2020 ISP Appendix 8. Resilience and Climate Change

July 2020

Important notice

PURPOSE

This is Appendix 8 to the Final 2020 Integrated System Plan (ISP), available at https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp.

AEMO publishes this 2020 ISP pursuant to its functions under section 49(2) of the National Electricity Law (which defines AEMO's functions as National Transmission Planner) and its broader functions under the National Electricity Rules to maintain and improve power system security. In addition, AEMO has had regard to the National Electricity Amendment (Integrated System Planning) Rule 2020 which commenced on 1 July 2020 during the development of the 2020 ISP.

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VERSION CONTROL

Version	Release date	Changes
1.0	30/7/2020	Initial release

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Summary

This Resilience and Climate Change appendix provides detail on changes that are impacting the resilience of the NEM, including climate change. It explores solutions and ongoing work that will evaluate and mitigate these risks to Australian energy consumers.

Key insights

Power system resilience is the ability of the system to limit the extent, severity, and duration of system degradation following an extreme event. It has long been embedded in good energy system planning and operation practices but is in long-term decline, necessitating a renewed focus. The decline in resilience is 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.
- New generation sources are increasingly being dispersed from central locations with strong network links to the main load centres, into remote, electrically weaker, areas of the grid distant from the load centres, changing the risks and vulnerabilities of the system.
- System control services are increasingly complex, and the power system is reliant on the integrated testing and performance of these systems to avoid the risks of cascading system impacts.
- Societal services are increasingly interconnected risking cascading societal impacts.
- An increasing focus on quantitative cost benefit analysis over good design principles, which excludes mitigation for risks that are difficult to quantify and value.

Through the ISP stakeholder engagement process, stakeholders have expressed a strong desire for further consideration of resilience to climate events, and resilience more broadly.

The 2020 ISP considers resilience in two main ways:

- **Risk analysis and risk evaluation** – where possible, risk processes consider both the impact of acute and chronic hazards. Where captured, these risks contribute to the estimation of system reliability, security, and calculated project market benefits. While efforts have been taken to improve risk analysis and evaluation to capture resilience, many acute hazards remain excluded from this ISP due to limitations in both climate and energy system modelling.
- **Planning standards** – planning standards consider resilience when developing physical designs, and technology solutions. Through this consideration, these solutions enhance system resilience, but may not yet appropriately address all current and future risks.

Due to the considerations for resilience in solution design, AEMO remains confident that the optimal development path will strengthen the resilience of the energy system, particularly with projects such as VNI West and Marinus Link accelerated relative to the projects' optimal timings arising from risk and market benefit analysis alone. Additional actions and investments are required to avoid further decline in resilience over time.

AEMO has undertaken reviews of current approaches to planning and design considerations regarding how climate and other resilience factors are treated. Most countries have differing approaches to planning for resilience, and no common approach in existing regulatory frameworks for dealing with resilience to climate change or other resilience risks. In many cases, the approach is implied as part of "good engineering practice", an approach that is increasingly challenged by regulatory frameworks, but is increasingly necessary to support the integration of IBR.

A8.1. Introduction

This appendix is part of the 2020 ISP, providing more detail on changes impacting the resilience of the NEM, and solutions and ongoing work that will evaluate and mitigate these risks to Australian energy consumers.

The ISP sets out an optimal development path for the NEM that serves both power system needs (reliability and security) and public policy needs in the long-term interest of consumers. The reliability of the power system means that it will continually achieve a real-time, safe balancing of supply and demand for energy: see Section A2.

Resilience in the power system is well embedded in good energy system planning and operating practices. In the context of this ISP, AEMO has adopted the CIGRE definition: "*the ability of a power system* to *limit the extent, severity, and duration of system degradation following an extreme event*"[1].

Current limitations in both climate and energy system modelling mean that comprehensive modelling of extreme weather and power system events is not yet possible. For example, many climate models do not currently represent extreme events like storm or cyclone events well, and their impact on the power system can be difficult to predict. As such, the benefits of resilient system designs to extreme events are not currently captured within the ISP cost benefit analysis. AEMO will continue to advance consideration for climate risks in decision-making to ensure outcomes are as robust as possible.

This appendix is structured in the following way:

- The characteristics of resilient energy systems.
- Where the 2020 ISP has considered physical climate risks, and associated implications.
- The direct and indirect exposure of energy systems to climate change.
- Domestic and international examples of climate risk mitigation.
- Further considerations and next steps.

A8.1.1 Energy system resilience

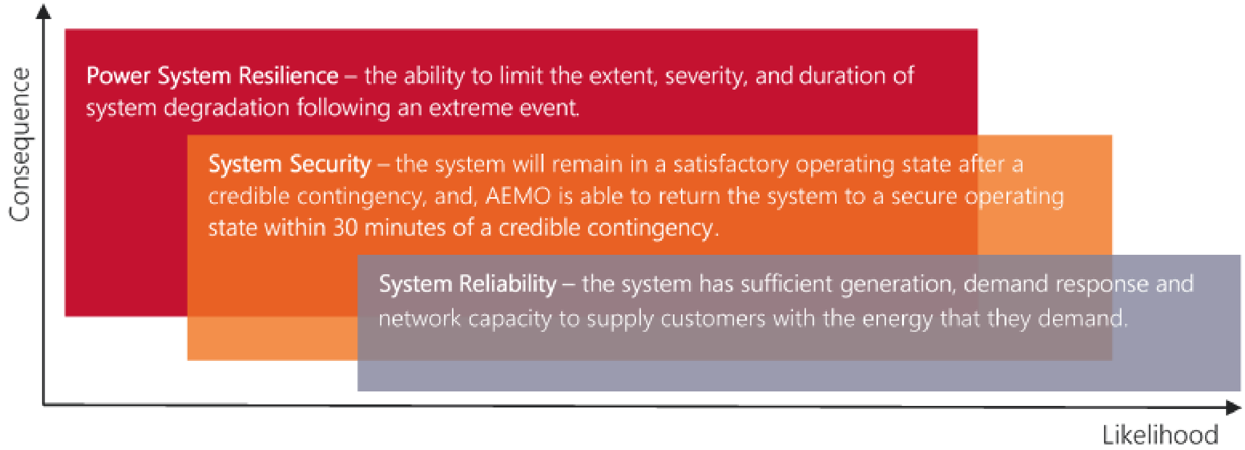
Resilience has long been embedded in good energy system planning practices. It refers to the ability of a system to **resist, absorb, accommodate to, and recover from** the effects of a hazard in a timely and efficient manner[2]. There are numerous working definitions of power system resilience, including the definition of resilience above, developed through CIGRE working group 4.47, that AEMO applies to this ISP.

Resilience differs from, and extends beyond, other industry risk management definitions of 'reliability' and 'security'. Figure 1 shows the definitions and how they overlap to the degree that a hazard would be considered under the security or reliability definitions.

[1] CIGRE C4.47 WG Members. 2019. *Defining power system resilience reference paper*. Electra No.306 – October 2019.

[2] United Nations Resolution 69/283. *Sendai Framework for Disaster Risk Reduction.* 2015-203017.

Figure 1 Conceptual relationships between definitions relative to impact magnitude



Australian energy consumers have historically enjoyed the benefits of resilient energy systems; however, numerous compounding changes, described below, are eroding these benefits, so resilience requires a renewed focus:

- **Power system transition** – the rapid transformation of the power system and current market arrangements continue to test the boundaries of the power system technical operating envelope. Newer generation has little or no short-term overload capabilities, meaning they are unable to assist or prevent collapse for situations they have not inherently been designed for. While traditional generators are kept in large generator buildings, variable renewable generation sources (both VRE and DER) are exposed to a broad array of climate hazards. Traditional generation locations are well supported by strong meshed networks with substantial redundancy; emerging generation hubs currently lack these characteristics, amplifying the impacts from physical climate risks.
- **Climate change** – 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.
- **System control services** – Special Protection Schemes (SPSs) and Remedial Action Schemes are increasingly used to defer investments in physical assets. The quantity of schemes is becoming challenging, with increasing interdependencies with other schemes and protection settings, and shared communication infrastructure. An increased reliance on software-based solutions, unless properly designed and fully tested (including comprehensive system-wide integration testing), could create unexpected exposures to cyber threats or risk of compounding effects.
- **Cyber security** – in the energy sector, the increasingly distributed supply chain, the pervasive use of information and communications technology, and the convergence of Information Technology (IT) and Operational Technology (OT) are rendering critical systems and infrastructure across the country increasingly more at threat unless they are being well designed and maintained against the increasing threat of cyber incursions.
- **Societal integration** – the role of energy in society is changing and becoming more integrated. Electricity, gas, water, transport, communications, health, and other services are increasingly interdependent. Consumers are more focused on services they want and need to run their business or use in their life, not the amount or type of energy, and many of the services that they use rely on electricity as the primary energy source. Consumers are also focused on what they get for the cost of these services. With an increasing reliance on services that depend on energy comes increasing expectations. The management of

hazards increasingly requires an integrated consideration of full societal implications consistent with customer expectations and willingness to pay.

- **Quantitative cost benefit analysis –** the use of quantitative cost benefit analysis has become central to the justification of all regulated investments and market structures. Limitations in both climate and energy system modelling mean that full risk quantification of acute hazards is impractical. Limitations in economic and social cost modelling used to develop value of customer reliability estimates for widespread and long duration outages were also acknowledge by the AER[3]. However, this does not diminish the importance of understanding and managing these risks.

Energy system planning involves complex engineering and analytical processes to understand and manage identified risks to power system and consumer outcomes. These processes may not be fully capturing the degradation in resilience. However, resilience *thinking* is broader than current process, extending to prudent risk management against hazards that may not be specifically identified. This more holistic approach to resilience provides a richer understanding of emerging risks to power system, and through that to consumer and societal outcomes.

To the degree that current processes allow, AEMO has sought to include cost-effective resilient characteristics in the development of the solution design and technology that form the optimal development path.

