside the grid system, for example, an individual or community may choose to tolerate the consequences, enhance societal resilience with emergency backup generation at community facilities, or enhance individual resilience by building micro-grids or residential or community batteries. This will be further discussed below, however, it highlights that there is a tension where building individual resilience may actually deplete whole of power system resilience.

It is not the role of this project to define resilience more precisely for the power system, but notably, both definitions cited above emphasise the time-dependent nature of an extreme event[21], and the need to consider what happens before, during and after the event[22]. The time-dependent nature of extreme events is discussed further in Section 3 and Table 2.

2.4. Current frame for decision-making and the role of climate information

Extreme weather events can affect any part of the electricity system and consequences will typically increase with the severity of events, however, the relationship between the severity of the event and the consequence to the power system is not simple. While distribution networks (DNSPs) are the most widespread component of power systems, they supply only a local geographic area, limiting the impacts of extreme weather to discrete local communities. Distribution networks are typically configurable, allowing for rapid restoration. Conversely, transmission networks (TNSPs) cover large distances to connect generator supply with customer demand. While transmission networks include redundancy where possible, there is a greater risk that extreme weather in one location will constrain generator availability or destabilise the system such that a widespread outage could impact customers in another location. Transmission networks are highly customised and can be very slow to achieve full restoration. Thus, generator supply and transmission networks are considered more critical asset classes for power system resilience.

---

[19] United Nations Office for Disaster Risk Reduction (UNISDR), *2009 UNISDR Terminology on Disaster Risk Reduction*, Geneva, May 2009 (http://www.unisdr. org/we/inform/terminology)

[20] National Disaster Risk Reduction Framework, Department of Home Affairs, 2018 **https://www.homeaffairs.gov.au/emergency/files/national-disaster-risk-reduction-framework.pdf**

[21] See also Moreno, R., Panteli, M., Mancarella, P. Rudnick, H., Lagos, T., Navarro, A., Ordonez, F. and Araneda, J.C., *From Reliability to Resilience, planning the Grid against the Extremes*. 1540-7977/20©2020IEEE July/August 2020.

[22] This also consistent with other sectors and jurisdictions, for example in New Zealand, planning for resilience uses the 4R framework: Reduction, Readiness, Response and Recovery.

The requirement for consumer acceptance of investment for resilience is complicated by the fact that when an extreme weather event affects a DNSP the local communities may lose power but also experience the impacts in other ways. This contrasts with the impact on a TNSP where the consequences of the event are often experienced by communities distant from the physical event.

The Australian Energy Regulator (AER) issues guidelines to apply to the assessment of new investments; the Regulatory Investment Test (RIT) guidelines[23] require transmission networks to consider High Impact Low Probability events by:

1. Exploring reasonable scenarios where relevant HILP events are likely occur;
2. Costing the impact of the specified HILP events;
3. Weighting the economic impact of the event by a reasonable estimate of the probability of its occurrence.

The events explored here, those which are most extreme and tend to occur as compound events, present a particular challenge to this paradigm as compound events do not easily lend themselves to formal likelihood analysis (such as average return interval – ARI[24]). The probability of individual compound weather events is by definition near-zero as they reflect the intersection of two or more extremes and there are numerous ways in which individual extremes can interact. It is also not at all clear what is a 'reasonable' scenario[25] for compound events that may involve extreme values of several variables.

The questions around what is 'reasonable' and the lack of ability to provide probability or POE[26] information mean that the systemic impact of extreme and compound weather events cannot be treated using current AER guidelines. However, as explored in Section 2.1, climate change is contributing to the frequency and severity of these events so alternative decision-making approaches will need to be developed (see Section 4.2).

3. Assess climate-related risk

Climate science can identify extreme and compound events in the climate projections and these can be used to support decision-making. For this purpose it is helpful to separate extreme weather events which are usually driven by a single weather incident or variable (such as heatwaves or wind gusts) from compound events. (Note, the compound events which lead to disasters could include non-weather events such as cascading system faults, but only compound weather events will be considered here.)

---

[23] Australian Energy Regulator RIT-T application guidelines – December 2018, 3.8.3 High impact, low probability events.

[24] ARI is a statistical term which estimates the average period of time between recurrences of a particular event. Individual events may occur more or less frequently, but in the long-run the time between them will tend to converge to this value.

[25] Note, while the AER uses the term 'scenario' in the RIT-T guidelines, we will use the term 'case study' to describe a single, time-bounded event.

[26] POE is a statistical term which gives the probability of an event at or more extreme than the threshold specified. The ARI and POE are related being the inverse of each other.

3.1. What is an extreme or compound weather event?

For variables with a clear climate-change related trend, such as temperature, the probability of an extreme event, such as record high temperature or heatwaves, can be calculated, in which case the AER guidelines can be applied. The project is providing information about the changes of key climate variables over the next 60 years. These variables including temperature, wind, Forest Fire Danger Index (a composite index of weather which can create dangerous bushfire conditions), solar radiation and rainfall. The project will produce regional maps of trends in these variables which can be used to identify how local *extremes* are likely to change with climate change.

In the context of the electricity system 'non-credible contingency events' are defined in the **National Electricity Rules Clause 4.8.15** by the magnitude of the consequence, rather than by cause. These are events that "impact critical transmission elements or that impact the transmission system of multiple National Electricity Market regions" (AEMC Reliability Panel clause 8.8.1). This definition does not provide guidance on the probability or type of extreme weather and climate events but focus group attendees variously considered it as beyond the 99th percentile or as a 1 in 200-year event.

In climatology "compound events can be (1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined, even where the two single events are not extreme *per se*"[27].

Table 1: Observed trends and projected changes in climate variables extremes of relevance to the electricity sector. The projected uncertainty ranges are for 20-year periods centered on 2030, 2050 and 2090, relative to 1986-2005, for RCP2.6 and RCP8.5. For 2030 and 2050, the projected changes for RCP2.6 are similar to those for RCP4.5. Confidence ratings are based on the amount of evidence and level of agreement between lines of evidence.

Climate variable	Observed trend	Change by 2030	Change by 2050	Change by 2090	Confidence rating	Source
Annual average temperature	+1.4 C from 1910-2019	+0.6 to 1.4 C	+0.5 to 1.5 C (RCP2.6) +1.5 to 2.5 C (RCP8.5)	+0.5 to 1.5 C (RCP2.6) +2.5 to 5.0 C (RCP8.5)	Very high	NESP ESCC Hub (2020)
Extreme rainfall intensity (considering 20-year return period)	Spatially variable intensity	+10% hourly and +7% daily (but with large variability) (weak)	+5% to 15% hourly; +4% to 10% daily RCP2.6 +10% to 30% hourly; +8% to 20% daily RCP8.5	-15% to -5% (RCP2.6) -50% to -20% (RCP8.5)	Medium (low for summer and high for winter)	BoM and CSIRO (2020) NESP ESCC Hub (2020)
Annual number of days > 35 C	Increased from 1910-2019	+ 20–70%	N/A	+ 25–85% (RCP2.6) +80–350% (RCP8.5)	Very high	CCiA (2015) ESCI (2021)
Extreme windspeed	Uncertain	Increase in south and east	Increase in south and east	East: -56 to +33% (median +8%) (RCP8.5)	Low	ESCI (2021)

---

[27] Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Extremes (SREX), 2012 **https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf**.

