Supplementary Information

to

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Overview

It is by now well recognised by the energy sector that current regulations do not sufficiently require, incentivise or enable distribution networks (Networks) to plan for and better respond to extreme weather events and other shocks.

This deep dive into energy resilience reveals that only by integrating all dimensions of resilience, will it be possible to deliver a resilient energy system. A robust definition of energy resilience needs to:

- Include the social, cultural and the institutional dimensions, as well as the technical.
- Be futures oriented
- Include attention to adaptability and flexibility
- Include consideration of both specific site-specific solutions, but also the broader system.

The report argues that current regulatory assumptions around reliability and resilience are worth re-examining, given the changes in the energy system in the past 30 years. In the 1990s as Network business became progressively privatised, we created a regulatory system based on neoclassical economics that assumed politics could be 'taken out' of planning decisions and businesses would be free to make rational decisions that would – with the correct incentives – produce the most efficient public outcome. As we have seen since then, the essential nature of energy means that in practice this has been difficult and political imperatives have affected regulatory incentives like network reliability targets. The South Australian system black outage in 2016 provides a perfect example of the political, cultural and social complexity of energy resilience. The intense public pressure and scrutiny that surrounds decision-makers around extreme events like bushfires or floods means that idealised economic instruments that overly simplify human behaviour and systems change are unlikely to be a helpful governance framework moving forward as climate impacts intensify.

Rather than seeking to take the politics out of governance, we suggest there are robust resilience planning and measurement tools that can increase accountability and improve decision making and planning. In any case, all market designs are political in that they favour a particular institutional design. Social scientists argue there is no such thing as an a-political techno-economic system. Any design reflects a set of values that can be described and analysed through empirical analysis. The distrust and displeasure held by Australians about the National Electricity Market framework is only one example of this.

Reliability versus resilience

Our stakeholder interviews revealed significant differences in how resilience is conceptualised. Regulators tend to see it as an extension of reliability – just involving longer outages or larger areas. They also expressed a lack of opportunity to fully consider resilience definitions and implications across their work. Yet others in fields adjacent to energy tended to have a more multi-faced definition of resilience which encapsulated human impacts and institutional capacity. We find these differences in view reflected in our literature review. Reliability is about average network performance and seeks to minimise outage time during normal conditions and planned outages. It is generally focused on low impact, high probability events concerning static systems, such as faults, overloads and maintenance. Reliability metrics cover the spatial area affected, number of customers, or minutes of outage. Resilience, on the other hand, refers to the ability of a system to recover from high impact, low probability events such as extreme weather events and cyberattacks. Resilience refers to what happens during the event as well as the immediate and long-term aftermath, including the lived experiences of people. This is in contrast to reliability which focuses on the impacts to the energy system. A resilient response to an event could mean a return to stability, either the previous “normal” or something else involving changed practices, policies, technology configurations and so on. In other words, while reliability may imply a return to the previous, ‘normal’ state of operation, resilience does not require it. **A key insight we have learnt from our study of reliability metrics is that their simplifications leave out context that is important for people, especially during disasters, and as a result resilience will not be improved if it is pursued through the same conceptual paradigm as reliability.**

Effective approaches to resilience are multi-dimensional

When resilience becomes reduced to a metric, and the metrics become a target, our review shows they tend not to lead to an effective resilient design/response. **Instead, the most promising methods for integrating resilience into energy system design and planning will likely require an ongoing process of assessment and evaluation, including metrics for a range of dimensions as defined by communities and stakeholders.**

While a resilience approach could be taken at an entire grid-scale (as one of our participants suggested could be done through the Integrated System Plan), most of the methods we reviewed focus on a distribution network. Methods for assessing resilience can be either summative, which evaluate existing levels of resilience for external reporting and benchmarking, or formative, which aim to build resilience through the assessment process itself. Methods need to be connected to choices that can be made by Networks, focus on what is important to people and the environment, and be open to public scrutiny.

Summative assessments used standardised indicators for the purpose of comparison and to aggregate toward higher-level reporting of resilience. Summative assessments can also be used to assess risk and vulnerability in order to direct investments towards greatest need. Formative assessments comprise an ongoing process of seeking and interpreting evidence in order to make sense of current levels of resilience and gain agreement on ways to improve resilience. Formative assessment is not suitable for compliance auditing. It involves paying attention to what builds, maintains and breaks down resilience; where undesirable resilience should be disrupted; and desirable resilience can be enhanced. This is achieved by using probes and centring critical conversations among relevant stakeholders.

In both summative and formative assessment methods, the existing strengths and embedded knowledge in networks’ asset planning can be built upon. What is missing is an incentive pathway and methods that encompass the human focus, complexities and timescales of resilience.

Resilience metrics should be stakeholder led and will cover relevant dimensions of energy use

Within a method for assessing resilience, various metrics are likely to be useful. Metrics that focus on the impacts on people, social/institutional and technical resilience, specific and general resilience, and with consideration of the future and the ability to adapt over time are known dimensions of resilience. It is highly likely this process will require both qualitative and quantitative approaches: qualitative assessment based on conceptual frameworks and semi-quantitative indices, and quantitative assessment using probabilistic and deterministic metrics as well as modelling. Importantly, resilience should be studied with reference to specific hazards, such as bushfire in a certain area. We suggest that a single metric cannot serve a multifaceted, context-specific goal such as resilience.