A8.1.2 Features of a resilient NEM

The definition of resilience described earlier provides insight into the outcomes society could expect from a resilient energy system. As extreme events are by definition difficult to predict and desirable to minimise, the leading indicators of success must be identified. The resilience goals of society will be more likely to be achieved in a cost-effective manner when these characteristics are part of the design of future energy systems.

A global program called 100 Resilient Cities[4] has explored the characteristics of resilient systems in the context of urban resilience. Many of these characteristics are embedded in good energy system planning practices, and the potential responses to build resilience are often quite similar. In its report to accompany the ISP, the Brattle group indicated that "*many climate risks have similar potential responses, including consideration of geographic diversity of transmission lines, increasing physical robustness of the assets, increasing monitoring and the use of sensors for early alerts for potential severe events*"[5].

Considering characteristics described in existing literature and good industry planning practices, AEMO has identified six features important to planning for a resilient energy system. Additional features may require consideration when developing cybersecurity, market and operational approaches to resilience. The six features are:

- **Robust asset specifications** – individual assets and assets systems are well constructed and managed using robust design specifications. Specifications are designed to resist the majority of hazards in both the present and future operating environment. For long lead time items, an appropriate quantity of spares are kept to expedite recovery in the event of loss.
- **Redundancy and operational flexibility** – asset systems, and the system as a whole has sufficient operational flexibility in the presence of increasing and coincident hazards to manage contingencies and return the system to a normal secure operating state. This includes flexibility or cost-effective redundancy in transmission paths, generation, and other energy resources.

[3] AER. 2020. Widespread and Long Duration Outages – Value of Customer Reliability Consultation Paper, at https://www.aer.gov.au/system/files/AER%20-%20Values%20of%20Customer%20Reliability%20Review%20-%20Widespread%20and%20Long%20Duration%20Outages%20Consultation%20Paper%20-%20Updated%2021%20April%202020.pdf.

[4] See http://www.100resilientcities.org/.

[5] The Brattle Group. 2020. Potential for Incorporating Climate-Related Risks onto Transmission Network Planning, at https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp/2020-isp-inputs-and-assumptions

- **Effective control systems** – control systems (including SPSs, system integrity schemes, and remedial action schemes) are generally effective, automated, and do not require perfect foresight of the nature of non-credible contingencies and the inter-operability between various control schemes. If well designed, these schemes can absorb, rather than amplify, the impact of a contingency event. However, with increasing prevalence of the range of schemes being introduced in an increasingly complex power system, care needs to be taken in the design and testing of the schemes. Key risks to the resilience of the power system depend on the availability and reliability of communications links in these systems, the interaction with a range of other schemes and protection settings across the power system, ability to isolate equipment for maintenance, and the need for error reporting and alarming. To manage these risks, there is a need to adhere to good design standards, which consider both credible and non-credible contingencies to avoid the risk of cascading failure.
- **Islanding capability** – if the power system is designed well and appropriate investments are made to enable this level of resilience, the power system should ideally be able to securely split down into regional or even sub-regional electrical islands under extreme events, to minimise the total consumer impacts and aid rapid restoration.
- **Geographic diversity** – energy systems are normally designed to avoid single points of failure due to location specific hazards – however, this design principle is being challenged with coincident weather patterns now having a greater impact across large amounts of infrastructure (for example, high winds affecting multiple generators). Transmission lines are separated over multiple, diverse corridors using looping or meshed designs. Connection points and generator hub locations are spatially distributed, diversifying both the exposure to hazards, and generation and load profiles – but it is only with sufficient network that the underlying risk exposure to a common fuel source (e.g. wind or sun) can be managed through diversity with resources in other areas.
- **Generation source diversity and ability to forecast** – the portfolio of generation assets is diverse and considers weather and fuel-specific hazards. There is sufficient fuel flexibility and storage to manage shocks in fuel, supply chain availability, and water or wind droughts. Renewable generation locations have local weather measurement services that allow for effective now- and near-casting of output and hazards.

Case study – Latrobe Valley to Melbourne

The Latrobe Valley, incorporating the towns of Moe, Morwell and Traralgon, is the location of Victoria's brown coal generation fleet. Given the historical importance of brown coal as a fuel source, transmission lines that connect this region with Melbourne are of great significance. The transmission system design includes both redundancy and geographic diversity, comprising three corridors with four lines (see corridors in the map below).

A system design that used a single corridor would have been less costly. Instead, the system was designed to provide resilience against hazards using geographic diversity and an appropriate amount of redundancy. As the location of generators shifts it is important that resilient designs are implemented where cost effective throughout the system to ensure energy consumers continue to experience the benefits they have come to expect.

A8.1.3 Cyber security

The increasingly distributed supply chain, the pervasive use of information and communications technology and the convergence of IT and OT renders critical systems and infrastructure across the country increasingly more vulnerable to compromise.

Cyber security is becoming more important due to the increasing number, sophistication and intensity of cyber-attacks to energy systems. The Finkel Review[6] notes that, during the first publicly acknowledged incident to result in a power outage, in December 2015 in Ukraine[7], "restoration efforts were delayed as the attack disabled control systems, disrupted communications and prevented automated system recovery".

Market participants, including AEMO, are applying learnings from global incidents as part of their efforts to counter the evolving cyber security threats facing the Australian energy sector, in particular ransomware and system compromise. Recent examples of attacks globally include:

- Taiwan's state-owned CPC Corp impacting card payments (April/May 2020).
- Data breach at EDP in Portugal (April 2020).
- US natural gas compressor shut down for two days (February 2020).

Protecting the Australian energy sector against cyber threats is a key part of ensuring energy system resiliency. Recommendation 2.10 of the Finkel Review involves the ESB delivering an annual report which includes "an assessment of the Australian Energy Market Operator's cyber security capabilities and third party testing".

Over recent years there has been an increasing inter-relationship between NEM systems and ICT and connectivity, which further increases the cyber threats to the system. Examples include supervisory control and data acquisition (SCADA) systems increasingly using internet connectivity to transmit control signals to generators, as well as the growth of DER being connected to open networks for communication.

[6] The Australian Government. 2017. Independent Review into the Future Security of the National Electricity Market, at https://www.energy.gov.au/sites/default/files/independent-review-future-nem-blueprint-for-the-future-2017.pdf.

[7] BBC. 2017. Ukraine power cut 'was cyber-attack', at https://www.bbc.com/news/technology-38573074

The Brattle group also noted the link between planning the energy system and cybersecurity to mitigate risks associated with different types of hazard often had similar solutions:

> "*Planning for climate resilience may overlap with other areas of resilience planning, notably cyber security. Increasing the use of advanced sensors and communication is likely to significantly increase resilience and mitigate the risks and potential damage from extreme events*".

In 2018, AEMO began working with industry on a proactive, voluntary work program to improve cyber security preparedness in the energy sector. This work included forming a Cyber Security Industry Working Group (CSIWG) and developing an Australian Energy Sector Cyber Security Framework (AESCSF) specifically to assess the Australian energy sector's current cyber security maturity and inform increased cyber preparedness[8].

AESCSF has initiated several streams of work to examine, explore and uplift cyber security across the energy sector. The Readiness and Resilience Working Group (RRWG) was established to improve the cyber security maturity and preparedness of energy sector organisations. The aim of the RRWG is to:

- Build and propagate a best practice approach for the energy sector to prepare for, prevent, detect, respond and recover from cyber security incidents, and
- Strengthen cyber security incident response and recovery arrangements at a state and national level to effect a coordinated and swift management of incidents to reduce impacts and maintain community confidence.

The RRWG coordinates the energy sector's involvement in sector specific, state, and national level cyber exercises. The 2019 national electricity exercise (GridExV) jointly led by AEMO and the Australian Cyber Security Centre examined:

- Improving awareness and mitigation of cyber security threats and vulnerabilities in the energy sector.
- Sharing knowledge and propagating best practices to improve cyber security arrangements in the energy sector.
- Strengthening organisations' arrangements to prevent cyber security incidents causing disruption to business operations.
- Improving organisations' arrangements to detect and alert others of cyber security incidents affecting the energy industry.
- Strengthening coordination of cyber security response and recovery arrangements, within individual organisations and across the energy industry.

A8.1.4 Fuel security

Energy and fuel security are key concepts that also need to be considered when planning and designing a resilient energy system. In June 2020, the Australian Government announced a fuel security package, which includes working to increase Australia's domestic fuel storage capacity[9]. AEMO will work with the Australian Government where necessary to assist in implementing this package. Increased storage and flexibility of fuel will enhance the resilience of Australia's energy systems to a variety of supply chain impacts.

Planning for a system resilient to cyber-attacks and providing fuel security involves being reflective and learning from past incidents, being resourceful in how we use resources, ensuring integration, and also designing a system that is robust in the face of an increasing frequency of events in the future.

[8] AEMO. 2019. Australian Energy Sector Cyber Security Framework, at https://aemo.com.au/en/initiatives/major-programs/cyber-security/aescsf-framework-and-resources.

[9] The Australian Government. 2020. Australia's future fuel security package, at https://www.energy.gov.au/government-priorities/energy-security/australias-future-fuel-security-package.

A8.2. Resilience in the 2020 ISP

While the concept of resilience is considered throughout the 2020 ISP and influences technical system modelling, economic modelling, transmission augmentation design and REZ design, AEMO has always considered resilience in long-term planning.

The inaugural ISP in 2018[10] also considered resilience. As an example, it outlined key climate change projections which are expected to influence the future energy infrastructure, supply, and demand in the NEM. Key areas of climate investigated included extreme temperature, precipitation, bushfires and wind. AEMO has worked to build on the analysis in the 2018 ISP to expand planning considerations in the 2020 ISP.

Since the 2018 ISP was published, AEMO released an ISP Insights report entitled "Building power system resilience with pumped hydro energy storage"[11], which provided an update on how AEMO had refined and updated its assumptions and models related to hydro schemes and new pumped hydro energy storage (PHES). This update was made prior to the 2020 ISP, as it was deemed important to provide the transparency on the new information obtained to "*deliver timely information to stakeholders to support action to increase the future resilience of the power system in the NEM, without waiting for the next ISP*".

