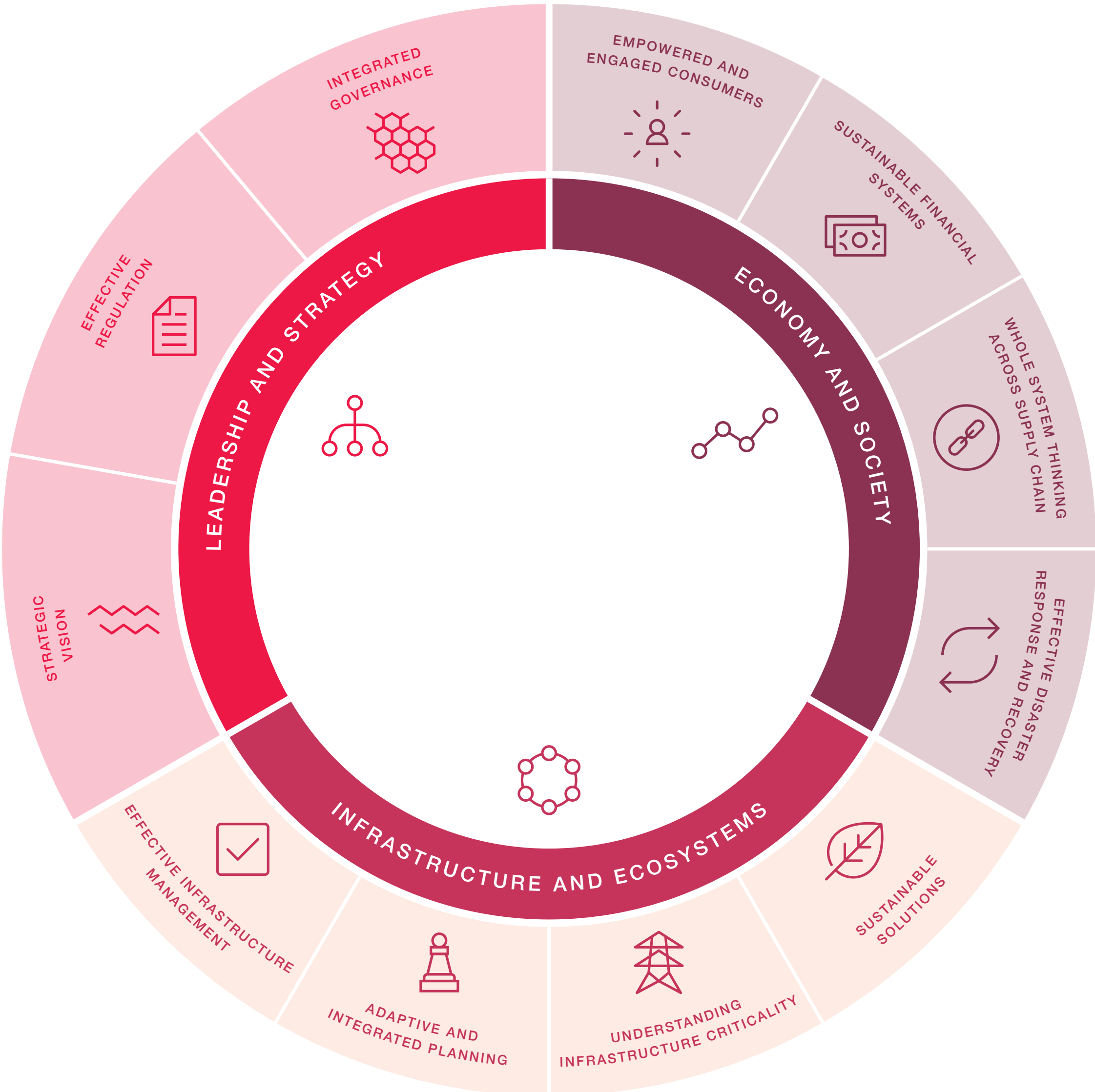
ARUP

ENERGY RESILIENCE IN AN INTERCONNECTED WORLD

Future-proofing energy systems: The Energy Resilience Framework



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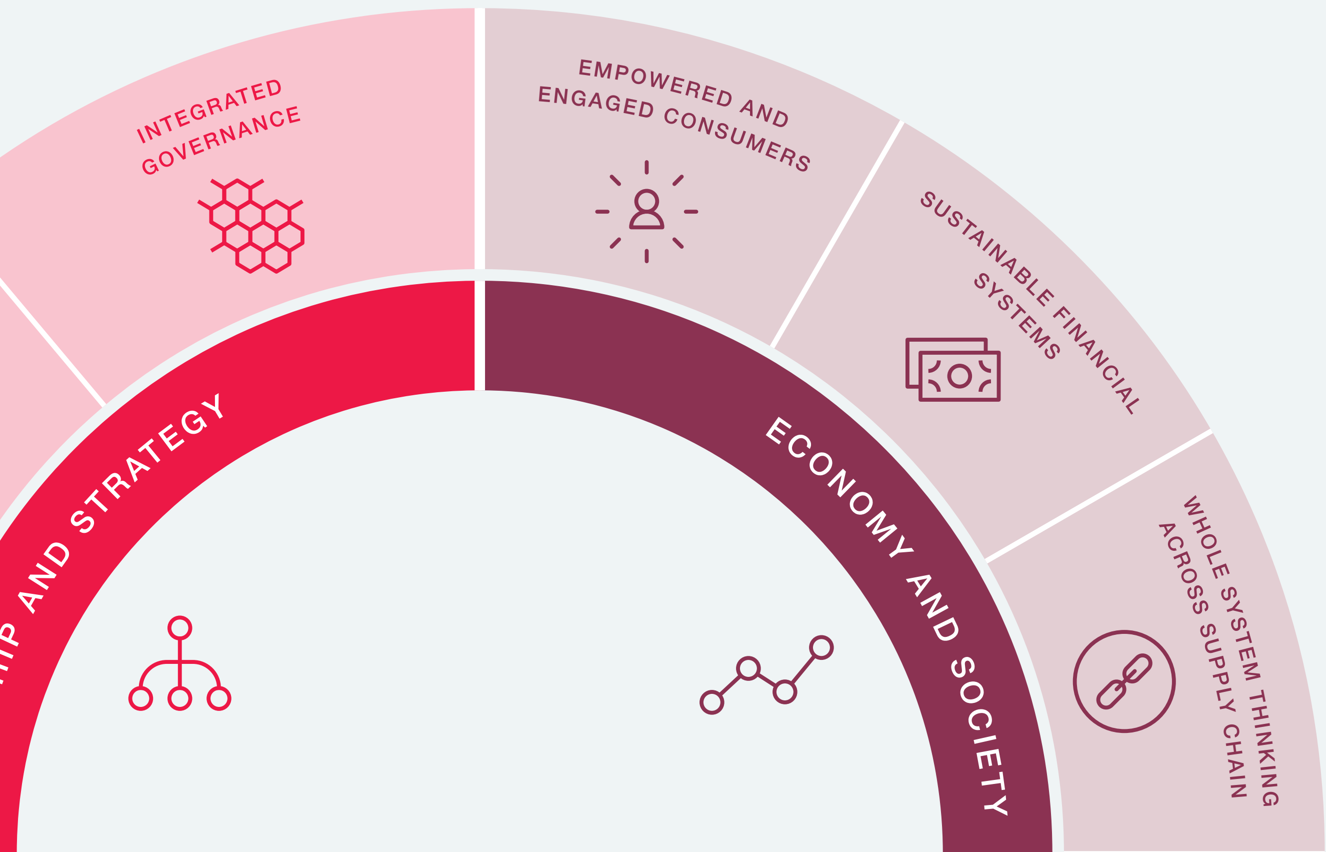
In an evolving, connected and interdependent society, secure and resilient energy provision is critical.

The events which challenge consistent energy provision are becoming more prolific, wide-ranging, and of greater magnitude. What's more, the context for energy provision globally is changing rapidly.

There is no 'silver bullet' to a resilient energy system, it requires consideration of and response to a wide range of technical and non-technical factors.

The Arup Energy Resilience Framework allows stakeholders working within energy systems to set the context for considered evaluation and provision to ensure greater resilience in an evolving landscape where energy is a critical part of a wider ecosystem.



ENERGY SYSTEM RESILIENCE IN AN EVOLVING LANDSCAPE

Framing a multifactorial approach to resilient energy

Supply and delivery of energy across our built environment is evolving. Over-provision and substantial redundancy is being replaced by a fine-tuned, dynamic and highly interactive approach as we journey towards reduced emissions, minimised costs and increased certainty.

Energy demand is no longer a passive end-point in a chain of energy supply - it is a dynamic, interactive part of an increasingly complex, interdependent and interactive whole system.

Boundaries between energy, mobility, water and digitalisation are increasingly blurred. Commercial, technical and human interactions mean that the impact from an event in one sphere rapidly and often automatically cascades to the others, then feeds back to further stress the first.