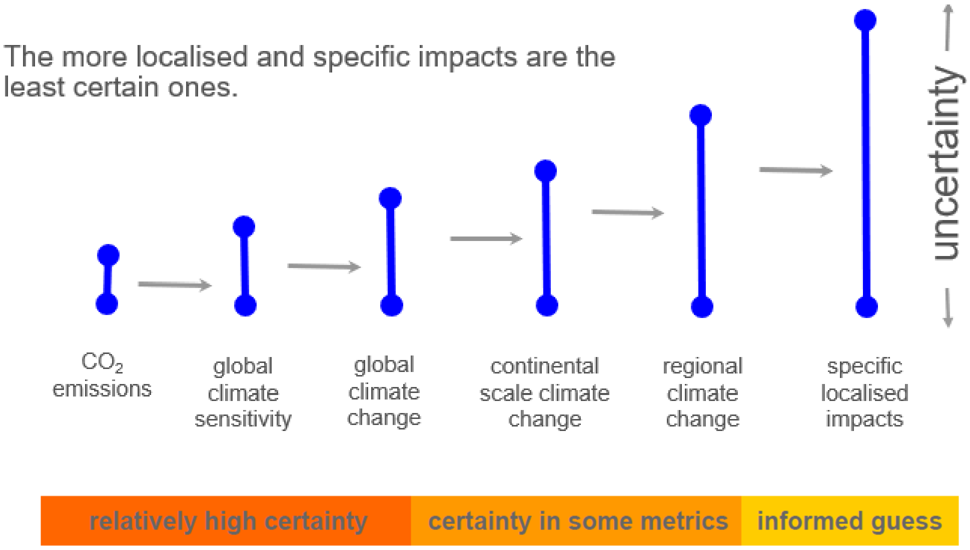
				South: -49 to +45% (median +7%) (RCP8.5)		
Number of East Coast Lows	-10% from 1986-2019	-15 to -5%	-15 to -5% (RCP2.6), -30 to -10% (RCP8.5)	-15 to -5% (RCP2.6), -50 to -20% (RCP8.5)	Medium	NESP ESCC Hub (2020) ESCI (2021)
Annual number of extreme fire weather days (> 90th percentile)	Increased since the 1950s, especially in southern Australia.	East: 0 to +30% Elsewhere: +5 to +35%	East: 0 to +30% (RCP2.6), 0 to +60% (RCP8.5) Elsewhere: +5 to +35% (RCP2.6), +10 to +70% (RCP8.5)	East: 0 to +30% (RCP2.6), 0 to +110% (RCP8.5) +5 to +35% (RCP2.6), +20 to +130% (RCP8.5)	Medium: East coast High: elsewhere	BoM and CSIRO (2020) NESP ESCC Hub (2020)
Category 4-5 Tropical cyclone (TC) frequency in Australian region	Little change (noting large variability)	Little change or small increase	Little change or small increase	Little change or small increase	Low-medium	BoM and CSIRO (2020) NESP ESCC Hub (2020)
Large hail (>2.5cm diameter) frequency in city-scale regions	No information (current: about 5-10 per year in eastern regions and 0-5 per year elsewhere)	Little change, but potential increase in east and poleward shift in features	As for 2030	As for 2030	Low	BoM and CSIRO (2020) NESP ESCC Hub (2020)

Estimating the likelihood of extreme events has typically taken the form of statistical, or extreme value analysis of past climate data, for example temperatures at a location. For those locations with long-term information (typically more than about 50 years) this approach can give good estimates of the occurrence of all but the most extreme events (which may not be sampled in the data). However, a changing climate makes these history-based approaches increasingly poor, with many temperature-related events increasing in frequency and intensity as the planet warms with reduced frequency or uncertain changes also noted for some other hazard types (see Table 1). An alternative approach which is used here is to use climate models driven by realistic scenarios of future greenhouse gas emissions to explore future extremes. At a suitable resolution, these models can provide detailed realistic extreme value information, though uncertainty increases further into the future, at smaller scales and for the more extreme events (Figure 5)[28].

---

[28] More information on sources and magnitude of uncertainty can be found in ESCI guidance material – in preparation.

Figure 5: The physical uncertainty cascade



The analysis and prediction of compound weather events is an evolving science and methods will improve as simulations of future climate improve. Extrapolating historical information or climate projections to extremes may not provide meaningful information, and climate and power system responses are often non-linear. For most compound weather events very large ensembles of climate projections may provide some indication of changes in likelihood, but only if the model is realistic or reliable, which may not be the case for some phenomena such as tornadoes or local severe storms, which are highly localised and sit below the spatial scales currently represented in climate models.

Despite the above caveats, it is still possible to identify well-characterised events in climate projections to produce a case study with information that resembles a weather forecast with coincident variables and clear event sequencing. These quantitative case studies can be used to calculate the likely cost and consequence of the event for the power system.

3.2. Deriving extreme and compound weather case studies

However, for rare extreme weather or climate events, and for most compound events an alternative approach is needed. Zscheischler *et al.* [29] define compound weather events as "a combination of multiple drivers and/or hazards that contribute to societal or environmental risk", and propose a typology that can provide a basis for statistical and modelling approaches (see Table 1). This approach explicitly address the time-dependent nature of the event, which is consistent with electricity sector definitions of reliability; matching this typology to electricity system vulnerabilities could provide a basis for risk assessments and potentially could help guide adaptation options.

---

[29] Zscheischler, J. et al, *A typology of compound and climate events.* Nature Reviews, Earth and Environment 2020 https://doi.org/10.1038/s43017-020-0060-z

Table 1: A typology of compound weather and climate events and examples of events impacting on the electricity sector.

Types of compound extreme weather and climate events	Electricity sector examples[30]
1. Pre-conditioned compounding events	- Drought followed by extreme heat, leading to reduced water availability for peak power generation and excessive demands
2. Multivariate compounding events	- Extreme protracted heat, bushfire smoke and light winds leading to high demands and reduced output from renewable sources.
3. Temporally compounding events	- A sequence of extreme fire weather events and heatwaves over multiple days (October 2019 to January 2020) leading to numerous fires impacting transmission lines and repeated peaks in demand. - Weather event in one part of the network results in a systems trip and outage in another part (e.g. South Australia power issues in 2009 as a result of Queensland fault) - Series of closely-spaced East Coast Lows
4. Spatially compounding (e.g. the scenario we have developed, or the cyclones + floods scenario?) events	- Simultaneous heatwaves in multiple urban centres (December 2019)

Using the typology given in Zscheisler et al and Table 1, climatologists and electricity sector organisations could derive a set of case studies of compound events to support operational and investment decisions.

The ESCI team has produced one qualitative and one quantitative compound case study for use by the energy sector that match Type 1 and 2 events (see Attachments B and C and Table 2). The team looked for events in the climate projections that challenge known vulnerabilities of the power system, are not so rare as to make it impossible to provide some likelihood information, and which are well-modelled, providing coincident, quantitative information on a range of climate variables and indices such as temperature, rainfall, solar radiation, wind, and fire weather, for the timeframe of the event.

Table 2: Sources of case studies of extreme and compound weather events consistent with Zscheischler et al

Types of compound extreme weather and climate events	Sources of case studies
1. Pre-conditioned compounding events	These require climate modelling for quantitative case studies as the sequencing and severity of events under climate change may be very different from history. An example is given in Attachment C.