The stakeholder engagement undertaken throughout the delivery of the ISP, in itself, has contributed to ensuring views of stakeholders have been captured as regularly as possible, thus ensuring that critical insights gained have been incorporated into the ISP. A number of these insights directly link to maintaining the resilience of the network.

The 2020 ISP currently considers resilience in two main ways:

1. **Risk analysis and risk evaluation** – where possible, risk analysis considers both the impact of acute and chronic hazards. Where captured, these risks contribute to the estimation of system reliability, security and calculated project market benefits. While efforts have been taken to improve risk analysis and evaluation to capture resilience, many acute hazards remain excluded.
2. **Planning standards** – planning standards consider climate and resilience when developing physical designs, and technology solutions. Through this consideration, these solutions enhance system resilience, but may not yet appropriately address all risks.

Weather and climate considerations in both risk analysis and evaluation and planning standards are described in Section A8.3. Beyond weather and climate, the robustness of the candidate development paths was assessed through a range of scenarios, sensitivities and cross-checks (refer Appendix 6 and Part D of the ISP).

AEMO has sought to include cost-effective resilient characteristics in the development of the solution design and technology that form the optimal development path. In the 2020 ISP, AEMO has applied the principles of good engineering design in its approach to resilience in transmission planning through two criteria:

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[10] AEMO. 2018. ISP Appendices, at https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/isp/2018/isp-appendices_final.pdf.

[11] At https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2019/ISP-Insights---Building-power-system-resilience-with-pumped-hydro-energy-storage.pdf.

- **Do no harm** – ensuring that any new infrastructure does not lead to unsustainable deterioration in grid resilience. Building additional transmission lines along a bushfire prone transmission corridor would be an example of resilience deterioration.
- **Opportunistic** – where there is an opportunity to increase resilience at minimal cost to consumers, the more resilient option will be taken. This helps inform the decision-making process but is not a key driver of investment.

For example:

- When considering the need for new transmission links, route diversity and network architecture are key factors. Where cost-effective, route diversity such as building lines on new, geographically separate, easements is a straightforward approach to increasing resilience to external hazards. Network architecture, including looping or meshing rather than radial hub and spoke designs, can provide cost-effective improvements to resilience in the final network augmentation. Alternative technologies are also considered, including the use of batteries, local generation, and control schemes to build virtual transmission to reduce reliance on physical assets.
- Additional storage solutions provide redundancy and operational flexibility which will become increasingly important as new generation is connected in REZs, providing geographic and generation source diversity.

The optimal development path includes further interconnection within the NEM, which helps to improve the overall resilience of the network to events such as early retirement of large generation. Other projects identified, such as Project EnergyConnect, improve resilience by reducing the likelihood of having to operate in an islanding situation.

Table 1 below lists the ISP projects and explains how resilience was considered in decision-making.

Table 1 How resilience has been considered within the optimal development path

ISP status	Project	Considerations of resilience
Actionable ISP Projects	Project EnergyConnect	ElectraNet's PACR[A] notes that when undertaking an options appraisal to determine the route which had the highest net market benefits, consideration was made of the network hardening costs required for one of the options (Option D – 275 kV line between central South Australia and Victoria), to reflect operational risks associated with the route being prone to bushfire. In addition, this option would involve using Tungkillo substation that is also used by the Heywood interconnector. The loss of this substation would therefore lead to the loss of both interconnectors. These considerations have led to a solution that has robust asset specifications and provides further geographic diversity.
	HumeLink	The PADR[B] highlights the preferred option for this project (Option 3C) provides additional unquantified benefits over Option 2C that come from the additional geographic diversity opportunity it provides. This leads to a reduced risk from extreme weather events.
	Central-West Orana REZ Transmission Link	The Central-West Orana REZ Transmission Link has two competing network configurations named "Loop" and "Radial"; the key design difference is that the Loop option connects to the main grid at two locations, instead of one. The Loop option has a number of benefits, including lower system strength remediation costs, less impact on generation during planned and unplanned outages, and resilience benefits such as route diversity and smaller contingency sizes during planned outages. Central West has a history of large bushfires which have impacted the power system as well as a projected increase in fire danger in the future. See Section A5.5.3 in Appendix 5 for more information. The New South Wales Government aims to have sufficient capacity to cope with the two largest generating units in the region being out during a one-in-10-year heatwave to ensure a resilient electricity system[C].

ISP status	Project	Considerations of resilience
Actionable ISP Projects with decision rules to be met	VNI West	The options considered to satisfy the identified need of additional transfer capacity between New South Wales and Victoria along with supporting the efficient development of high quality renewable resources provide additional geographic diversity, and greater resilience to prolonged generation and transmission outages, and extreme events (including wind droughts) – refer Appendix 6.
	Marinus Link	The Marinus Link project involves the installation of a 750 MW HVDC interconnector using voltage source converter technology and monopole configuration. Given the converter stations are new, in addition to existing ones for Basslink, this provides redundancy to Basslink with additional geographic diversity, thus improving resilience.
Future projects	QNI Medium & Large	The Medium and Large QNI upgrades include a single 500 kV circuit (QNI Large upgrades this to a double circuit) between New South Wales and Queensland via the western part of the existing QNI. In addition, it involves establishing new 500/330 kV substations at Gunnedah/Narrabri site and new site West of Dumaresq (West Dumaresq). Both elements improve the overall resiliency of the network by providing route diversity (easements are not shared).
	Central to Southern Queensland Transmission Link	The Central to Southern Queensland Transmission Link includes a new double circuit Calvale-Wandoan South 275 kV line and associated reactive plant, increasing the resilience of the network by providing additional geographic diversity.

A. See https://www.electranet.com.au/wp-content/uploads/projects/2016/11/SA-Energy-Transformation-PACR.pdf.
B. See https://www.transgrid.com.au/what-we-do/projects/current-projects/Reinforcing%20the%20NSW%20Southern%20Shared%20Network/Documents/TransGrid%20HumeLink%20PADR%20-%20FINAL%20(AMENDED).pdf.
C. See https://energy.nsw.gov.au/media/1926/download#:~:text=The%20NSW%20Electricity%20Strategy%20is,price%2C%20while%20protecting%20the%20environment.

The 2020 ISP includes climate hazard scores for extreme temperature and bushfire resilience assigned to each REZ. The scoring involves consideration of the change in extreme temperature days and both the number and severity of bushfire events within the time horizon of the ISP help to provide guidance for stakeholders on how these factors impact each REZ. These scores highlight the importance of considering a changing environment in which future system elements must be designed to operate. AEMO continues to work with the Bureau of Meteorology (BOM) and the CSIRO to expand this analysis to consider other climate factors in system design.

Further examples of how the 2020 ISP has considered climate factors in market modelling and risk analysis are explained in Section A8.3 below.

A8.3. Forecasting climate impacts on energy systems

The 2019-20 summer was particularly challenging for Australia's physical gas and electricity infrastructure, with notable increases in heat and fire impacts consistent with climate change projections. A recent review[12] noted the impacts observed both generally and in the last summer, including:

- The increasing impact of both heat and fire on electricity systems, including both conventional and renewable generators like wind generation.
- The vulnerability of key transmission lines and other major energy infrastructure to fire impacts. This highlights the need to integrate resilience measures into the planning, routing, design and assessment of transmission projects and upgrades.
- The impact on gas infrastructure (required for gas-fired electricity generation) of increasing temperature periods that are at or above the design tolerance of pipelines and plant.

Energy systems are located throughout most populated regions of Australia and are therefore exposed to many varied weather and climate effects. Asset specifications and planning processes used in the sector have extensive consideration for Australia's extreme climate but need to be regularly reviewed in light of climate change. Without appropriate review, specifications and processes may become insufficient to capture increasing physical climate impacts, leading to a loss of power system resilience. This chapter outlines key climate change projections, potential energy system impacts and how they are considered in the 2020 ISP.

A summary of possible climate impacts is provided in Table 2, and these are explored further in a climate vulnerability scan (See Section A8.3.2).

Table 2 Summary energy system climate vulnerabilities

Vulnerability (projection for NEM regions)	Impact
Temperature **(Projected increases in both average and extreme temperatures)**	Reduces generator and network capacity and increases failure rates or maintenance/replacement costs. Extreme temperatures are also relevant to asset design specifications.
Bushfire **(Likely increases in extreme bushfire weather)**	Increasing frequency of dangerous fire weather poses a threat to most assets, with a particularly high operational risk to transmission lines due to heat and smoke. It is also an important consideration in transmission line route selection and design.

[12] AEMO. 2020. Summer 2019-20 NEM Operations Review. https://www.aemo.com.au/-/media/files/electricity/nem/system-operations/summer-operations/2019-20/summer-2019-20-nem-operations-review.pdf

Vulnerability (projection for NEM regions)	Impact
Wind and cyclones **(Possible decrease in high wind events and cyclone frequency, possible increase in cyclone magnitude)**	Wind generation is sensitive to any reduction in average wind-speed as well as to the frequency and magnitude of destructive gusts. Thus, it affects wind generation output, plant profitability and design specifications. High winds also reduce the capacity and threaten the integrity of transmission lines; making it an important consideration for network capacity assessments, design specifications and analysis of failure rates.
Rainfall, dam inflows and flooding **(Likely decrease in precipitation, possible increase in extreme rainfall events)**	Reduces water available for hydro generation. Increases requirement for desalination loads. Flood events require consideration for asset design specifications and expected failure rates.
Coastal inundation **(Projected increase in sea level)**	Increasing sea levels may impact on some low-lying generation, distribution and transmission assets.
Compound extreme events **(Possible increase in frequency or magnitude)**	Compound events, where extremes in multiple variables occur simultaneously or in close sequence have the potential to cause substantial disruption. These events can be compounded by associated non-climatic factors such as infrastructure failure or staff fatigue.

Where climate trends are quantifiable, AEMO captures these in market modelling within the ISP. Further details are provided within Appendix 9.