At its heart, improving resilience is about creating the kind of future that we collectively desire. As such, there will always be some level of contestation because people have different understandings of the problem and expectations of the future. Rather than assume that we can sweep this under the carpet through an optimal technical solution, it is important to include energy users in decision-making. In areas as diverse as municipal budgeting, to water management and infrastructure planning, we now know that involving people in decision-making leads to better, more appropriate solutions, as well as smooth project implementation as people are more likely to trust that their concerns have been addressed. In any case, public involvement in resilience planning is even more important since they need to understand the options and uses of energy during extreme events. The public are more likely to understand these options if they have been involved in the planning.

Improving energy resilience starts with challenging current assumptions

Interviews with energy stakeholders revealed important and deeply held assumptions about governance that shape people's appetite and openness to reform for resilience. For example, there is genuine concern for some participants inside market bodies about changing any rules that might challenge the principle of competition that underpins the mechanism for accountability/efficiency in the national electricity rules. As such, any alternatives to the current system are often viewed through a strongly techno-economic framing. Such a framing appears out of step with the evidence base around what can lead to a more resilient system and more than certainly will create blind spots. This tension would need to be resolved before regulatory reform could progress.

A key concern and tension around improvements to resilience emerged for stakeholders around the level of uncertainty and consistency in climate modelling coupled with a lack of understanding about what solutions may best improve resilience. Local solutions need to demonstrate cost-effectiveness so that the principles of equity and efficiency are not undermined since network costs are spread across all users in the network. At the same time, because of the growth of local energy assets (rooftop solar/battery systems) network resilience now covers a policy domain that is separate from Networks – because of vertical disaggregation. This creates new complications for assessing and creating solutions for energy resilience. **The resultant regulatory complexity will likely be a major challenge in localised attempts to build resilience.**

Stakeholders with a lot of experience in community contexts articulated that there is a strong desire for localised solutions. People are attracted to local solutions around domains like food and energy because they feel such systems can provide more accountability, sustainability benefits and authentic relationships between consumers and the people that maintain critical systems. **This interest and desire for local solutions may be a cultural change that is not well understood or recognised by many policy and industry professionals.** While these stakeholders believed in community involvement and engagement, they were generally cautious of communities' ability to self-organise and hold sole responsibility for managing these systems. As such institutional trust is likely to be a core part of delivering future solutions around improving resilience.

Capacity building will be needed

The theme of capacity-building emerged as being significant across our interviews and is also a theme that is covered in the literature review. Generally speaking, energy professionals believed Networks have not been enabled to build capacity to anticipate and design for the future. They also believed in the need to include the public in resilience planning, a point that was raised in resilience metric development. An implication is that not only will there be a need to build skills and capacity about institutional flexibility and anticipating the unexpected, but also that there will be a need to bring on professionals skilled in community development and engagement.

Resilience generally relies on a multi-scaled approach, as covered in the literature review. The local scale is important for communication, coordination and service delivery, as well as engagement as already discussed. Stakeholder interviews revealed that local government and regional Network depots are important local institutions in extreme events. **But while many placed a lot of expectation on local government, viewing them as in the ‘sweet spot’ of having institutional capacity and accountability, while being able to deliver local services, local government themselves held a different view.** Local government intervieews spoke of increasing expectations from them of service delivery without adequate resourcing. Their funding base has not traditionally been set up to cover the sorts of sustainability and resilience solutions that the community increasingly expect of them. If local governments are expected to form part of resiliency solutions both their resourcing and organisational cultures will likely need to shift.

Resilient energy systems

Understanding and improving resilience

Resilience is a complex, evolving topic with application in many different fields. Before discussing tools for the measurement of resilience, it is important to define the concepts, dimensions and high-level attributes of resilient systems. These descriptions provide guidance on the scope of issues that should be considered and included within a measurement approach. We find that resilience must be considered as both social—involving people and institutions—and technical, involving the material infrastructures that provide services. Furthermore, there is agreement that a compartmentalised approach to improving resilience—for example, by only focusing on energy, one community, or on an individual technical system—is insufficient. In addition to specific systems, the bigger picture of the NEM and its social and technical infrastructures must be included.

There are always trade-offs with creating a new tool. The ones that are more accurate may be more expensive to implement. At the same time, the simpler tools may fail to capture all the dimensions of resilience, and networks or governments may end up investing resources that do not boost resilience at all. In reviewing innovative approaches to improving energy system resilience we find some promising openings. Approaches that seem fit for purpose for boosting resilience will likely require an ongoing process of assessment and evaluation, including metrics for a range of issues as defined by communities and stakeholders.

While distribution companies will always be a key actor in improving energy resilience, other types of actors like households, community groups, and local and state governments also have views about how resilience can be defined and how it should be improved. The role of these other organisations and individuals are not well articulated now and stakeholders hold different views and expectations about who is responsible for energy resilience. We cover existing methodologies that suggest ways to bring together stakeholders to plan for and respond to resilience gaps.