---

[30] See, for example, **https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-events-and-reports/power-system-operating-incident-reports**

2. Multivariate compounding events	It may be possible to provide probability information on multivariate events by considering them in combination[31] or by calculating a joint probability density function[32]. Individual events could be informed by history with the addition of a climate signal[33]. A qualitative event was developed for the first ESCI case study and a summary is included in Attachment B.
3. Temporally compounding events	Case studies can be constructed from combining historical extreme events, for example the 2020 ESOO[34] takes the bushfire events of 'Black Summer' 2019/2020 and estimates the consequence if these events coincided with a period of historically high demand in early February.
4. Spatially compounding events	A compound case study of this type could also be constructed by taking historical events adjusted for climate trends (e.g. temperature) but changes in underlying climate drivers, such as ENSO and IOD[35], mean that the future may be very different from the history, so a plausible case study would require large ensemble climate modelling

It is also feasible to construct 'synthetic' compound event case studies using the historical record, informed by meteorological expertise, and applying known climate trends (such as increases in temperature or rainfall). In cases where compound events are derived from the historical record, caution should be exercised as construction of the event is limited by our experience and imagination, and the climate system and electricity system of the future may respond in non-linear ways. For example, the system may remain stable but then hit a tipping point, or a combination of events which are not by themselves extreme may, in combination or in less resilient parts of the grid, result in extreme impacts on the electricity network. Given that any constructed event is susceptible to human biases it becomes more important that these case studies should be developed with wide consultation across the sector and the support of the AER and ESB, a point emphasized in the sector focus groups. Unfortunately, it is beyond the scope and resources of the ESCI Project to provide this set of case studies, but it is a recommendation of the project that this happens.

An alternative approach is to identify case studies from climate projections, as demonstrated in Attachment B. The innovative approach piloted by the project has demonstrated that it can be done, however producing a full set, with estimates of the probability of *any* high-impact compound weather

---

[31] A. Dowdy and J.L. Catto (2017) Extreme weather caused by concurrent cyclone, front and thunderstorm occurrences. Sci. Rep. 7, 40359; doi: 10.1038/srep40359

[32] I. G. Watterson and P. H. Whetton (2011) Joint PDFs for Australian climate in future decades and an idealized application to wheat crop yield. AMOJ, 61, 221-230. Also I. G. Watterson (2011) Calculation of joint PDFs for climate change with properties matching recent Australian projections. AMOJ, 61, 211-219.

[33] See ESCI technical documentation on delta-scaling or quartile matching historical information to provide estimates of likely future weather. (In preparation)

[34] AEMO 2020. Electricity Statement of Opportunities. https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-reliability/nem-electricity-statement-of-opportunities-esoo

[35] ENSO: El Nino Southern Oscillation, IOD: Indian Ocean Dipole. These are large scale climate phenomena with irregular periodic variation which affect the climate of much of the tropics and subtropics. See ESCI Webinar on the changes in bushfire risk as an example of how these affect compound weather events in Australia.

event occurring, is a very resource intensive body of work. The proposed approach is to sample the "phase space" in a changing climate for future extremes; ideally, the sample should be sufficiently large that it starts to approximate a POE/ARI approach[36]. This is a major endeavour, well beyond the resources or scope of the ESCI project but it is likely to be of broad benefit to other sectors including the emergency management and finance sectors.

4. Adapting for greater resilience in the electricity sector

Even though some extreme and compound weather events are increasing in frequency and severity there is no standard approach in the electricity sector to considering these events in investment decisions. There is also no mechanism in the current regulatory framework to support the assessment of resilience in the face of severe compound weather events[37]. In addition, the regulatory framework in Australia specifically excludes the consequence of high impact events from networks service delivery obligation[38] limiting both the mechanism and the incentive to plan for future disasters. Focus groups noted that the lack of ability to make a case for investment in resilience can result in higher operational expenditure (not recoverable through regulatory mechanisms) and increased insurance premiums which can conceivably cost more to consumers than investments in resilience.

4.1. Consequence modelling for extreme and compound events

It has already been noted that when planning for system adaptation one challenge is that compound events affect large areas of the network, making it hard for individual asset owners to plan effectively. Investments that support resilience tend to result in higher reliability (few outages), but the converse is not always true[39], for example additional redundancy may improve reliability but will not necessarily improve system resilience[40]. Investing in widespread system 'hardening' to protect against compound events through stronger infrastructure will result in additional costs passed on to consumers who may not be affected by a compound event.

An additional challenge is the non-linearity of power system response to weather events. Extreme and compound weather case studies can be developed, but power system consequences will depend on asset and infrastructure configuration, engineering specifications and the location and vulnerability of consumer populations. Additional work is needed to identify geographic parts of the network which are particularly susceptible to these events. It is not clear that the electricity system currently has the capability to model the system response and provide consequence information needed to support investment decisions.

---

[36] Noting that POE/ARI need to be adequately constrained by the data as well. Otherwise there are large uncertainties associated with such maps that will need to be communicated.

[37] Note: the discussion below excludes relatively frequent e.g., 1-in-10 year, extreme events that can be identified through climate data sets provided through the ESCI project; investments to adapt to these events can be accommodated within the current regulatory framework.

[38] See NER 3.9.3C which defines reliability in the context of the (system) reliability standard, inclusions, exclusions and the definition of unserved energy.

[39] Cainey, J.M., Resilience and Reliability for Electricity Networks, 2019 **https://www.publish.csiro.au/rs/pdf/RS19005**

[40] Moreno, R., Panteli, M., Mancarella, P., et al, From Reliability to Resilience; Planning the Grid Against the Extremes. IEEE power and energy magazine, 1540-7977/20©2020IEEE, July/August 2020.

4.2. Decision-making models

A clear and consistent message from the electricity sector focus groups was that a set of case studies of extreme and compound events would be of value to the sector and to the finance and insurance sectors which support it (see section 5: Conclusions and recommendations.) While a qualitative assessment may yield insight on the materiality of the risk, a quantitative assessment is required to fully appreciate the multiple interactions between weather variables and the electricity system. This is particularly so for complex systems and more extreme or compound events for which the impact may be difficult to determine.

Individual TNSPs and DNSPs use case studies to stress test operational responses. These include: developing a deep understanding of how asset specifications limit or enhance potential response; dynamic system management informed by this understanding; and policies and procedures which include proactive hazard management (such as clearing potential bushfire fuel) and personnel deployment. One focus group attendee described using compound weather case studies as "training the chefs to use all the ingredients". Case studies can also stress-test investment decisions – for example, 'breaking the tie' between two possible investment cases if one is found to generally be more resilient. While these uses illustrate the application of extreme weather case study for asset or operational decisions, the widespread and unpredictable nature of compound weather events means that planning for increased resilience would benefit from leadership from the electricity sector market bodies.

Using a single extreme event case study risks the result that the system is well adapted to that event but potentially maladapted to different kinds of events. This underscores the need for a standard set of case studies, and this is the approach that other sectors (e.g. finance) and jurisdictions (e.g. the UK) have taken and is described below.

UK use of 'least worst' regret analysis for their electricity sector planning

A 'least worst' assessment is used for electricity planning in the UK and is applied when it is difficult or inappropriate to attach probabilities to future scenarios[41]. It involves "quantifying the worst possible outcomes for a set of strategic choices, and then identifying the choice with the 'least-worst' outcome. In other words, a 'least-worst regrets' solution finds the safest path that avoids the worst possible outcomes"[42]. This is a pragmatic option which avoids having to subjectively weight views of the future[43] and is useful when[44]:

- There is a significant temporal lag between making the investment decision in an asset and it becoming operational, so that the context and hence the optimal investment could change in the intervening period.