In addition to capturing the latest assumptions on PHES as per the ISP insights paper, AEMO has applied the Representative Concentration Pathway (RCP)/ Shared Socio-economic Pathway (SSP)[13] framework (focusing on RCPs) to long-term planning and forecasting scenarios. Each of the ISP scenarios is linked to a particular RCP that is applied to both emissions constraints (where aligned with the scenario narrative) and projected physical operating environment.

AEMO uses reference years to represent weather variability. The annual weather variability of the reference years are preserved within the market modelling as they are run sequentially[14]. For some variables, the reference years have been climate adjusted to incorporate projected trends while retaining short- and medium-term weather variability. By ensuring the scenarios contain appropriate climate adjustments, factors that affect the outcomes of each scenario – like temperature, irradiance, wind and dam inflow projections, as well as the frequency and severity of extreme weather events – are appropriately considered. In particular, two of these outcomes are explicitly captured within the inputs and assumptions used in the market modelling:

- **Temperature change** – each scenario has assumptions on the increase in temperature on consumer demand throughout the time horizon of the ISP; and
- **Hydro inflow** – each scenario has assumptions on the reduction in hydro inflows throughout the time horizon of the ISP.

In both cases, the assumptions map to the RCP allocated to each scenario [15]. More detail is provided in Table 3 below.

[13] A definition of RCPs is at https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html#rcp, and a definition of SSPs and how they can be combined with RCPs is at https://www.ipcc-data.org/guidelines/pages/glossary/glossary_s.html.

[14] For example, when 2014 is simulated, 2015 always follows.

[15] For more information on Representative Concentration Pathways (2.6, 4.5, 6.0, 8.5) see https://www.climatechangeinaustralia.gov.au/en/publications-library/technical-report/. Additional RCPs (1.9, 3.4, 7.0) are emerging through work by the Intergovernmental Panel on Climate Change (IPCC) sixth assessment due to be published in 2020-21 and are developed on a comparable basis. Hydro reductions consider both rainfall reductions (global climate model [GCM] trajectories for the 'Southern Australia' supercluster in which almost all hydro facilities are located, at www.climatechangeinaustralia.gov.au. Median projection based on ACCESS1.0, high and low sensitivities on GFDL-ESM2M & NorESM1-M GCMs) and estimates of the effect of reduced rainfall on broader dam inflow reductions (informed by http://www.bom.gov.au/research/projects/vicci/docs/2016/PotterEtAl2016.pdf).

Table 3 2020 ISP scenario dimensions relating to climate-resilience

ISP Scenario	Slow Change	Central	Fast Change	High DER	Step Change
Representative Concentration Pathway [RCP] (average temperature rise by 2100)	RCP 8.5 (>4.5°C)	RCP 7.0 (3.0-4.5°C)	RCP 4.5 (2.5-2.7°C)	RCP 7.0 (3.0-4.5°C)	RCP 1.9/2.6 (1.4-1.8°C)
Median Hydro inflow reduction by 2050	-18%	-14%	-7%	-14%	-4%

The ISP market modelling considers a range of technical limitations across the transmission network and generation fleet. These include the following elements that relate to climate change resilience:

- AEMO uses continuous ratings for system normal pre-contingency load flow analysis. Ratings on modelled transmission elements change according to the instant of time considered in each model solution. In summer, transmission element capability ratings are generally lower because higher ambient temperatures reduce the capability for those elements to dissipate heat. Transmission elements may be operated above their continuous ratings for short periods of time.
- Seasonal ratings also apply when considering the planned seasonal availability from generators.
- Inter-temporal energy constraints limit the generation production, reflecting energy limits on generation. For example, hydroelectric generators with storage facilities are influenced by seasonal or annual water inflows, and the decisions to use stored water throughout the year.

A8.3.1 The Electricity Sector Climate Information (ESCI) Project

AEMO is collaborating with the BOM and CSIRO on the Electricity Sector Climate Information (ESCI) Project. The project is funded by the Australian Government for $6.1 million over three years, finishing June 2021, to improve climate and extreme weather information for the electricity sector, as part of a response to the Finkel Review. The project objectives are to:

- Support NEM decision-makers to access and use tailored climate information to improve long-term climate risk planning.
- Develop and demonstrate a best practice methodology for analysing climate change risks that can also be used by other sectors, for example, telecommunications.
- Contribute towards a longer-term vision for the next generation of climate projections and seamless climate and weather services.

The project is designed to improve the reliability and resilience of the NEM to the risks from climate change and extreme weather. The project will tailor climate change data and information to ensure it is usable by the people who need it, to support improved long-term climate risk planning for electricity infrastructure.

Outputs include:

- Standardised climate risk analysis methodology.
- Climate risk assessment framework.
- Extreme weather event scenarios.
- Guidance material for target audiences.
- Weather/climate data via web portal.
- Communication products for target audiences.
- Case studies.
- Capacity development, training and advice.

Project output can be found at https://climatechangeinaustralia.gov.au/en/climate-projections/future-climate/esci/.

Work from this project has informed vulnerability scans, some ISP quantitative analysis, and is considered in the application of good planning practices that underpin the ISP's optimal development path. This project is due to complete in 2021, so the 2022 ISP will be better placed to incorporate this improved climate information. The following section provides some of the insights and output already gained from this work.

A8.3.2 Climate vulnerability scan

AEMO has built on the work from the ESCI project to identify vulnerabilities of the energy system to climate. The following section explores:

- The identified vulnerabilities.
- Their impacts on the energy system.
- The degree to which the risks are captured in current ISP processes.
- Recommendations for improvements to market modelling.

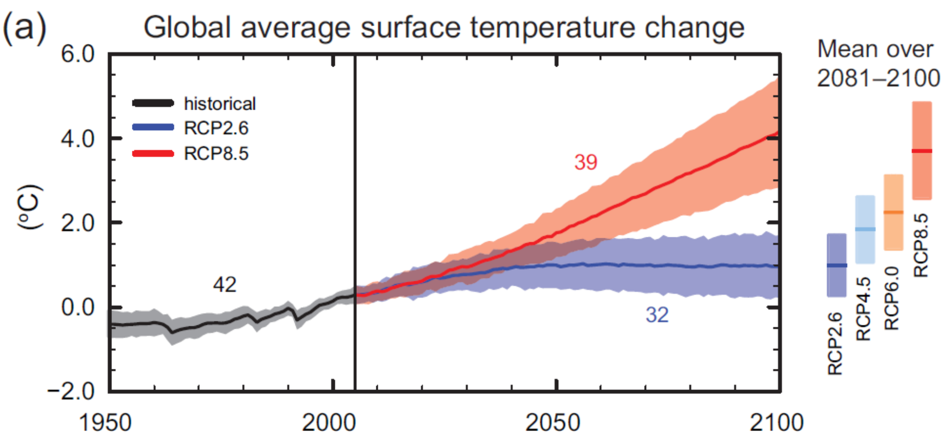
In this chapter, AEMO uses the CSIRO and BOM[16] definition of *confidence* for climate projections.

A8.3.2.1 Temperature

Extreme heat is one of the largest stresses of Australian energy systems because it simultaneously affects consumer behaviour and the electrical and mechanical performance of generators and networks. 2019 was Australia's warmest year on record [17], and both average and extreme temperatures are projected to rise further with a high degree of confidence [18].

Figure 2 shows the projected change in global average surface temperature under various emissions scenarios; from RCP2.6, a scenario with very low to net-negative global emissions, to RCP8.5, a high global emissions scenario. In the study period of the ISP (2020-50), temperature is projected to increase regardless of scenario, consistent with increasing concentrations of atmospheric greenhouse gases. The greatest scenario variation is apparent in the latter half of the century.

Figure 2 Projected global average surface temperature change



Source: IPCC. 2013. Figure SPM.7 https://www.ipcc.ch/report/ar5/wg1/.

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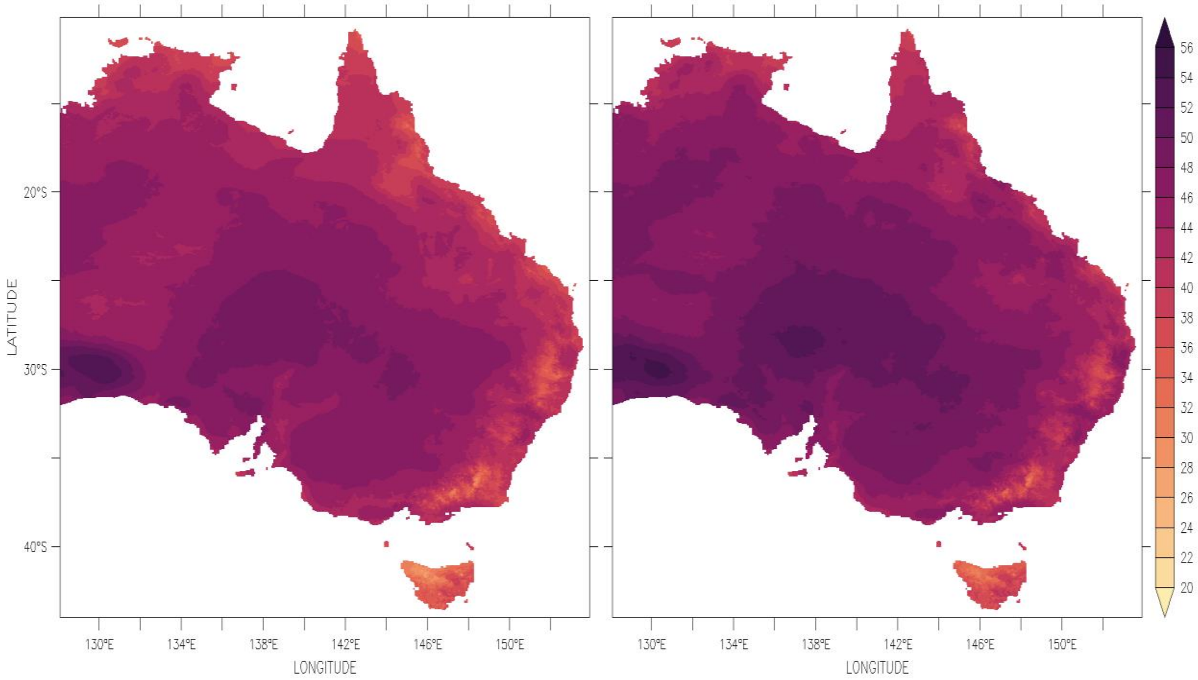
[16] CSIRO and BOM 2015, Climate Change in Australia Technical Report. page 2. at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

[17] BOM. 2020. Special climate statement 73 – extreme heat and fire weather in December 2019 and January 2020, at http://www.bom.gov.au/climate/current/statements/scs73.pdf.