Impacts of disasters on people

As we have noted, the exclusion of MEDs from performance metrics means that there are limited regulatory incentives to keep the lights on during disasters, or for network solutions which may make a return to power faster post-disaster. The AER’s proposal to deal with MEDs made a general concession to social impacts without seeking to understand or mitigate them. This is significant given that outages can be caused and exacerbated by extreme weather events such as (in NSW) the Black Summer bushfires of 2019-20 and the February, March and July 2022 floods. Delays in fixing outages that occur during MEDs, mean that the outages can spill over into non-MEDs. Existing methods for calculating VoLL for those days also omit the human impacts of disasters, which are likely more serious to human health and wellbeing than the convention VoLL assessment accounts for.

The NSW Government's Flood Inquiry stated that essential services "are never more important than in an emergency" [34] and that loss of power "had a compounding effect on other services" (p. 154). During disasters, outages affect the ability to send and receive emergency warnings, the operation of evacuation centres, the ability to charge phones, radios and torches, the operation of water supply and sewerage services, access to essential businesses such as post offices, banks, service stations and pharmacies, and access to heating and cooling [34]. During fires, loss of power to on-site water pumps can remove people's ability to defend property, or where there is on-site power, firefighting chemicals can pollute stored rainwater making it unpotable.

Ongoing outages also stymy recovery activities, with a key factor driving outages during disasters being the vulnerability of the network infrastructure itself [34]. Outages and shortages interrelate and have compounding effects on each other, and addressing one vulnerability can exacerbate another; for example, using a car to charge devices risked of draining the battery or running out of fuel[35]. The critical nature of loads during and following a disaster is not accounted for in VoLL methods, nor are issues such as the intensified level of stress or intersectional vulnerability accounted for.

Disaster events particularly exacerbate the existing energy inequality and insecurity experienced by low-income households, both at the sociodemographic and household micro level—for example, job security, housing quality, tenure—and at the macro level of energy and telecommunications infrastructures [36]. Social and behavioural factors such as energy practices and access to and proficiency with energy technologies can also shape the vulnerability of low-income households[36]. In some areas, transient groups such as tourists can be a source of resentment and seen as consumers of finite resources that do not contribute[35]. In grappling with these issues, Chen et al.[36] propose a range of indicators that could be used to study energy burdens during disasters (**Table 1**).l

Table 1: Dimensions of energy inequality and insecurity and considered measures in the context of disasters. Adapted from Chen et al.[36].

Dimensions	**Concepts**
Contextual	Changes in health, social and economic context
Demographic	Restrictions to certain populations Household characteristics Socioeconomic status Gender and race/ethnicity
Technical and home environment	Built environment characteristics Occupancy patterns Purchase behaviour Electricity price

	Changes in other activities
Socio-psychological	Positive and negative emotions Perceived mental and physical impacts Community environmental impacts
Energy policy	National and local policies for helping low income households
Energy infrastructure	Vulnerability of infrastructure systems Direct and indirect loss Infrastructure resilience and recovery

With all this in mind, we can now add to the existing limitations of VoLL calculation methods specifically within the context of an extreme weather events:

- They do not consider the heightened consequences of certain facilities losing their load during the response and recovery phases of a disaster (e.g. where a hospital has a higher than normal patient load, or where loss of load causes compounding effects)
- They do not consider the increased likelihood and duration of power outages during a disaster compared to at other times
- Averaged customer damage functions do not consider the different socio-economic vulnerabilities of different customers which may be further exacerbated during a disaster
- They do not consider the presence of alternative energy sources (e.g. a gas bbq, a wood stove or a diesel generator), an emerging issue as all-electric households become more common, or where bushfire smoke reduces solar output
- They do not consider the community or infrastructure-scale contexts of preparation, vulnerability and support.

An overview of the concept of resilience

Resilience is a concept covered in many different fields. It originated in materials engineering, focused on the ability of a system to recover from an accident which can be improved via anticipation, robustness (or ‘hardening’) against sudden events, and recovery[15]. Under this engineering paradigm, resilience could be quantified as the time the system needs to return to a steady state within a stable domain[37]. For an electricity system or other critical facility, this definition of resilience relates to a network’s ability to recover from a major incident by recommencing services to as many end users as possible and minimising time without the service[2,4]. Notably, it is not concerned with what happens to people (i.e. the human impacts) and the natural environment during the outage. The engineering conception of resilience usually involves a local system and short-term preventative and corrective action[14,37]. Over time, engineers realised that organisational practices were a key cause or contributor to sudden events, and hence that the crossovers between the human and technical worlds were important[15]. As a result, resilience has become an important concept in fields such as risk management and energy security[37].

The resilience concept broadened in the 1970s when it was picked up by ecologists and psychologists. Ecologists viewed resilience over the long term and at a regional scale[37]. An ecological perspective prompted focus on adaptation, as did the psychological view of resilience, which usually relates to the ability of an individual to adapt to adversity[37]. More recent explorations of resilience in the context of engineering also include adaptiveness to unforeseen events[13,14,37]. Restoration of an energy system’s functions following a disturbance could mean a return to previous conditions or transformation into a new desirable system[38].