---

[41] Zachary, Stan. (2016). Least worst regret analysis for decision making under uncertainty, with applications to future energy scenarios. **https://www.researchgate.net/publication/305779725_Least_worst_regret_analysis_for_decision_making_under_uncertainty_with_applications_to_future_energy_scenarios**

[42] An analysis of electricity system flexibility for Great Britain, Carbon Trust, November 2016. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/568982/An_analysis_of_electricity_flexibility_for_Great_Britain.pdf

[43] Network Options Assessment Methodology Review, UK National Grid

[44] Ibid.

- The asset being invested in will have long operational life so there is a risk that the investment will become stranded if the situation changes during its life.

Lloyds use of Realistic Disaster Scenarios:

Lloyd's insurance market requires insurance syndicates operating in the market to use "Realistic Disaster Scenarios" (RDS) to stress test their portfolio. Lloyd's provides three sets of disaster scenarios: a compulsory set for all syndicates, a set of specialist scenarios if estimated losses exceed a threshold, and two events which syndicates define themselves[45]. Syndicates are required to quantify and report on their expected losses under all these scenarios, which are geographically diverse and vary by asset and peril[46]. Lloyds changes this set of scenarios each year to avoid syndicates adapting to the list.

Other examples of decision-making practices using case studies:

The Brattle Group report prepared for AEMO in June 2020[47] identified three types of planning approaches:

1) The use of expected value to quantify benefits and costs. This is the most common approach and requires probability weighting of extreme events.
2) The use of a “least regrets” approach to make investment decisions. 'Least regrets' uses case studies to compare across a number of plans with the goal of minimizing the maximum "regret" (the UK examples discussed above is a variation on this approach).
3) The use of “robust planning” (minimax outcome) to ensure that the worst outcomes can be managed with the least cost. Investment options are evaluated to minimize the costs of the potential worst-case outcome, in practical terms, this approach would likely reflect planning for the worst-case scenario of inputs.

More information and examples of where these are used can be found in the body of the report.

A common theme is that the case studies need to be accompanied by a rigorous assessment of cost or consequence. This can be described as a series of conversions to transform meteorological information into an actionable decision (Figure 6).

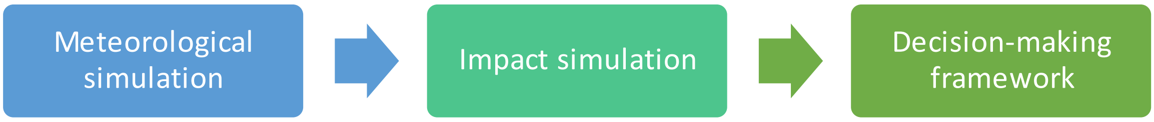
---

[45] Realistic Disaster Scenarios (RDS) **https://www.lloyds.com/market-resources/underwriting/realistic-disaster-scenarios-rds**

[46] See for example: RDS 2020 Scenario Specification, January 2020. **https://www.lloyds.com/~/media/files/market-resources/underwriting/2-rds-scenario-specification--january-2020.pdf?la=en**

[47] Change, J., Donohoo-Vallett, P., Ruiz, P.and Brown, T., Potential for Incorporating Climate-Related Risks into Transmission Network Planning; a review of frameworks and responses. Prepared for the Australian Electricity Market Operator, June 2020. **https://aemo.com.au/-/media/files/major-publications/isp/2020/brattle-group-report.pdf?la=en**

Figure 6: The process of converting meteorological data into actionable information (Adapted from: Brayshaw 2018[48])



Thus, the case studies would be used as input into quantitative modelling of consequences, and then into decision-making through a "user preference" step: a decision-making framework which includes a definition for resilience and metrics to assess relative improvement. This does not yet exist in the Australian electricity regulatory system.

This approach has been demonstrated in the ESCI case study on an extreme/compound event where the quantitative event developed for the project (Attachment C) was used as input to system supply and demand models. This resulted in derived estimates for customer unserved energy (USE) which could be used to test potential risk mitigation responses.

5. Conclusions and recommendations

5.1. Summary of findings from the focus groups

We have used Focus Groups (see Attachment A) to understand the priority and means by which resilience planning features in network decision-making. The focus groups highlighted the following:

1. The participants generally recognise the risks that a changing climate and more extreme events pose to network resilience. The risks are highlighted by recent extreme-related outages and associated impacts that are occurring on a background of a changing climate and increased system complexity.
2. Both networks and finance participants would like a standardised approach across the industry for responding to and estimating the consequences of future HILP events.
3. Consumers need to be part of the conversation as system adaptation to increase resilience may include local solutions including self/community-adaptation. Case studies need to be accessible to support understanding of compound extreme events, as consumers will need to be involved in decision-making. Consumer appetite for risk may also be different when faced with extreme events compared with reliability decisions[49]
4. Paradigm shifts in policy, regulation and behaviour benefit from a strong narrative – case studies of compound events can provide this narrative and potentially open new adaptation option for consideration. (Examples of this are the political response to actual events such as the 2016 islanding of South Australia after windstorms.)

The focus groups were unanimous in agreeing that a set of case studies of compound weather events for use by the sector, provided by a credible authority, is desirable. While quantitative case studies are preferred, qualitative case studies would be useful in the absence of fully characterised synthetic case studies. The project notes that case studies are being used in other sectors and jurisdictions to guide adaptation decisions for increased resilience.

---

[48] Brayshaw, D.J., The Nature of Weather and Climate Impacts in the Energy Sector. In Weather and Climate Services for the Energy Industry, Troccoli, A. (ed.), 2018. https://doi.org/10.1007/978-3-319-68418-5

[49] Moreno et al, 2020

5.2. Summary

It is clear that the sector would benefit from a standard set of case studies that would test the impact of extreme and compound events on the NEM. In the absence of a regulatory framework for investment decision-making for resilience, these case studies would still provide benefits through

- Testing and refining operational responses to disasters
- Allowing comparison across a portfolio of assets or investments to identify common vulnerabilities to a compound event
- Assessing potential consequences of extreme events, particularly for stringy or isolated parts of the network, to facilitate whole of system (including community) exploration of ways to increase resilience
- Differentiating between different (similarly priced) investment options by stress-testing the potential investments using case studies
- Supporting a whole of system response, in particular by testing the system modelling and operational responses of the market operator

A case study, (or scenario), approach is consistent with recommendations emerging in financial and insurance risk management processes, for example, as a recommendation of the **Taskforce for Climate Related Financial Disclosure** (TCFD), and the National Disaster Risk Reduction Framework[50]. A full set of case studies should be produced in collaboration with market bodies, and in further consultation with the sector. Section 3.2 can provide guidance on producing case studies in the absence of further investment in large ensemble climate modelling, and other ESCI data outputs can provide information on ARI or POE of some climate extremes.

Producing a suite of quantitative case studies from the climate projections is a very resource-intensive exercise. The innovative approach piloted by the project has demonstrated that it can be done, however producing a full set, with estimates of the probability of *any* high-impact compound weather event occurring, requires a very large ensemble of climate projections and significant scientific resources. This is beyond the resources of the ESCI project but should be considered as it is likely to be of broad benefit to other sectors including the finance sector and the emergency management sector.

---

[50] Australian Government, Department of Home Affairs. 2019. Climate and Disaster Risk: What they are, why they matter and how to consider them in decision making. 3 Guidance on Scenarios
https://www.aidr.org.au/media/6932/04-scenarios.pdf

Attachment A: Summary of key messages from focus groups

Six Industry focus groups were conducted on the utility of case studies of extreme events in investment and adaptation decision-making for the sector. All focus groups started with a presentation defining risk vs resilience for the sector, discussing the underlying drivers of increases in extreme and compound weather events and the importance of decision-making around these events. All focus groups had ESCI team members present and observers from DISER and Climate-KIC.