[18] IPCC 2013. Climate change 2013: The physical science basis. https://www.ipcc.ch/report/ar5/wg1/.

Global warming is not spatially uniform and will have differing impacts throughout Australia. Figure 3 shows how extreme (10% annual probability of exceedance [POE]) temperatures are projected to change under a high emissions scenario (RCP8.5), showing variation over Australia. In general, most parts of Australia are expected to warm by approximately 2^0C; Northern Victoria, for example, has a 2000-19 10% POE temperature of 46-48^0C and a 2040-59 projected 10% POE temperature of 48-50^0C.

Figure 3 10% Probability of exceedance temperature (°C) for 2000-2019 (left) and 2040-2059 (right)



Note: the 2000-2019 historic map is sourced from Australian Water Availability Project (AWAP), the 2040-59 map is the 90th percentile of a large ensemble of downscaled climate simulations for RCP8.5. Sourced from: CSIRO & BOM 2020. 10% Annual POE temperature projections. Available from the ESCI website at https://climatechangeinaustralia.gov.au/en/climate-projections/future-climate/esci/

Some of the known interactions between heat and the power system are documented in Table 4.

Table 4 Identified energy system vulnerabilities to heat

Energy system consideration	Interaction	ISP consideration
Consumer demand	Consumer demand is very responsive to temperature and humidity, among other variables, where low temperatures drive increases in heating loads, and high temperatures drive increases in cooling loads. Of particular importance are tolerance and other behavioural characteristics in terms of consumer responses to temperatures – people are more likely to use cooling more often and for longer at the end of a long hot summer than for equivalent days at the start of summer. DER are likely to perform similarly to other electrical components with reduction in performance during high temperatures, particularly if not designed for local conditions.	Short and medium-term weather variability is captured in the weather reference years used in market modelling for consumer demand traces, which are scaled to reflect projected temperature increases. An increase in the number of reference years could be used to further improve the representation of climate variability.

Energy system consideration	Interaction	ISP consideration
Electricity networks	Network assets including lines, cables, and station equipment (including transformers, switchgear, inverters and control equipment) are rated for operating temperatures. Increasing ambient temperatures generally decrease available capacity of the network while simultaneously leading to increased reliance by consumers on electricity for cooling. Overhead transmission lines are subject to sagging, presenting physical and safety risks if not managed effectively. Cables and associated equipment can also be subject to heat. Some assets have steep reductions in capacity once design temperatures are reached, including thermal generation, station equipment, and cables. High operating temperatures stress many network components, which when combined with high electrical loading, sometimes results in higher than usual rates of asset failure.	Short and medium-term weather variability is captured in the weather reference years used in market modelling for network rating traces. The 2022 ISP will incorporate more analysis, including detailed scaling to reflect temperature increases.
Gas systems	Gas infrastructure also experiences capacity reductions and increasing risk of degradation [A].	The main focus of the analysis in the ISP to date has been on the impacts of extreme heat to electricity infrastructure.
VRE generation	VRE generators like wind and solar are directly responsive to weather including temperature, and many are impacted with reduced performance under higher temperatures. It is very important the PV cells, wind turbines, batteries, and associated inverter equipment and switchgear are designed for Australian conditions, including temperatures in summer currently reaching 40-50 C during the day, depending on location. Numerous current installations of wind generators shut down during high temperature periods, and average fleet output during high temperature periods is expected to reduce as temperatures increase. Current solar generators are not expected to suffer from heat related declines in output to the same extent [B].	The impact of high temperature derating or shut down is captured in part in market models, and the approach could be developed further to more comprehensively assess high temperature events and dynamics. By capturing VRE temperature impacts more thoroughly, modelling may indicate an increased need for dispatchable capacity, or changes to VRE design specifications (with associated cost) to minimise impact. .
Thermal generation	Thermal generators are rated for output considering ambient temperatures and the temperature of available cooling water. Increasing maximum temperatures may decrease summer ratings or require additional investments in the power stations to maintain current levels.	Seasonal ratings are applied when considering the planned seasonal availability from generators. Further consideration of the impact of projected temperature increase will be considered in the next ISP. By capturing temperature impacts more thoroughly, modelling may indicate an increased need for dispatchable capacity like PHES.
Batteries	Like other electrical components, batteries and associated equipment (inverters, switchgear, control systems) are likely to suffer reduced performance during high temperatures, (unless designed for local conditions).	With more detailed analysis and operational experience, future heat impacts on batteries and associated equipment will be able to be considered more comprehensively.

A. AEMO. 2020. Summer 2019-20 NEM Operations Review, at https://www.aemo.com.au/-/media/files/electricity/nem/system-operations/summer-operations/2019-20/summer-2019-20-nem-operations-review.pdf.

B. CSIRO, BOM & AEMO. 2020. Heat impacts on variable renewable energy generation output, at https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/esci/.

A8.3.2.2 Bushfire

Calendar year 2019 was Australia's warmest and driest year on record, and fire weather for December 2019 was the highest on record [19], with bushfires observed throughout New South Wales and Victoria. Bushfire smoke and raised dust affected eastern New South Wales, the Australian Capital Territory, and central/eastern Victoria for much of December 2019 and January 2020. During this time, the NEM suffered numerous bushfire-related unplanned outages and lack of reserve (LOR) events. Extensive smoke haze from extreme fire conditions created additional challenges for demand and solar forecasting.

Figure 4 Historical fire activity

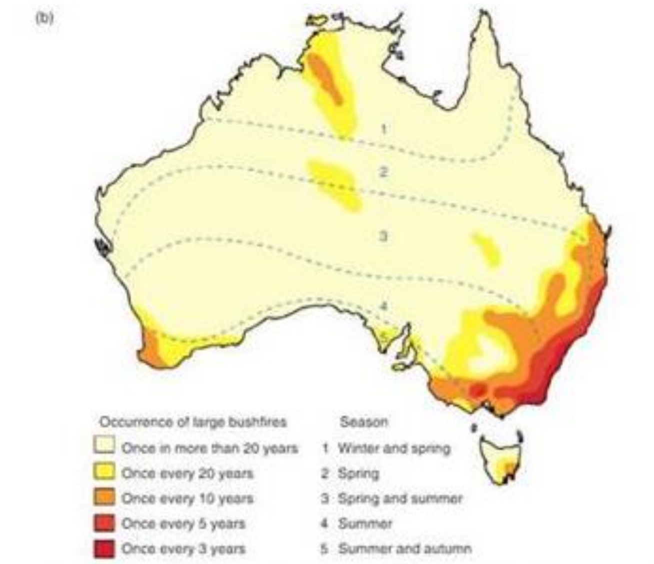
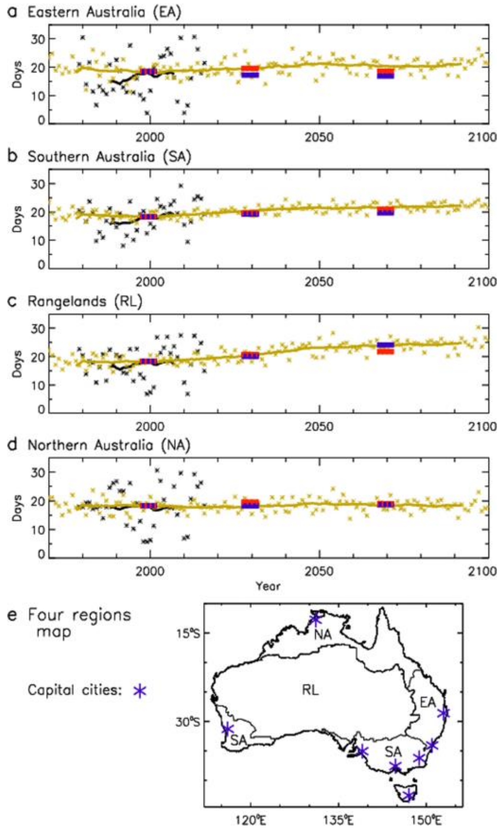


Fig. 8. Depictions of Australian fire activity (*a*) widely cited map, following Luke and McArthur (1978). (*b*) recent official map purporting to show 'occurrence of large bushfires' (Commonwealth of Australia 1996), derived from Cheney (1979). (*c*) map of contemporary fire seasonality and extent as derived here which (i) lumps together certain RAINCLASS regions based on similar fire activity seasonality based on FHS and FAA (refer Fig. 7), (ii) indicates main burning period (given as black horizontal bar in legend derived from Fig. 7) and the mean extent (%) of FAA per region, 1997–2004 (refer Table 2).

Russell-Smith, J, et. al. 2007, Bushfires 'down under': Patterns and implications of contemporary Australian landscape burning, at https://www.researchgate.net/publication/228969191_Bushfires_%27down_under%27_Patterns_and_implications_of_contemporary_Australian_landscape_burning.

Figure 5 Projected change in high fire weather days



Dowdy, A, et. al. 2019, Future changes in extreme weather and pyroconvective risk factors for Australian wildfires, at https://www.nature.com/articles/s41598-019-46362-x.

Collectively, the 2019-20 bushfires challenged the electricity system, highlighting the need to harden assets to more extreme climatic conditions and consider opportunities to enhance the resilience of the NEM [20]. The risk of bushfire is driven by four factors, covering both climate and human considerations:

1. Weather.
2. Sources of ignition.
3. Quantity, dryness and spread of fuel load.
4. Fire suppression.

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[19] BOM. 2020. Special climate statement 73 – extreme heat and fire weather in December 2019 and January 2020. http://www.bom.gov.au/climate/current/statements/scs73.pdf.