To help us consider how resilience is different to similar ideas, Nik et al.[14] compares resilience to the associated concepts of stability, reliability, robustness and flexibility (Table 2), finding some overlap but also some key differences. Resilience covers phases like resisting, adapting to, preparing for, and recovering from an extraordinary event[14]. Cainey[4] similarly outlines different approaches to network resilience depending on whether they occur in preparation for or following an event or outage.

Table 2: Relationship between energy system resilience and adjacent concepts [14].

Concept	Similarities with resilience	Sometimes considered part of resilience	Differences to resilience
Stability	Capability to return to equilibrium		Maintaining state of equilibrium
Reliability	Service interruption and energy supply loss	Considering known threats	High probability, low impact scenarios
Robustness	Low probability, high impact scenarios	Resistance to change against extremes	Counting for predictable extremes
Flexibility	Adapting to interruptions and extremes Withstanding disturbances with minimum impact		High probability, low impact scenarios

Because it is unrealistic to design a system that can withstand anything (i.e. robustness), a system should be resilient which means it can quickly restore function after a disturbance[38]. This could mean a return to previous conditions, or transformation into a new desirable system. In the case where energy infrastructure has been destroyed by an event, replacement with more flexible and resilient systems, rather than building back the same, may be a community expectation[39].

Climate risks

Considering the adaptive capacity of an electricity system inevitably brings in the unfolding reality of global climate change. Firstly, unprecedented events become foreseeable using projections of the future climate[14] which means future conditions can be reflected in system design. Secondly, actions taken in the short term to decrease vulnerability should be consistent with actions taken in the long term to mitigate the carbon intensity of energy supply[15]. And thirdly, systems should be able to change. For example, to change individual energy sources should one become unworkable (which could mean change in the moment, or over time), or to change alongside the broader-scale transition from centralised to decentralised generation[38]. These second and third points may raise tensions regarding the role of fossil fuels.

Socio-technical co-production

Resilience can be understood as socio-technical co-production. Technical systems are entangled with the social and economic systems that people rely on for wellbeing, and technical artefacts are the manifestation of political, economic and social activities[40]. Non-technical inputs and social characteristics of energy system resilience include, for example, behavioural change among end users (e.g. towards solar-battery ownership), innovative policy and regulatory support from governments (e.g. the way resiliency is valued and incentivised), new financing models and new business models, political economies of the place systems operate (including the relationship between community vulnerabilities and resilience), and the technical, managerial and entrepreneurial capacities of community members[40].

Resilience is about the futures we want

Resilience involves trade-offs between actors and interests. Often resilience can tend to favour the status quo, those who are already advantaged, or a situation that is socially unjust and/or ecologically unsustainable[41]. As an example, the emergency response, relief and recovery arrangements during the Black Summer disproportionately excluded Aboriginal people and their cultural heritage[42]. At the same time, while some types of ‘stability’ (like historical gender inequality) can be unhelpful and alienating, other types of stability are important, for example having reliable organisations that deliver support in a way that is trusted by the public[15,38]. Because of the presence of these trade-offs and oversights, Harris et al.[41] advocate for *negotiated resilience. Negotiated resilience* means paying attention to the different views about what preparing for, and responding to, an extreme weather event looks like at different scales. Understanding resilience as fundamentally about the type of future people want also broadens out the skill set of the workforce required to build resilience. Truly building resilience in some cases will be about shifting power imbalances and cultural change (as raised in the example of Indigenous experiences of the bushfires). This adds skilled facilitation, mapping power asymmetries and accountability gaps, and community development expertise to the technical expertise usually associated with building resilience.

Box 1: Network perspectives of resilience

Essential Energy recognises the critical role that electricity networks play in overall community resilience and the need to work together with our communities, in both the planning and response phases of extreme events. Specific community resilience activities that Essential Energy is planning to undertake or support during the FY24-29 period include:

- Enhanced community consultation (e.g. through forming links with communities, local governments and first responders) and support (e.g. for community refuge centres, handing out small generators)
- Community awareness (e.g. through expanding the Public Safety Electrical Awareness Plan and related activities such as school visits and attendance at community events) and training (e.g. for community leaders, community organisations and emergency response teams)
- Industry collaboration (e.g. through the links between networks and Resilience NSW, and the Energy Charter #Bettertogether Resilience Working Group)
- Support for initiatives such as the Minderoo NSW Resilient Communities.

In surveys, the majority of Essential Energy customers supported increased resilience, subject to testing before larger sums of money are invested. Essential also asked customers for their views on whether high risk parts of the network should be turned off on extreme fire risk days, to manage the risk of network-initiated bushfires. Responses to this were very mixed. As such, further work is required before any decisions are taken on whether, or how to include this as a control on the Essential Energy network.

The figure below shows the key principles underlying Essential's approach to network resilience; these are from the joint consultation paper[12]. These principles are underpinned by criteria, methods and tools taken from Essential's Risk Framework, supplemented by quantitative modelling to help understand the expected long-term impacts of climate change on the EE network for a range of climate perils including fire, flood, storms (east coast lows) and heatwaves.

Essential Energy already manages for a resilient network through existing network and contingency planning and emergency management arrangements. However, the changing climate plus increasing reliance on networks driven by electrification require enhanced focus and maturity going forward.