Focus groups:

1. 8 Regulatory economists and policy analysts: 4 TNSPs, 4 DNSPs, 1 from regulator (Aug 3)
2. 10 Network engineers and planners: 3 TNSPs, 7 DNSPs, 1 other (Aug 5)
3. 10 AEMO engineers, forecasters and planners (Aug 7)
4. 6 representatives of energy consumers, 4 representatives from other parts of the sector (AEMC, T/DNSPs) (Aug 17)
5. 9 members of the ESCI reference group (ERG) (Aug 18)
6. 13 Finance and Insurance industry representatives, 2 reps from T/DNSPs (Aug 19)

Questions: While these differed slightly by focus group, all groups were asked variations on:

- Could compound extreme event case studies be used in your organisation?
- Would you find the evidence from these case studies compelling?
- What decision-making processes would this be applicable to and what are the barriers?

Conclusions/key messages:

Focus group 1: Regulatory economists and policy analysts

- Extreme events are a major concern, but there is no standard way of considering them in planning – it should be an industry-wide conversation
- Consumer acceptance of the evidence is key to regulatory approval, networks need a plain English narrative they can take to consumers on why/how to think about extreme/compound events.
- Regulatory incentives are contradictory – non-credible events are not included in planning but networks are incentivised to keep OpEx low (as they have to carry it for 5 years), tension with their mission to reduce customer impact.
- Regulators are comfortable with history – what is the consequence of an event that happened? What is the probability of it happening again? They are less comfortable with a pro-active approach. Anything new will need to be based on sound science.
- Other relevant points:
    - Hardening the assets only works for part of the network, the problem with extreme events is widespread impacts
    - Insurance considers the question of starting fires, rather than protecting the assets

Focus group 2: Network planners and engineers

- Knowing how different phenomena changes in different regions would be useful – e.g., heat in the south, TC in the north, storms in the east. Maps are helpful. Knowing whether all networks have the same event at the same time is helpful.

- Operational response – need case studies to practise. We can build in resilience 'ingredients' but we still need something to train 'the chefs' on
- AER guidelines require that investments are based on: Probability x Consequence which creates an issue for HILP events. More common events are more easily accommodated in this paradigm – can provide more reliable probability estimates and so are perhaps more tractable for the regulators.
- Qualitive approaches may be appropriate for the very low probability events but need good descriptions to accompany them. Very helpful to have standard set of case studies, developed by people outside the sector but comparable across networks. This will make a better case for regulators
- Interested in knowing if there are new events that we haven't previously seen – can the projections help us imagine what we have never seen?
- Increasing costs of network resilience, if we can demonstrate it using case studies then this could mitigate increased insurance costs. Both these get passed on to consumers, so insurers behaviour is also a factor here.
- Resilience may sit with the consumers rather than the power industry. How does one then articulate to the consumer the nature of future hazards? The customer may respond by building their own resilience rather than funding network resilience.

Focus group 3: AEMO planners, engineers and forecasters

- Major emphasis on the modelling of the electricity grid. Discussions were quite technical with quite a bit of commentary on the increasing difficulty of modelling more complex systems. Introduction of newer technologies and generation mix with less well understood characteristics create issues and challenges.
- Economic settings don't really support examination of the extreme, high impact - low probability events. Hence systems are designed/calibrated around events which are closer to average.
- Design specs are mainly to smaller contingencies (smaller impacts). Excursions are addressed through "fail safes". Models are tuned to small excursions not the more extreme outcomes. This means impacts are less certain when the systems are less resilient and more complex.
- The sector tries to eliminate risk in a general sense through design – e.g., accommodate higher wind ratings, higher temperatures. Growth of renewables means the impact of weather are coming through supply as well as demand, creating more complexities.
- Extreme scenarios to stress test the system would be good. Summer 2019/20 provided a few examples including December 22 and January 4. More scenarios are required, but how many are needed is unclear.
- Need cost benefit to justify an investment. Focus on building resilience, rather than focusing on single hazards.
- Regulators are spooked by the large increases in costs which have largely come out of the distribution assets. This has led to large price increases for consumers. Hence focus on cost-benefit analysis.
- Tangible examples (realised) events will tend to drive decisions. Forecast events may be "dismissed" – that won't happen etc, probability too low etc.

Focus Group 4: Consumers and consumer representatives

- Nervousness about the use of case studies to replace AER (likelihood/consequence) methods. Case studies can be developed for high impact events, but they don't speak to their likelihood. Better information may not inform better investment decisions if these don't fit into the AER framework.

- Very low appetite amongst consumers to spend more. Would rather suffer the impacts and then focus on reinstating the services, but customers may end up paying whether they like it or not (e.g., rebuild cost after an extreme event), and may pay for huge infrastructure investments in resilience which becomes stranded assets
- Difference in willingness to pay for more predictable/single-variable events which they see regularly, than widespread and compound events where they pay for outages that may not affect them. For a single event it may be clear that investment in infrastructure is more cost effective than recovery, but for compound (widespread) events hardening the whole system is very expensive and management and recovery of worst affected areas may be better achieved in other ways
- Understanding the whole of system response to a compound event might make the system more resilient rather than simply focusing on the "strengthening the grid". E.g., use of batteries, more flexible approaches etc. Most outages are in distribution, so why pay for hardening of generation and transmission system. Consumers want to see not just the case study, but the range of possible responses, including operational and consumer-led adaptation options
- Case studies may in fact make the case that large-scale investment in system hardening may only benefit a small part of the network and is NOT the answer. Consumer groups see these as valuable in that case.

Focus Group 5: ESCI cross-sector Reference Group (ERG)

- Involvement of the AER is critical – no framework for extreme events will be successful unless it has the support of the regulator
- Need a clearer definition of resilience (the project/ERG can work on this) so we have metrics
- Set of scenarios (climate trends) – can include probabilities
- Standard set of case studies for compound events – can use to calculate consequence and compare events, may help in differentiating between investment options
- Would like more information about how other jurisdictions make decisions (methodology) e.g Brattle Group recommendations, Sandia Labs metrics
- Consider working group with ESB – must go beyond market bodies

Focus group 6: Finance and insurance

- If the electricity sector doesn't understand its own risks, then insurance is not likely to.
- Can't really get around the probability question from a finance and insurance point of view. Understanding and financing risk relies on calculations of probability.
- Past history is a really important tool for stress testing – can the system survive these events? What does it take to do that? Then, will the impact/cost of future events be greater. This information is useful in the absence of probabilities. We want to know will it be more or less frequent? Will it be worse than history?
- Lloyds comes up with a set of scenarios – types of events that generate a 1 in 200 year loss and this provides a framework for decision-making. Not just single events, compound events. Change every year to avoid adapting only to those events
- Case studies will be very valuable for stress-testing across different parts of the economy, both physically and by sector. We really want to see that the sector has done this stress-testing. Standard set of scenarios would allow comparison within a portfolio and across sectors

Attachment B: Qualitative compound event case study

Qualitative scenarios have an advantage in having the flexibility to be adjusted to specific vulnerabilities and are relatively inexpensive to produce. However, they have the disadvantage of relying on expert advice and consensus, and the availability and continuity of that advice when applied as a repeatable process.

For the first ESCI workshop in May 2019 the team produced a detailed description of a compound weather event that occurs over a three-week period, nominally in 2023. The qualitative scenario is plausible in that it is supported by expert understanding of the current climate and global warming. The event identification provides coincident, quantitative information on a range of climate variables and indices such as temperature, rainfall, irradiance, wind, and fire weather, for the timeframe of the eventand is very similar to the events of the summer of 2019/20.