[20] AEMO. 2020. Summer 2019-20 NEM Operations Review, at https://www.aemo.com.au/-/media/files/electricity/nem/system-operations/summer-operations/2019-20/summer-2019-20-nem-operations-review.pdf.

Extreme fire weather has increased in recent decades, especially in southern and eastern Australia, and this has been associated with an increase in the length of the fire season[21]. Most climate change projections indicate that weather conducive to bushfires will become more frequent and more intense. Figure 5 shows the mean expectation amongst climate projections for increasing days with high fire weather. In southern and eastern Australia, this equates to a 30% approximate increase in the frequency of fire-conducive weather days by 2050 under RCP8.5. Some individual climate models project an increase in extreme bushfire weather of up to 165% by 2090 under RCP8.5 [22].

Changes to the climate may also influence the rate of ignition and fuel load. Long term changes in temperature and rainfall are changing the spread and type of vegetation across Australia. In 2020, bushfires damaged vegetation types not previously expected, further indicating that climate change is changing the quantity and spread of vegetation more susceptible to bushfires. Figure 4 shows the historical fire activity observed across Australia. Given the compounding changes in vegetation and fire weather, experts in the climate science field predict a spread in the areas at high risk, and an increase in fire frequency and intensity. All of these factors pose challenges for fire suppression.

Many of Australia's high bushfire frequency regions intersect with populated regions and subsequently with energy systems. Table 5 lists some of the known interactions between bushfires and power systems.

Table 5 Identified energy system vulnerabilities to bushfire

Energy system consideration	Interaction	ISP consideration
Gas production	Gas facilities may stop production when bushfires are nearby. For example, during fires near the open cuts in the Latrobe Valley, gas facilities nearby were also affected.	The main focus of the analysis in the ISP to date has been on threats and risks from fire to electricity infrastructure.
Electricity distribution networks	Overhead distribution network assets are prone to damage during bushfires, which results in consumer outages. Distribution networks can sometimes be a source of ignition, that when combined with fuel and adverse weather can start bushfires. Managing the risk of bushfire ignition sometimes also results in consumer outage.	Bushfire risk to distribution networks and measures taken to address this by DNSPs is currently beyond the scope of the ISP.
Electricity transmission networks	Overhead transmission network assets can sometimes be damaged during bushfires. It is more common, however, that lines are reclassified to reduce the security risks arising from arcing due to heat and smoke. Failures and line reclassification reduce throughput, increasing costs and the risk of consumer outage.	The impact of destructive events is addressed through system security and risk management margins. There is growing evidence these margins may need to be reconsidered for future extreme events.
Solar generation	Dust and smoke are known to reduce solar PV generation output. In some cases, this may persist until cleaning or sufficient rainfall.	The impact of dust and smoke is captured in part in market models, and the approach could be developed further to more comprehensively assess all weather events.
All physical assets	All physical assets are subject to the risk of destruction should adverse bushfire conditions arise.	The impact of bushfire events is not thoroughly captured in risk analysis but will be explored in the 2022 ISP. By capturing extreme impacts more thoroughly, modelling may indicate an increased need for robust and resilient network and system security and risk management margins.

[21] BoM and CSIRO. 2018. State of the Climate 2018. http://www.bom.gov.au/state-of-the-climate/State-of-the-Climate-2018.pdf

[22] CSIRO and BOM 2015, Climate Change in Australia Technical Report. table7.8.1, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

A8.3.2.3 Wind

Extreme wind events challenge energy systems in numerous ways. Australian standards apply for design of towers to address risks from extreme winds, especially in areas prone to very high wind speeds and cyclonic conditions. Nevertheless, towers can and have been damaged in extreme and focused wind events. For example, wind damage to transmission lines was a key factor in both the September 2016 South Australian black system[23] and 2020 South Australia islanding event[24].

Wind patterns in Australia are associated with the location and seasonal movement of broad-scale circulation systems, that vary from northern to southern Australia. Trends in mean and extreme winds therefore vary between northern Australia, southern mainland Australia, and Tasmania.

In the near future (2030), changes to mean wind speed are projected with high confidence to be small compared with natural variability. However, under higher emissions scenarios, projected variations include:

- Decreases in winter wind speed across southern mainland Australia.
- Decreases in autumn and spring wind speed across south-eastern mainland Australia.
- Increases in winter wind speeds over Tasmania[25].

Based on current climate projections, tropical cyclones are projected to become less frequent, however those that do occur are projected with a greater proportion of high intensity storms with stronger winds and greater rainfall. The projected expansion of the tropics indicates that a greater proportion of storms may reach south of Bundaberg[26].

Some of the known interactions between wind and the energy systems are documented in Table 6 below.

Table 6 Identified energy system vulnerabilities to wind

Energy system consideration	Interaction	ISP Consideration
Electricity networks	Overhead network assets can be damaged during extreme wind events, either directly, or by airborne debris. Damage sometimes requires substantial resources and time to rebuild. Design standards apply to ensure towers are designed to deal with expected wind stresses, especially in areas subject to cyclonic winds.	The impact of destructive events is addressed through system security and risk management margins. There is growing evidence these margins may need to be reconsidered for future extreme wind events.
Wind generation	Changes to average wind speeds will change average wind generation. Some wind generators shut down during high wind events.	The impact of high wind shut down is captured in part in market models, and the approach could be developed further to more comprehensively assess all weather events.
All physical assets	All physical assets are subject to the risk of destruction should adverse wind conditions arise.	More work will be needed to assess the full dimension of impacts and risks from destructive events, and thereby assess cost effective approaches to address what are by nature, high impact, low probability events.

[23] AEMO. 2016. Preliminary Report – Black system event in South Australia on 28 September 2016, at https://www.aemo.com.au/Media-Centre/-/media/BE174B1732CB4B3ABB74BD507664B270.ashx.

[24] AEMO. 2020. Summer 2019-20 NEM Operations Review, at https://www.aemo.com.au/-/media/files/electricity/nem/system-operations/summer-operations/2019-20/summer-2019-20-nem-operations-review.pdf.

[25] CSIRO and BOM 2015, Climate Change in Australia Technical Report. p127, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

[26] CSIRO and BOM 2015, Climate Change in Australia Technical Report. p130, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf. NESP ESCC (2019) Tropical cyclones and climate change in Australia. http://nespclimate.com.au/wp-content/uploads/2019/11/A4_4pp_brochure_NESP_ESCC_Tropical_Cyclones_FINAL_Nov11_2019_WEB.pdf.

A8.3.2.4 Rainfall

Drought impacts on hydro generation can be material drivers of supply scarcity. The time in drought is projected to increase over southern Australia with high confidence, consistent with the projected decline in mean rainfall. Time in drought is projected to increase with medium to low confidence over NEM regions. The nature of droughts is also projected to change with a greater frequency of extreme droughts, and less frequent moderate to severe drought projected for all regions[27].

While seasonal rainfall is projected to decline in southern and eastern Australia, extreme daily rainfall events (wettest day of the year and wettest day in 20 years) are projected to increase in intensity with high confidence[28]. Extreme rainfall events have the potential to impact a variety of assets and operational situations. Some of the known interactions between rainfall and energy systems are documented in Table 7 below.

Table 7 Identified energy system vulnerabilities to projected change in rainfall

Energy system consideration	Interaction	ISP Consideration
Hydro generation	Reductions in streamflow and higher storm water wastage reduce water available for hydro generation.	Short and medium-term weather variability is captured in weather reference years used in the ISP's market modelling for hydro dam inflows, which are scaled to reflect projected declines. Reference years include dry years to explore the impact of drought. An increase in the number of reference years could be used to further improve the representation of climate variability.
Thermal generation	Reductions in streamflow reduce cooling water availability.	In the NEM, the impacts of streamflow on the current thermal generation fleet are not considered as critical as other factors that more directly impact performance, such as temperature.
Consumer demand	With reducing water availability, many industries and communities will need to adjust water consumption, practices and behaviour in ways that may change energy consumption. Water desalination, agriculture and industry are likely impacted.	Industrial surveys have been used to effectively capture medium-term expectations. Capturing the deeper effects of longer-term structural changes will require further consideration.
All physical assets	All physical assets are subject to the risk of flooding and destruction should extreme rainfall conditions be unfavourable upstream of their location.	More work will be needed to assess the full dimension of impacts and risks from destructive events, and thereby assess cost effective approaches to address what are by nature, high impact, low probability events.

A8.3.2.5 Coastal inundation

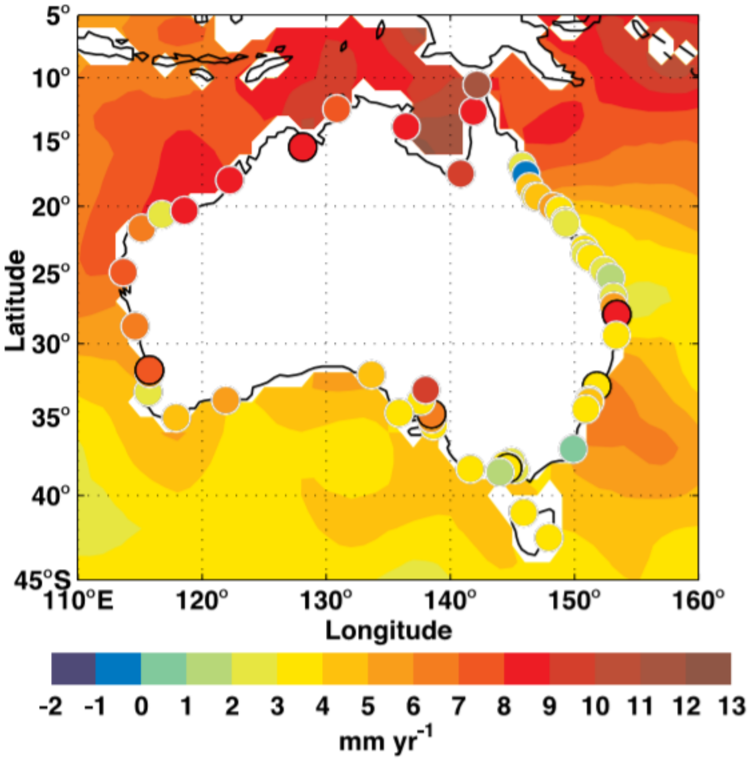
In line with global mean sea level, Australian sea levels are projected to rise through the 21st century with a very high confidence. They are likely to rise at a faster rate during the 21st century than over the past four decades, with 2090 sea level increases projected for the Australian coastline of 450-820 mm under RCP8.5[29]. While most energy system assets would be unaffected, numerous low-lying generation, transmission and distribution assets may be affected, requiring consideration for asset management and new asset designs.