Essential Energy's approach to resilience is guided by a number of recent authoritative reviews and publications including:

- The Royal Commission into National Natural Disaster Arrangements[43]
- Infrastructure Australia's publication: A Pathway to Infrastructure Resilience, which includes guidance for both short term actions and transformational change[44]
- The AER note on key issues of network resilience[45]

In 2022 Essential Energy were participants in a joint industry consultation exercise aimed at learning more about stakeholders' views on network resilience. More recently, they commenced a major project to undertake a climate change risk and impact assessment for the Essential network.

The learnings from these various sources have underpinned a range of 'no regrets' investments, more of which will be identified throughout the Regulatory period, as understanding of the effects of climate change and the associated impacts on the Essential network improves.

To support our planning and decision making around network resilience, Essential are developing a Resilience Framework that builds on their Risk Framework (described above) by ensuring additional focus on:

- adaptation
- speedy recovery
- cascading or widespread system effects (including supporting an interconnected system)
- increased levels of uncertainty associated with extreme events
- Essential Energy's role as part of community resilience.

Once finalised, the framework will be integrated into business decision making, in the same way as the Risk Framework.

Dimensions of resilience

Parameterising resilience such that it can be assessed or managed is a difficult task because the concept has its origins in so many different fields[46]. What should be counted or included in an assessment of resilience? The previous section argued that resilience should:

- be designed for future climates
- be consistent with mitigation of climate change (as well as biodiversity loss and other large-scale environmental harms)
- be flexible, and adaptable over time
- encompass social considerations including a diverse, negotiated process of resilience with attention to conflict and interests at multiple scales.

This section will expand this definition to discuss what could/should be included within the scope of an assessment of resilience.

As a starting point, Hamborg et al.[47] argue for the need to identify the entity of which resilience is an attribute. For energy systems, technical and social infrastructures in particular are recognised as being interdependent[48], so resilience is about electricity supply to energy users. In turn, this relies on the persistence of institutions that govern this supply and also public trust and understanding about this supply arrangement.

Specific and general resilience

Resilience can also be differentiated between an entity or system: as either *specified* resilience which is the resilience of a specific part of a system; or *general* resilience which is the generic capacity of a (usually larger, more complex) system to cope with uncertainty and surprise, encompassing adaptive capacity(Table 3) [48]. Specific resilience aligns with first-order observation and single-loop learning, and general resilience aligns with second-order observation and double-loop learning[a,47,48]. However, there is no clear line drawn

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[a] Single-loop learning involves working towards a set outcome, whereas double-loop learning involves questioning and exploring underlying assumptions and could stimulate new goals and outcomes[49].

between the two: ‘specific’ could mean the resilience of a single building, or a microgrid, or something larger. Van der Merwe et al.[48] argue that resilience investments need to be balanced across both specific and general resilience, because effort channelled into developing one kind may reduce the other. This implies that energy system governance should not focus on only one (type of) entity – it should implement or cooperate with measures to improve resilience at different scales.

Social and technical resilience

Both social and technical infrastructure require focus (Table 3). Delina et al.[40] argued that for climate-vulnerable islands (geographical or otherwise), energy system resilience can be achieved by regarding them as sociotechnical assemblages where engineering innovation is co-produced alongside social and institutional shifts.

Non-technical inputs and social characteristics of energy system resiliency include:

- behavioural change among end users (e.g. towards ownership of energy systems, as opposed to being passive recipients)
- innovative policy and regulatory support from governments (e.g. the way resiliency is valued and incentivised)
- new financing models and new business models
- political economies of the place systems operate (including the relationship between community vulnerabilities and resilience)
- technical, managerial and entrepreneurial capacities[40].

A salient example of the importance of institutional settings to resilience was the South Australian 2016 system black event, which was caused by distributed indistinct events and resulted in a major loss of power[50]. The event revealed the difference between the resilience of specific generation assets versus that of the general system, and the subsequent review highlighted the need for technical and institutional changes, both specific and general.

Table 3: Conceptualising and assessing resilience of essential services produced by socio-technical systems[48].

Entity	**Specific System**	**General System**
Risk Type	Specific risk	Novel, unknown risks
Goal	Persist	Cope
Strategy for Technical Infrastructure	Robustness	Flexibility
Strategy for Social Infrastructure	Skills, capabilities, plans	Collective human agency, agility, and volition

Resilience within governance

Governance refers to the processes, systems and actors involved in addressing collective active problems, deal with market failures, and ensure the provision of public goods, as well as making and enforcing rules[51,52]. It is useful to think about institutions of governance at three levels, from highest to lowest:[53]

- **Constitutional**: State or national-level rules that determine what happens at the next level down including who participates and how collective-choice rules are made. Rules at this level change slowly. The National Energy Objective (NEO) and the processes embedded in the market bodies and Energy Security Board (ESB) are examples of constitutional level governance
- **Collective-choice**: The processes and rules around establishing and changing operational systems. For example, specific market rules, safety and planning regulations
- **Operational**: Day-to-day situations and the rules directly affecting them. Rules at this level can change quickly.

These levels describe a nested arrangement whereby groups might produce and consume electricity according to their own rules but are still part of, and accountable to, a regulated grid (multi-level governance)[54].