A comprehensive description of this case study is provided in Annex C of ESCI First Scenario Report – it is described below.

The compound weather event

The case study for 2021-2023 was been conceived as a sequence of antecedent (precursor) climate events, ahead of a record-breaking heatwave at the summer peak, however, it can be seen as one extended climate event. The events are designed to be slightly beyond those captured in the recent historical record, however it is worth noting that a small step-change in climate could result in major impacts, as there may be physical responses which are non-linear at the extremes. For example, some infrastructure, including (but not exclusively) solar panels, wind farms, and the Basslink interconnector, have thresholds beyond which they do not function.

The physical scenario

The sequence of weather and climate events, natural hazards, and NEM vulnerabilities and impacts tested at each stage of the case study are as follows:

Antecedent conditions

- A prolonged (multi-year) drought, with similar characteristics to the Millennium Drought, is affecting the whole of southeast Australia.
- The 2021-2022 summer saw near-El Niño conditions in the Pacific, with very dry conditions across southeast Australia.
- Winter 2022 saw very warm and dry conditions across southeast Australia, affecting SA, VIC, TAS and southern NSW, driven by Indian Ocean temperatures (positive phase of the Indian Ocean Dipole).
- The conditions also reduce soil moisture and lead to the further curing of vegetation, elevating the bushfire risk.
- Streamflows are substantially reduced across eastern Australia. Low flows in particular, are observed in southern Murray-Darling basin, Victoria and Tasmania.

Spring 2022

- An early start to spring, with record-breaking heat in August.

- Summer-like conditions occur from September onward, with a heatwave in November peaking at over 40 °C in Adelaide, Melbourne and western Sydney, followed by Brisbane as the heat moved north.
- A very active spring bushfire season in northern NSW and southeast QLD including northern rivers and inland border regions. Widespread dust storms across Vic and NSW.

Late 2022

- A hot start to summer, with a succession of slow-moving high pressure systems over large parts of central and southeast Australia. Cool changes are weak and brief, as frontal systems fail to push significantly into the subtropical-ridge, and slip south of the continent as heat continues to build over inland Australia.
- The persistent and large high pressure systems lead to generally calm conditions.
- Overnight temperature reductions are generally limited over southeast Australia.
- Severe rainfall deficiencies persist. Water restrictions are in place.
- A 3-day heatwave affects South Australia and Victoria prior to Christmas, peaking at 43 °C in Adelaide and 41 °C in Melbourne.

January 2023

- An extended, two-week January heatwave affects the eastern states, after starting in southern Western Australia in early January, with intense heat in the first week, and little relief in the second.
- A stationary high over the Tasman Sea directs hot, dry air across the country and into the southeast, aided by a severe Tropical Cyclone off the northwest coast of Australia (which strengthens the upper ridge through anticyclonic potential vorticity advection).
- Victoria recorded four consecutive days over 41 °C, with three over 43 °C and elevated heat conditions overnight. Heat wave conditions persist over some part of eastern Australia for over two weeks. Several regional towns break their all-time temperature records, with temperatures around 48 °C. Many locations exceed forecast maximum temperatures. Winds are lower than expected overnight.
- The intense heat reaches northern Tasmania. Temperatures reach 41 °C at Launceston on days 5 and 6 of the event, and approach 35 °C along the Tasmanian north coast.

February 2023 heat wave and bushfires

- An unprecedented February heatwave event, and bushfires fanned by gale force winds and record-breaking temperatures, provides an extreme climax to the sequence of heatwaves since November 2022.
- The duration and intensity of the heatwave are unprecedented for South Australia and Victoria for February, lasting for 6 days, (with a slow moving high or extended ridge south of the continent; similar to the week before Black Saturday 2009) —with critical extreme weather days in the middle of the week.
- Calm conditions over February 3-6.
- Friday 3 February 2023 sees the first of five days of at least 41 °C in Adelaide. The extreme heat reaches Melbourne on Saturday, the first of four days above 40 °C. Temperatures in the high 30s or low 40s persist in Canberra, Sydney and Brisbane over most of the 3-9 February 2023 period.
- On Tuesday 7 February 2023, increased winds drive temperatures in Adelaide to record-breaking 49.2 °C, exceeding advance and real-time forecasts for maximum temperature.
- The approaching front also drives temperatures in Melbourne to 45 °C late on Tuesday 7 February 2023.
- Fire danger reaches Catastrophic or Code Red (the Fire Danger Index is increased due to the prolonged drought and lack of soil moisture). The approaching front on Tuesday 7 February 2023 sees a number of bushfires ignite, then fanned by the high winds. Out of control fires burn across the state, including large fire-grounds near Benalla in north-east Victoria and near Dartmoor in western Victoria.

- Emergency services are stretched, the Victorian and Tasmanian Fire Services allow some fires to burn due to lack of resources.
- The heat-wave persists into Wednesday 8 February and Thursday 9 February 2023 in NSW and Sydney.
- Wednesday 8 and 9 February Southeast QLD and Brisbane affected by severe thunderstorms.

Using this scenario, participants in the first ESCI workshop identified system vulnerabilities and potential short and long-term impacts. This information has been used throughout the project to design useful data output for the sector and to identify investment and operational decisions which may be vulnerable to climate change as topics for detailed use cases

Attachment C: Quantitative compound event case study

To develop a quantitative, or 'synthetic', case study an event was identified in the climate projections with the synoptic characteristics of “Black Saturday”. This included a multi-jurisdictional heatwave followed by a strong cold front, driving high winds, low humidity, and random bushfire ignition in southeast Australia.

Using climate projections means that the climate change signal is fully integrated in the numerical simulation; this is in contrast with methods that take an historical event and manually adjusts some aspects according to current observed or projected trends. A significant advantage of generating numerical simulations of extreme events using the full field of variables within a regional climate model is the ability to use that data in downstream quantitative risk models. In addition, while we can be quite confident about broad trends in weather patterns going forwards, how these will interact in individual extreme events is quite uncertain and best represented by detailed climate model simulations.

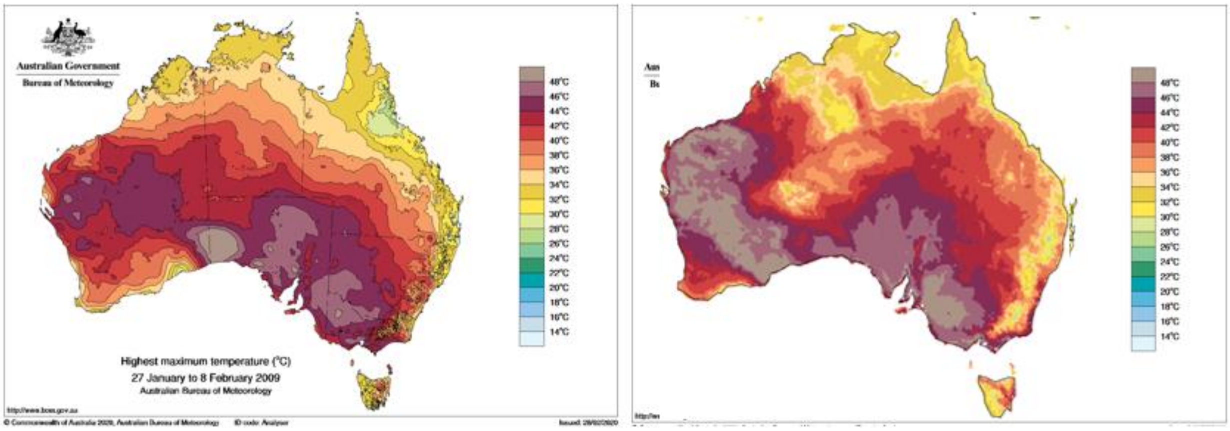
This case study is informed by weather and climate impacts leading up to and including the 'Black Saturday' bushfires of 2009. The scenario includes:

- Drought leading up to the event, and dangerously high Forest Fire Danger Index (FFDI) in some parts of the NEM.
- 6 days of multi-jurisdictional heatwave like that which occurred in January 2009 but on a planet warmer than the present due to greenhouse gas emissions.
- A strong cold front, driving high winds.
- Random bushfire ignition (as this is not susceptible to modelling).