[27] CSIRO and BOM 2015, Climate Change in Australia Technical Report. p123, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

[28] CSIRO and BOM 2015, Climate Change in Australia Technical Report. p122, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

[29] CSIRO and BOM 2015, Climate Change in Australia Technical Report. p152, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

Figure 6 Sea level trends from January 1993 to December 2010



Source: CSIRO and BOM 2015, Climate Change in Australia Technical Report. p150, at https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.

A8.3.2.6 Compound extreme events

In climate science, compound events can be:

- Two or more extreme events occurring simultaneously or successively,
- Combinations of extreme events with underlying conditions that amplify the impact of the events, or
- Combinations of events that are not themselves extremes but lead to an extreme event or impact when combined[30].

For example, the confluence of background warming trends, background drying trends and natural variability saw extreme heat and low rainfall across Tasmania during the spring, summer and autumn of 2015-16. October 2015 saw the third-highest mean monthly maximum temperature on record for the state, record low monthly rainfall and record high fire danger. These conditions rapidly transitioned to record atmospheric moisture and heavy rainfall in June. Tasmania experienced significant impacts from these events, including drought and fires, followed by flooding[31].

While climate scientists often report on changes in individual climate variables, disaster events that are most impactful and hazardous tend to be the result of the combined influence of extremes in multiple variables occurring simultaneously. Climate change can have a significant influence on the frequency, magnitude and impact of some types of compound events. While many chronic and acute climate trends can be projected for consideration in quantitative risk management, the projection of future compound extreme events is regarded as a significant scientific challenge[32]. Collaboration with BOM and CSIRO through the ESCI project (see Section A8.3.1) indicates that extreme compound weather case studies should be used to explore these

[30] IPCC. 2018. Changes in Climate Extremes and their Impacts on the Natural Physical Environment. p118. https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf.

[31] BOM. 2018. State of the climate 2018 – Australia's changing climate. http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml .

[32] BOM. 2018. State of the climate 2018 – Australia's changing climate. http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml .

events, despite the lack of probabilistic climate information. While each event is individually unlikely, the combined probability of disastrous events is high.

A8.3.2.7 Recommendations arising from climate vulnerability scan

The vulnerability scan and review of current process identified that numerous impacts in current and future climates could be better captured in forecasting and market modelling processes. Once included, these improvements will help justify the timing and quantity of system projects that will enhance outcomes consistent with consumer expectations and willingness to pay. Table 8 summarises priority recommendations identified to overcome current challenges. Lower priority improvements to better capture climate impacts may also be developed with consideration for effort required.

Table 8 Priority forecasting recommendations arising from climate vulnerability scan

Recommendations	How these are being/will be addressed
Ensure power system component models appropriately capture performance during periods of extreme.	AEMO will improve several models in advance of the 2022 ISP: • Update wind generation model to better capture high wind and temperature cut outs. • Update thermal generation model to better capture high temperature effects as temperatures rise. • Update line rating and failure model to better capture transmission performance and outcomes in a changing climate.
Ensure reference year weather is scaled to, or sampled from climate projections.	AEMO will apply additional scaling for model inputs in advance of the 2022 ISP for: • Temperatures for transmission line ratings. • Temperatures for conventional and VRE generation ratings/output.
Use extreme compound weather case studies to explore and mitigate high impact climate risks.	AEMO will identify and calculate a variety of single and compound extreme weather case studies. The use of case studies will elucidate extreme risks that can complement quantitative risk analysis that covers less extreme operating conditions.

A8.4. Planning for a climate-resilient network

In planning for a resilient energy system, AEMO has considered current planning practices and how these may need to change to meet the challenges of new hazards and risks to the NEM.

Australia's systems have historically had substantial inherent resilience within the system by the nature of their network architecture (strong corridors designed to reliably transport bulk energy from centralised generation basins to load centres), with essential system security services inherently provided by the generation, and, initially, surplus generation in many regions.

All of this is changing in the transition of the power system, and in many cases the assumptions of something important just being there is challenged. Increasingly, specific power system needs must be planned for, not assumed. The nature of external hazards is changing, due to climate change, and the change in the network topology itself.

Appropriate measures for resilience need to consider forecasts of increased high temperature days and increased frequency and severity of extreme weather events. For example, the value of customer reliability (VCR) must be fully informed by these increasing hazards, to help inform the appropriate investments to meet the desired level of reliability.

Since the capital investments made today will need to continue to operate reliably for multiple decades, they need to be designed to manage predicted future climate changes and extreme weather events.

In planning for a resilient network, AEMO has undertaken a review of how transmission and distribution operators consider the changing climate and its impacts on energy systems.

The next sections are structured as follows:

- A summary of how NSPs are planning for a climate-resilient network.
- Examples internationally of how climate-related risks are incorporated into transmission and distribution planning.
- Implications for planning standards in the NEM.

A8.4.1 Example network planning climate considerations in the NEM

As part of final ISP development, AEMO interviewed TNSPs and DNSPs to gain an understanding of how they address the needs for changing climate impacts within the NEM.

From a planning perspective, consideration of a changing climate has manifested itself through decision-making relating to:

- Expenditure relating to new network investments through the RIT-T process. and

- Expenditure to improve the resilience of the existing network.

A8.4.1.1 New network investments through the RIT-T process

In some cases, RIT-Ts underway or recently completed have included a consideration of resilience to climate impacts. These have two recurring themes:

- **Line route diversity** – all respondents who have considered investments where new lines are considered are of the view that selecting the option that would lead to increased line diversity would mitigate risks associated with potential extreme weather events at minimal additional cost.
- **Difficulty in justifying the additional cost to provide climate resilience** – it is currently difficult to justify the additional cost for measures to improve resilience of the energy system to future climate effects. The risk is that investments may not be optimally designed for the needs for resilience to future climate change, and that this inherent limitation may not be fully appreciated until the future climate is experienced.

A8.4.1.2 Current regulatory arrangements for planning resilient networks

Within planning more broadly, NSPs adopt different approaches depending on the state they are in, partly due to the differing legislative and regulatory frameworks within each state.

The NER[33] contain both the reliability standard (3.9.3) and Network Performance Requirements to be Provided or Co-ordinated by Network Service Providers ((Schedule 5.1).

The reliability standard itself is outlined in Section 3.9.3A, and states:

> "*The reliability standard for generation and inter-regional transmission elements in the national electricity market is a maximum expected unserved energy (USE) in a region of 0.002% of the total energy demanded in that region for a given financial year*."

NER Section 3.9.3 also provides that USE relates to power system reliability incidents resulting from a single credible contingency event but does not include power system security incidents resulting from multiple contingency events, protected events, or non-credible contingency events. Therefore, while the reliability standard relates to climate resilience in some ways, it would not apply in cases where an extreme weather event leads to a cascading effect of multiple contingencies.

While AEMO has endeavoured to consider future climate change in this ISP, more comprehensive analysis is planned for the next ISP off the back of the ESCI project (see Section A8.3.1). Some NSPs are also looking at climate resilience within the context of state planning standards for reliability.

In particular, AEMO wishes to work with all stakeholders to achieve increased clarity on how the industry should be planning for the changing climate, and how this could be used to inform potential amendments to planning standards if needed.

A8.4.1.3 Other themes from NEM network operator consultation exercise

NSPs incorporate resilience planning and assessments into their functions in a variety of ways. Some have defined what resilience means internally, as well as climate resilience. There are also examples in the NEM where NSPs have considered the impact of high temperatures and extreme weather events on investment decisions. There are cases where TNSPs have implemented solutions beyond existing design standards where the additional costs to the consumer of doing so and achieving a more robust system were negligible.

The majority of TNSPs have attempted to forecast future changes in temperatures and the frequency and severity of extreme weather events, but most of these examples involved taking historical data and extrapolating this out for the time horizon considered necessary for each individual project.

[33] See https://www.aemc.gov.au/regulation/energy-rules/national-electricity-rules/current.

Standalone power systems and remote area power systems (SAPS and RAPS) are increasingly being considered and implemented as a means to improving resiliency in areas particularly susceptible to bushfire and extreme wind events[34].

A8.4.1.4 Recommendations arising

Table 9 Recommendations arising from NSP consultations, and proposed responses

Recommendations	How these are being/will be addressed
Work with stakeholders to understand approaches to risk mitigation solutions such as geographic diversity, with the aim of developing a common approach to identifying the need for an intervention using resilience metrics or scorecards.	AEMO will continue to work with all stakeholders to understand current approaches to planning for a changing climate, as well as identifying best practice which will help to inform the development of a consistent approach across the NEM, and one that also recognises the interests of consumers.
Work with stakeholders to consider approaches to measuring and quantifying the benefits associated with climate risk mitigation through planning and design solutions.	AEMO will develop a list of potential solutions that can be implemented to reduce risk to a changing climate from extreme temperatures and weather events in a manner acceptable to consumers.
Further consider the inter-relationship between national and state planning standards and climate resilience, including the potential for expanding the scope of planning standards to include explicit consideration of climate resilience.	AEMO will work with stakeholders to include appropriate consideration of risks associated with extreme temperatures and weather events in planning standards. AEMO will work with stakeholders to develop national frameworks that complement state planning standards.
Expand AEMO's engagement on climate resilience to wider groups of stakeholders.	AEMO will work with stakeholders to understand and develop best practice approaches to network and system planning in a changing climate, including developing the framework to adopt key learnings from other sectors (for example, insurance, Infrastructure Australia). AEMO wishes to also work with stakeholders to establish how to utilise the set of standardised climate scenarios and risk framework being delivered by the ESCI project..