The preceding discussion suggested that resilience is best served by focus at multiple scales: on both specific and general resilience, as well as social and technical aspects. The changes that the electricity system is currently undergoing provide an opportunity to reconsider and reconfigure governance for the future. Centralised system governance involves a relatively constrained number of actors and tasks are usually handled by a central regulator with clear and established chains of accountability[54]. Decentralisation could increase the number of actors and complexity involved in governance. This could have benefits to resilience, but could likewise be chaotic if institutions do not interact coherently[55].

Governance at the small scale has particular benefits that are not shared by centralised, large-scale governance. It can provide access to local knowledge, create multiple fronts of learning across many groups, and build trust and mutual respect[55,56]. Clearly, based on the previous discussions resilience is well served by these benefits. On the other hand, governance at the large scale can be useful for tackling difficult problems such as corruption, negative forms of discrimination, free riders and strategic behaviour by the wealthy. Imposed regulation at the global scale can ensure overall outcomes, such as reducing greenhouse gas emissions, and avoid gaming or leakage (shifting emissions elsewhere). At the highest level there is also consistency and scale, and hence potential for major investment and innovation[55]. These differences speak to a key challenge of a future, decentralised and resilience energy system, which is to find ways to involve local people without undermining the equity that the large-scale institutions provide.

Governance for resilience is also relevant within an organisation and should also occur at multiple scales:[48]

- At the operational level, focusing on ensuring the day-to-day ability to absorb disturbances
- At the tactical level, focusing on continuous improvement, adaptive risk management and the ability to ‘bounce back better’ should the opportunity arise
- At the strategic level, transforming the organisation towards long-term sustainability in the context of inevitable change and disruption.

In general, governance for resilience needs to be accountable, which means to accept and assign responsibility for addressing the various changes and challenges that are unfolding.

Methods for assessing resilience

Methods for assessing resilience can be either summative, which evaluate existing levels of resilience for external reporting and benchmarking, or formative, which aim to build resilience through the assessment process[48]. Methods need to be connected to choices that can be made by networks, focus on what is important to people and the environment, and be open to public scrutiny.

Summative assessments used standardised indicators for the purpose of comparison and to aggregate toward higher-level reporting of resilience[48]. The AER's VCR process is an example of a summative assessment of reliability. Summative assessments can also be used to assess risk and vulnerability in order to direct investments towards greatest need[14,15]. Efforts to identify parameters of resilience for the purpose of measurement are described and discussed further below.

Formative assessments comprise an ongoing process of seeking and interpreting evidence in order to make sense of current levels of resilience and gain agreement on ways to improve resilience. It is not suitable for compliance auditing. Assessment involves paying attention to what builds, maintains and breaks down resilience; where undesirable resilience should be disrupted; and there desirable resilience can be enhanced[48]. This is achieved by using probes and centring critical conversations among important actors[48].

In both summative and formative assessment methods, the existing strengths and embedded knowledge in networks' asset planning can be built upon. What is missing is an AER incentive pathway and methods that encompass the human focus, complexities and timescales of resilience.

Within a method for assessing resilience, various metrics are likely to be useful. The preceding discussion has emphasised the importance of multiple aspects when considering resilience: focus on the impacts on people, social/institutional and technical resilience, specific and general resilience, and with consideration of the future and the ability to adapt over time. Several authors argue for both qualitative and quantitative approaches: qualitative assessment based on conceptual frameworks and semi-quantitative indices, and quantitative assessment using probabilistic and deterministic metrics as well as modelling[38,57]. We suggest that a single metric cannot serve a multifaceted, context-specific goal such as resilience.

Parameters or characteristics of resilience

Any assessment of resilience needs to take care not to leave important aspects out. In this section, we identify generalisable parameters or characteristics of resilience in order to prompt thinking. Walker et al.[46] broke resilience down into component parts while also accounting for the types of complexity we have discussed in this report. They described the four components of resilience as follows:

- **Latitude**, the amount the system can be changed before crossing a threshold which, if breached, makes its ability to recover to a favourable state impossible or difficult
- **Resistance**, the ease or difficulty of changing the system
- **Precariousness**, the trajectory of the system and the distance between the system and the threshold
- **Panarchy**, how the three aspects above are influenced by systems at scales above or subsystems below the scale of interest.

For energy systems, these concepts are applicable across institutions and infrastructures. Resistance is of particular interest to institutional governance of resilience because post-colonial institutions have undergone relatively short periods of co-evolution and co-production, which means that appropriate feedback controls are not in place, and crossing a threshold is more likely[46]. On the other hand, hegemonic structures such as the economic principles of the energy market may be difficult to change, causing resistance. Panarchy is also relevant to governance because it encompasses scale (for example, a microgrid versus the entire NEM) as well as multiple or nested centres of governance. The rules which govern a microgrid while it is disconnected from the main grid could influence latitude, resistance and precariousness at that smaller scale.

Delina et al.[40] identify characteristics of resilient island energy systems:

- **As a system condition**: Responsive to specific vulnerabilities, powered by locally available fuels, demand-responsive, sustainable and renewable fuels, independent, modular and flexible, self-organised, diversified, appropriate technologies and affordable
- **As a set of processes**: Adaptable and resourceful, change and uncertainty welcoming, equitable, trusted and accountable end-users, inclusive and participatory processes, deliberative, collaborative and collective processes, and reflexive and local knowledge integrative
- **As a set of outcomes**: Reliable systems, robust systems, strong systems, radically transformed systems, optimistic end-users, positively adapted end-users, motivated end-users, increased equity, and improved well-being.