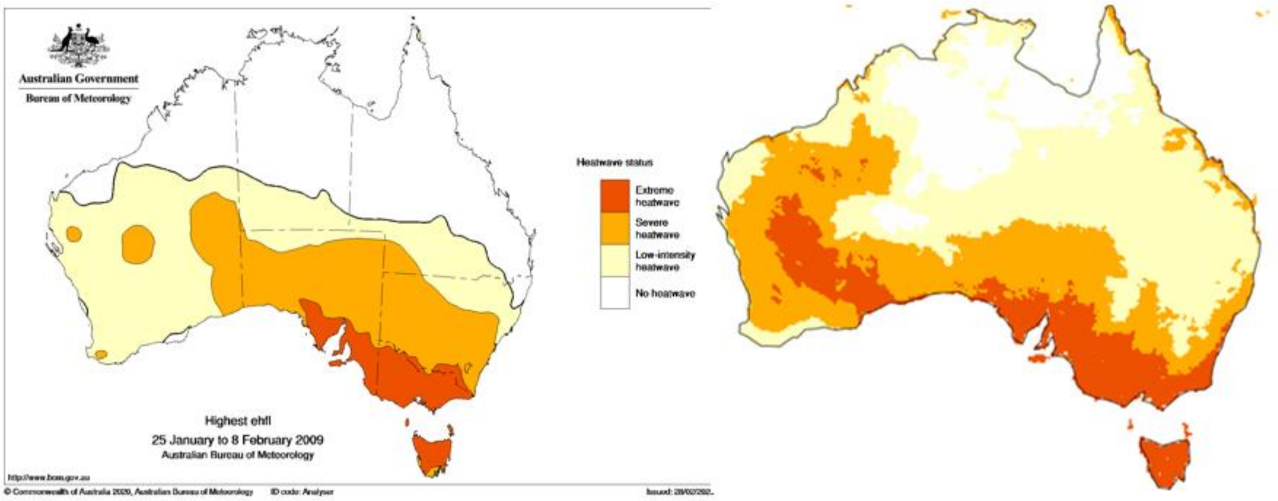
The quantitative event identified occurs in 2031 which is within planning timeframes for the AEMO Integrated System Plan (ISP). This makes it possible to model the cost and consequence of the extreme weather event using candidate development paths from the 2020 ISP scenarios as the future electricity system state in question. The impact of the weather event can be calculated as 'unserved energy', i.e. power outages, which can also be quantified as cost to consumers.

Figure C1: Comparison of climate conditions for Black Saturday, 2009, and this case study in '2031':

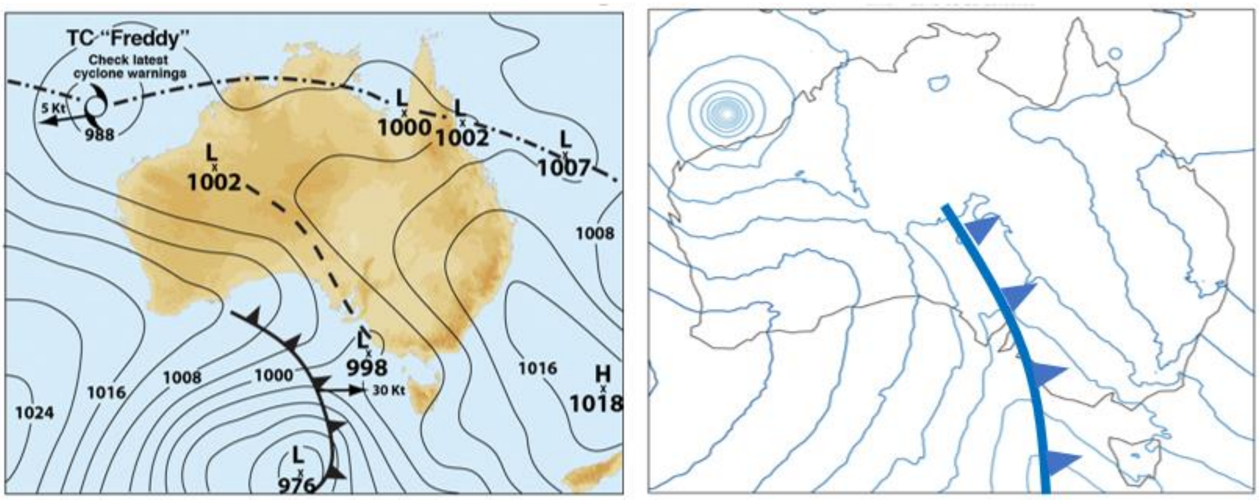
A: Temperature 2009 and in case study



B: Excess Heat Factor (EHF) 2009 and in case study



C: Strong cold front in 2009 and in case study



Methodology for identifying Extreme Scenario in the Regional Climate Model -

A set of indices were developed to identify potential case studies featuring extreme heat and fire conditions from the ensemble of future climate simulations.

The two features which distinguish the most severe events of this type is intense heat, followed by a very strong frontal passage (large change in temperature). Extreme temperatures usually lead to high fire danger in southern Australia during summer, while strong frontal passages are usually an indicator of strong winds before and near the wind change. The combination of these two measures leads to the most damaging fire weather days, such as Black Saturday and Ash Wednesday.

The two measures (extreme heat, and temperature change) provided a simple means of identifying a high-impact scenario (featuring extreme heat and fire weather conditions) from the large ensemble of climate model simulations. The following were adopted:

1. An index identifying extreme heat conditions, hereafter referred to as the ***Excess Heat Factor severity rating***; and
2. An index identifying strong frontal systems conducive to extreme fire weather, hereafter referred to as the ***Delta-T Frontal Index***

Periods of time in the future when both indices were particularly large were identified from the climate simulations as potential case studies.

Excess Heat Factor

The Bureau of Meteorology has an established index, known as the excess heat factor (EHF), for objectively defining heatwaves and heatwave severity (Nairn *et al.* 2015). This heatwave intensity index was created by combining measures of *excess heat*, the long-term temperature anomaly characterised by each location's unique climatology of heat, and *heat stress*, the short-term temperature anomaly measuring recent thermal acclimatisation.

Box A1. How to calculate the Excess Heat Factor severity index

The two ingredients in the EHF calculation are called excess heat indices (EHIs) and are calculated as follows:

$$EHI_{sig}^{i} = \frac{(\mathrm{T}_i + \mathrm{T}_{i-1} + \mathrm{T}_{i-2})}{3} - T_{95}$$

$$EHI_{accl}^{i} = \frac{(\mathrm{T}_i + \mathrm{T}_{i-1} + \mathrm{T}_{i-2})}{3} - \frac{(\mathrm{T}_{i-3} + \cdots + \mathrm{T}_{i-32})}{30}$$

where T_i denotes the daily mean temperature (DMT) on day i and T_{95} denotes the 95th percentile of the DMT calculated across the period 1980-2009*.