A8.4.2 International network planning climate considerations

AEMO engaged The Brattle Group to conduct a review of climate-resilient planning standards across select international locations[35], to understand how system planners are increasing the stringency of their planning criteria to account for climate change-related risks.

In summary, the key findings of this review are:

- Most jurisdictions are just beginning to develop policies, frameworks, and approaches to account for climate-related risks when planning of transmission networks.
- The Brattle Group did not identify a jurisdiction where a national policy and/or framework is setting comprehensive new standards and planning processes that take into account climate-related risks when developing electricity system resilience.
- The current North American approach for setting standards to account for climate-related risks in transmission network planning is very much decentralised, with each region/state and province conducting its own transmission planning, with location-specific considerations for climate-related conditions.

[34] See https://www.aemc.gov.au/market-reviews-advice/updating-regulatory-frameworks-distributor-led-stand-alone-power-systems.

[35] The Brattle Group. 2020. Potential for Incorporating Climate-Related Risks onto Transmission Network Planning, at https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp/2020-isp-inputs-and-assumptions

- In Europe, the transmission network owner and developer in Italy conducts system planning with significant considerations for increasingly severe weather conditions, including ice loading on overhead electric wires and increasingly strong storms.

System hardening is a term that is often used in relation to future resilience, but is applied in different ways across jurisdictions. Overall, there is limited evidence to suggest many other jurisdictions have attempted to develop a deep understanding of how the changing climate will impact resilience to electricity networks over a long-term planning horizon. Indeed, few of the jurisdictions observed plan their network over a longer timeframe than 10-15 years, which makes it difficult to capture effects of the changing climate in investment planning.

The Brattle report also notes that, while Italy is developing a proactive approach to mitigating climate risks, the North American approach has been largely reactive to specific extreme weather events occurring.

Although some of the solutions identified in the Brattle report to mitigate risks associated with climate-related risks are similar for different extreme weather events (such as installing smart grid devices to speed identification of faults and service restoration), others are unique to the weather event. For example, to mitigate risks associated with extreme heat events, examples related to system hardening include upgrades to transmission towers related to cooling, increasing or installing additional transmission capacity, replacing limiting wire sections to reduce transmission sag, or raising towers to avoid sag-related contact.

Other system hardening solutions common across extreme weather events include limiting consumers affected by outages by installing additional substations and breakaway equipment and by sectionalising fuses, and developing island-able microgrids with distributed generation, therefore increasing islanding capability.

Planning and operational solutions for extreme heat events include ensuring temperature assumptions for projecting load and transmission capability, and for determining cyclic ratings for transformers, are up to date, as well as including extreme temperature scenarios in future grid planning. In the case of bushfire events, solutions related to planning and operations include increased geographic diversity, increased redundancy in transmission systems, and extending the planning horizon to ensure the change in climate risk over time is being adequately captured.

The primary recommendations from the Brattle report, and AEMO's responses, are listed inPrimary recommendations from report into incorporating climate-related risks, and AEMO's responses Table 10 below.

Table 10 Primary recommendations from report into incorporating climate-related risks, and AEMO's responses

Primary recommendations	How these are being addressed
Develop a holistic review of climate vulnerabilities as well as potential resilience metrics and harmonisation of those metrics with existing regulatory requirements.	Through the ESCI project AEMO has developed a comprehensive view of climate vulnerabilities and is working to implement climate risk frameworks developed through the project. AEMO will work towards developing resilience metrics/scorecards that will form minimum national standards for all NSPs, both for transmission and distribution. The first step will be to identify leading indicators of good practice resilient systems. The minimum national standards will be reviewed annually through annual resilience plans.
Analyse mitigation approaches to climate-related risks, such as (a) route diversity, (b) the use of new and more resilient technologies and equipment, and (c) the use of advanced monitoring and alert technologies.	AEMO will develop a list of potential solutions that can be investigated as approaches to help adapt, minimise the impact of, or recover more quickly from, hazards and events due to climate change.
Develop a consistent approach across AEMO, regulators, and other stakeholders on decision metrics to be applied to system planning (for example, least regrets, average value),	AEMO will work with stakeholders to develop a common approach to measuring and justifying the benefits associated with mitigating risks associated with extreme temperatures or extreme weather events.

Primary recommendations	How these are being addressed
which should include concrete examples of potential outcomes under each approach.	
Assess the potential for a national approach to planning for climate-related risks, including establishment of minimum national standards, with best practices for meeting the standards (as mentioned above).	AEMO will use the growing evidence from the ESCI project and elsewhere, and work collaboratively with governmnents, industry and consumers to develop a framework to be used to plan the transmission network to mitigate risks from the changing climate.

In addition, secondary recommendations were also included. Table 11 below lists these recommendations, and how AEMO is addressing these recommendations within the context of the NEM.

Table 11 Secondary recommendations from report into incorporating climate-related risks, and AEMO's responses

Secondary recommendations	How these are being addressed
Use forecast climate risk data, to the extent feasible, relying on recent historical data when necessary.	AEMO will use outcomes from the ESCI project to continually improve forecast climate risk data, and will use this in addition to using historical data where appropriate.
Monitor the evolution of climate science to understand trends in projected climate risks, the availability of high-resolution data, and advances in the underlying science.	
Analyse interactions between the resilience of the electric power system with other infrastructure systems, including telecommunications, natural gas delivery systems, and water supply and delivery systems.	AEMO is involved in the Cross Dependency Initiative (XDI) project and other workshops with Infrastructure Australia (IA) to identify cross sector actions to build infrastructure resilience.

A8.5. Next steps

Within the next few months, many investment decisions will be made relating to the optimal development path. Therefore, it is important that stakeholders within the sector progress initiatives that are both currently underway and that have not yet started to better manage climate and resilience risks.

Longer term, further work is required to better capture climate risks and energy system resilience in ISP and AEMO decision-making. These improvements and further considerations take four main categories:

1. **Improve risk analysis and risk evaluation** – better capture and quantify climate and other risks in integrated market modelling and project benefits assessments. Increase the use of extreme weather and power system case studies to explore integrated resilience tail risks that cannot be fully quantified yet likely yield unacceptable outcomes for society.
2. **Improve planning standards** – better capture climate and resilience considerations and the appropriate level of consumer risk aversion in the process of energy system design and technology planning. Ensure proposed solutions that enhance the resilience of the system are built to high standards with fit for purpose asset and system specifications.
3. **Improve operator flexibility and procedures** – provide additional operator flexibility to manage system resilience and security in the presence of increasing and coincident hazards. Improve forecasts of near term weather and hazards.
4. **Improve cybersecurity risk management** – improve the cyber maturity of all energy market participants to understand where there are vulnerabilities, and ensure regulatory procedures are sufficient to deal with any potential cyber incidents in the NEM. Strengthen cyber security incident response and recovery arrangements at a jurisdictional and national level to effect a coordinated and swift management of incidents to reduce impacts and maintain community confidence.

AEMO resilience actions looking beyond the 2020 ISP are listed below.

Table 12 AEMO actions to enhance energy system resilience

Category	Description	Target date
Risk analysis and evaluation	Incorporate a broader selection of climate change trends in modelling input. In doing so, economic market benefits, reliability, and operability assessments will capture a broader suite of climate risks when the system is operating under mostly normal conditions. Improvements include: • Updated wind generation model to better capture high wind and temperature cut outs. • Updated thermal generation model to better capture high temperature effects as temperatures rise. • Updated line rating and failure model to better capture transmission performance and outcomes in a changing climate.	2022 ISP
Risk analysis and evaluation	Explore a range of extreme weather and energy system case studies to stress test the system beyond normal operating conditions. Use this analysis to explore implications on energy system planning, optimal outcomes and system resilience. Differentiate between more and less resilient risk mitigation solutions and build an evidence base for additional changes to planning standards and risk management approaches.	2022 ISP

Category	Description	Target date
Risk analysis and evaluation	Work with other social and infrastructure sectors to identify resilience needs and cascading societal impacts. Engage in collaborative adaptation to regional and location specific climate and weather hazards. Examples include work with NSW DPIE and Infrastructure Australia.	Ongoing
Risk analysis and evaluation	AEMO will work with NEM stakeholders to enhance the current approach to informing investment decisions to adequately capture both qualitative and quantitative benefits associated with resilience risk mitigation.	2021
Risk analysis/ improve planning	Consult on and enhance the six identified characteristics for consideration when planning for a resilient energy system. Develop resilience scorecards or metrics that identify the relative state of each characteristic, and the relative resilience benefits that risk mitigation solutions may achieve. Align these leading indicators with lagging indicators of observed incidents and outcomes.	2022 ISP
Improve planning standards	AEMO will use the growing evidence base of resilience risks to develop a framework to be used by TNSPs and DNSPs to plan the transmission network. This framework will include a list of potential solutions that can be implemented to mitigate resilience risk. In collaboration with NSPs, consumers and Jurisdictional planning bodies, AEMO will work to ensure these risks and frameworks are appropriately considered in planning standards in a way that complements jurisdictional planning standards.	2021
Improve operator flexibility and procedures	AEMO is engaging and collaborating on numerous reviews of power system operating procedures. This includes work by AEMC/COAG on power system security, DER voltage control, General Power System risk review.	Ongoing
Improve cybersecurity risk management	AEMO continues to work with the Commonwealth on uplifting cyber maturity in the energy sector. The release of the national 'Cyber Strategy 2020' will provide a focused road map on the direction, targets and supporting elements required to uplift the energy industry's response and build increasing resilience to the growing and evolving cyber challenge. AEMO has also initiated a multi-year, multi-faceted cyber uplift program to strengthen cyber capabilities with its crucial central role as the market operator	Ongoing