Drawing on conceptualisations of resilience from multiple disciplines (but especially ecology), Molyneaux et al.[37] identify the properties required for adaptation as redundancy (spare capital), efficiency (the strength of internal connections that mediate/regulate) and diversity (presence of alternatives). Efficiency (in the evolutionary sense of being specialised) can be in tension with the other two. They argue that one needs to understand the levels of redundancy, efficiency and diversity required for adaptation, and use those levels to indicate the resilience or vulnerability of a system.

Local and international examples

Joint DNSPs Collaboration

A collaborative project by the ACT, NSW, Tasmania and NT distribution networks[12] sought to find how they could best support communities in the context of extreme and changing climatic conditions, focusing specifically on what happens to their customers during MEDs or ‘bad days’. The networks propose to change their existing planning practices to better suit future conditions by developing a common risk assessment framework that brings in climate modelling. They proposed resilience metrics based on the calculation of net economic benefits based on forecast cost versus monetised value of risk over the life of the asset.

However, they also note that, despite the failed AER WALDO process, there is still merit in a standard method for valuing resilience. The networks note that safety and health impacts could be reflected in monetary terms using the Value of Statistical Life (VoSL) and Value of Statistical Life Year (VoSLY)[12].

Business case approaches

CutlerMerz[5] evaluated the business case for network investment in resilience-based stand alone power supplies for four case studies, including one islandable system, using cost benefit analysis. They found that systems were generally not feasible, but could be depending on locational characteristics such as remoteness, small population size or an old or unreliable existing power supply. In addition, locations with high assumed frequency of events like bushfires tended to be more feasible. The resilience benefit was quantified as ‘avoided bushfire unserved energy’ and ‘avoided bushfire line rebuild’. In practice, however, the lack of an agreed approach for WALDOs, nor for assigning probabilities to the frequency of occurrence of events, makes the business case methodology difficult to apply.

Anderson et al[58] sought to quantify the magnitude and value of energy resilience provided by renewable energy hybrid systems at the scale of a building or campus. Taking a bottom-up approach, they defined the magnitude as the time that the critical load is served during an outage and used an assumed VoLL. The value of resiliency was calculated as the assumed VoLL multiplied by the average critical load (in kW) served during the outage period. The presence of solar and storage increased the probability that the critical load would be served through the outage when compared to a diesel-only system. The authors then incorporated the calculated value of resiliency into the lifecycle cost of the hybrid system in order to justify the additional capital cost of installing solar and storage. Finally, they proposed that the value of resilience could be monetised via insurance premium discounts.

California Public Utilities Commission (CPUC) four pillars

The CPUC method, which is currently being developed, is a formative assessment method. CPUC developed a 'four pillar' method for optimising grid investments to maximise resilience with regard to climate change, equity disparity and interdependencies between critical infrastructure systems[18]. They consider resilience in terms of impacts to people, as opposed to reliability which measures impacts to systems. Furthermore, the assessment method treats each hazard separately which some scholars argue is necessary for resilience[38]. The pillars are a process of resilience valuation comprising four steps (Table 4).

Table 4: CPUC Four pillars resiliency valuation approach.

I Baseline assessment	Define area of study and load tiers (critical, priority, discretionary) Identify resilience targets per tier and define hazards Assess resilience when disrupted by each hazard, identify deficits and priorities
II Mitigation measure assessment	Identify mitigation options Assess ability of each option to meet resilience targets per hazard and compare costs
III Resiliency "scorecard"	Yet to be developed, but suggested as a weighting method for a basic benchmark of achievement. Envisaged as for comparison only
IV Resiliency response assessment	Based on modelling, or after a real disruption Conduct I Baseline assessment again Annual data collection of metrics after chosen option is implemented Assess achievement of targets and changes in community impacts

More so than a method for valuing resilience, CPUC's four pillar method is a framework for assessing and evaluating resilience which includes appropriate metrics defined case by case. These are not limited to energy but also include social, economic and environmental impacts, and impacts to other infrastructures. CPUS identified a range of potential metrics for defining and evaluating resilience targets, including[18]:

- Including MEDs in reliability performance indicators, and implementing them at a more geographically precise level, to compare with overall indicators and reveal more about individual customers' experiences
- Islanded microgrid performance, circuit by circuit, looking at energy served, how curtailment was chosen and carried out in practice, cause of outage, and number/duration/regularity of outages
- Community data including number of customers of different types, LGAs affected, income of affected people, use of food banks, VoLL and business losses, and non-participants of microgrids using microgrid services
- Community outage impact data including number of customers, critical facilities, community resource centres, and emergency services without power or served by a microgrid
- Energy and community infrastructure data
- Costs for mitigation measures.