In the first index (EHI_{sig}^{i}), called the significance index, a three-day-averaged DMT is compared directly against the 95th percentile for DMT. If EHI_{sig}^{i} is positive, then the TDP is unusually warm with respect to the local annual climate. Conversely, if EHI_{sig}^{i} is negative or zero, then the TDP cannot be considered unusually hot, and so in order for a heatwave to be present we require EHI_{sig}^{i} to be positive.

In the second index (EHI_{accl}^{i}), called the acclimatisation index, the same three-day-averaged DMT is compared against the average DMT over the recent past. If EHI_{accl}^{i} is positive, then the three days are warmer (on average) than the recent past.

The excess heat factor is then calculated as

$$EHF^{i} = EHI_{sig}^{i} \times \max(1, EHI_{accl}^{i})$$

where positive values of EHF define heatwave conditions for day i.

The heatwave severity rating for day i is then calculated by dividing EHF^{i} the by the 85th percentile value for all positive EHF values:

$$EHF_{sev}^{i} = EHF^{i}/EHF_{85}$$

The severity of a heatwave is classified from EHF_{sev} as follows:

Heatwave classification	EHF_{sev}
Low-intensity	0-1
Severe	1-3
Extreme	≥3

** The original EHF definition by Nairn et al. (2015) uses the base period 1971-2000. However, the period 1980-2009 was used in the ESCI study as this the earliest period of data available in the climate simulations.*

In the ESCI project, the future climate simulations were provided as timeseries at 132 discrete locations across the NEM. That is to say, the data was provided in point format rather than as a spatially gridded product. Accordingly, EHF_{sev} was calculated for each of the major demand centres in the southern part of the NEM (Adelaide, Melbourne, Hobart, Canberra and Sydney), providing five resulting timeseries of EHF_{sev} . These timeseries were then averaged together, as a means of approximating the heatwave conditions across the southern part of the NEM, providing a single timeseries denoted EHF_{sev}^{region}.

$$EHF_{sev}^{region} = (EHF_{sev}^{Adelaide} + EHF_{sev}^{Melbourne} + EHF_{sev}^{Hobart} + EHF_{sev}^{Canberra} + EHF_{sev}^{Sydney})/ 5$$

The ESCI project used EHF_{sev}^{region} as the index for identifying future heatwave conditions.

Delta-T Frontal Index

The scientific study by Reeder et al. (2015) found that the most catastrophic fire conditions in recent history in southern Australia have been associated with particularly strong summer cold fronts. They defined extreme cold fronts as one for which the maximum temperature at Melbourne is at least 17 ˚C cooler on the day following the front. Their study developed a simple index for identifying extreme fronts, here referred to as the Delta-T Frontal Index.

Box A2. How to calculate the Delta-T Frontal Index

Reeder et al. (2015) defined the index as follows:

$$DeltaT_{i} = Tx_{i} - Tx_{i+1}$$

Where Tx_i is the daily maximum screen level temperature (2 m temperature) at Melbourne on day i.

The ESCI project used $DeltaT_i$ as the index for determining if the synoptic environment over the southern part of the NEM is conducive to extreme fire conditions when combined with the EHF. This is exemplified by the case study presented in Section A.3.

Extreme Scenario Identification: Example

A demonstration of the methodology for identifying extreme scenarios is provided below.

Box A3. Data used in example

Climate model: *CANESM global climate simulation downscaled by CCAM.*

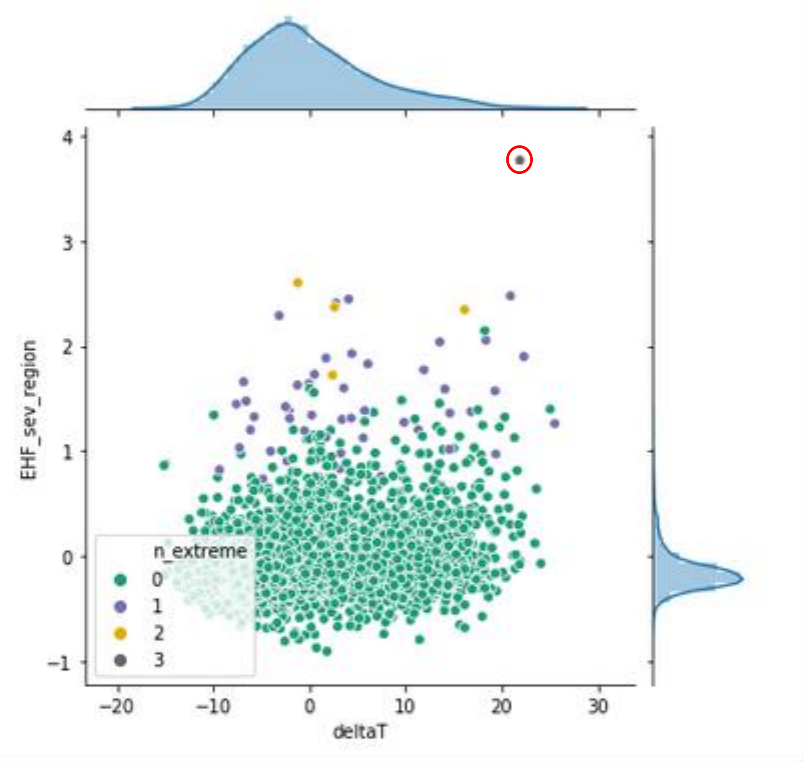
Period of data: *1980 – 2060*

Data provided at locations: *Adelaide, Melbourne, Hobart, Canberra and Sydney.*

Using the data listed in Box A3 and the methodologies outlined in Section A.2, the indices EHF_{sev}^{region} and $DeltaT_i$ were computed for each day over the period of data availability (1980-2060). The resulting indices are plotted in Figure C2. From Figure C2 there is one point in particular that stands out (25/01/2045), being the point closest to the top right corner of the plot. The very large value of EHF_{sev}^{region} indicates that extreme heatwave conditions are experienced across the southern part of the NEM on the day of (and days preceding) 25/01/2045. Furthermore, the strong $DeltaT_i$ value indicates that an extreme frontal system passes over the NEM on the afternoon of 25/01/2045, which would exacerbate the fire danger across the region.

This point in the climate projections, therefore, was identified as presenting a relevant case study. Closer examination (not shown here) reveals that during this event 'extreme' heatwave conditions were experienced in Melbourne, Adelaide and Hobart, while 'severe' heatwave conditions were experienced in Sydney and Canberra.

Figure C2: 〖EHF〗_sev^region (y-axis) and 〖DeltaT$(EHF)_{sev}$〗_i (x-axis) calculated for each day of the CANESM climate simulation, spanning 1980-2060.



The full case study data, shown in figure C1, is derived from the point (highlighted in red) in the climate projections.

Appendix C References

Nairn, J.R.; Fawcett, R.J.B. The Excess Heat Factor: A Metric for Heatwave Intensity and Its Use in Classifying Heatwave Severity. *International Journal of Environmental Research and Public Health* **2015**, *12*, 227-253.

Reeder, M.J; Spengler, T; Musgrave, R. Rossby waves, extreme fronts and wildfires in southeastern Australia. Geophysical Research Letters **2015**, doi:10.1002/2015GL063125.

ELECTRICITY
SECTOR
CLIMATE
INFORMATION
PROJECT