Sandia proposal: A performance-based resilience metric

Vugrin et al.[59] recommend that the resilience of a given power system to a specific hazard should be measured in terms of the consequences that will result if and when the hazard occurs, using consequence categories. The consequence categories and metrics should be selected based on their relevance to the utility, community, regulatory or other stakeholder involved in decision-making. The estimation of consequences should, where possible, be expressed statistically (including uncertainty, maximum consequence, probability etc) and in a metric unit (energy, time, money etc) that reflects the risk perspective of the decision-maker. For example, a consequence might be the magnitude of the outage, measured by the cumulative daily power outages in customer-days. The target might then be a certain number of customer-days. As a second example, the community impact measured by the number of specified emergency service assets without power for more than a given number of hours. The target might be met if zero hospitals, police stations and fire stations are without power for more than the given number of hours.

The resilience analysis process proposed by the authors (Figure 1) is similar to CPUC's four pillar approach[59].

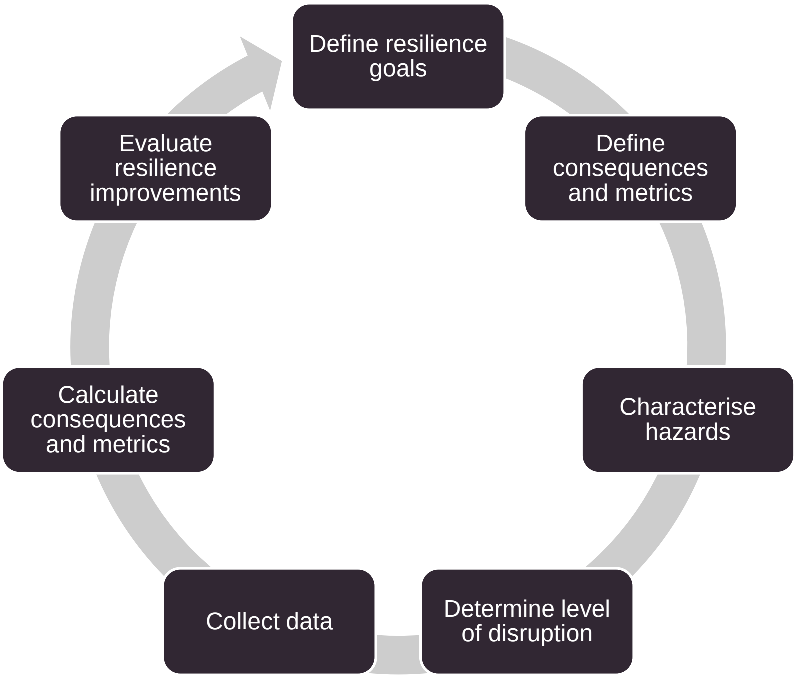

Figure 1: Vugrin et al. resilience analysis process[59].

Backcasting resilient energy futures

Kishita et al[31] were interested in designing scenarios of future resilience using backcasting. Backcasting is used to consider long term circumstances, for example, the reduction of greenhouse gas emissions needed to avert the worst consequences of climate change and the long lifespan of energy infrastructure. Resilient energy futures are fundamentally different to approaches aimed at achieving economic efficiency or environmental sustainability because they are focused on providing and maintaining sufficient services to people in the case where external shocks such as extreme weather events bring about the failure of the energy system[31]. The method uses fault tree analysis (FTA).

The authors sought to articulate a method for backcasting that accommodates different forms of knowledge. They defined the process in four steps (Table 5).

Table 5: Scenario design process for resilient futures[31].

Step 1: Preparation. Clarify the purpose of the scenario design, temporal and spatial boundaries, and constraints. Recruit participants to be involved in scenario design.
Step 2: Describing collapse futures. Delineate collapse future visions and pathways, so that resilient futures and pathways may be sought. Starting with an undesired event, participants work backwards determining its causes (and the causes of those causes). This FTA should clarify the relationship between the undesired event and its causal events. Participants review the scenario and its narratives and modify where necessary.

Step 3: Describing resilient futures. Participant's general countermeasures to overcome the risk factors identified in step 2. Describe the narrative story of resilient visions, review and modify as before.

Step 4: Describing pathways to the resilient visions. The participants prioritise countermeasures and place them on a timeline of when they should be taken. Describe the narrative story of pathways to connect the resilient future visions and the present. Review and modify.

Prescriptive performance standards

The UK regulator Ofgem has in place severe weather performance standards that require utilities to restore supply within set timescales depending on the severity of the event. The incentives are significant due to the level of compensation, but they are focused on rapid recovery rather than the capability to withstand major weather events[4].

Finland do not exclude severe weather events from reliability incentives, and require that service interruptions caused by storms or snowfall must not exceed six hours in urban areas, or 36 hours in other areas[4].

Cainey[4] suggests new performance standards and incentives for resilience that should apply on MEDs, such as time taken to reconnect x% customers—'CR-90' (reconnection of 90% of customers) being a standard used in some US states.

Wu and Sansavini[60] presented a model for optimising to techno-economic, resilience and reliability objectives. Their definition of resilience was the ability to anticipate, absorb and recover from extreme events with long durations, with active change in grid operation to mitigate impacts of the event. Islanding events were modelled stochastically with uncertain starting time and duration, without load shedding, and ramping up distributed energy resources (DER) to supply all loads (as well as other constraints). Recovery was modelled with the cost of buying back depleted stored energy. Ultimately, however, reliability and resilience results were reported using SAIFI, SAIDI and ENS.

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