POTENTIAL DISRUPTORS

The spectrum of events challenging resilience is also changing. Extreme climatic events such as tornadoes, dry weather fires and flooding not only exercise our energy systems, but also those systems and societal strength on which secure energy provision depends. Increased reliance on digititalisation introduces new risks of inadvertent or intentional events such as a cyber attack.

Regulatory and commercial models are rightly pushing new boundaries in the quest for ever higher value but moving from the ‘tried and tested’ can also attract unintended resilience consequences.

Ironically, as our energy systems are becoming increasingly automated, the human factors on which they are founded become more important. This includes strategic leadership and direction, clarity of vision, avoidance of groupthink, training, stakeholder engagement and strong governance.

OUTLINING RESILIENCE FACTORS

Building upon mature multifactorial resilience frameworks developed by Arup, including the City Resilience Index and the City Water Resilience Approach, we have developed the Energy Resilience Framework. This is intended to rebalance and emphasise the importance of non-technical factors on overall energy system resilience.

Drawing together three dimensions underpinned by 11 goals and 66 indicators, we bring renewed scrutiny to ensure that resilience evaluation and preparation encompasses leadership and strategy, economic and societal value as well as the physical infrastructure and its ecosystems.

This framework ensures that necessary weighting and attention is given to both technical and non-technical issues, particularly recognising that historical energy system failures manifest as having a technical cause, but often the underlying cause is non-technical.

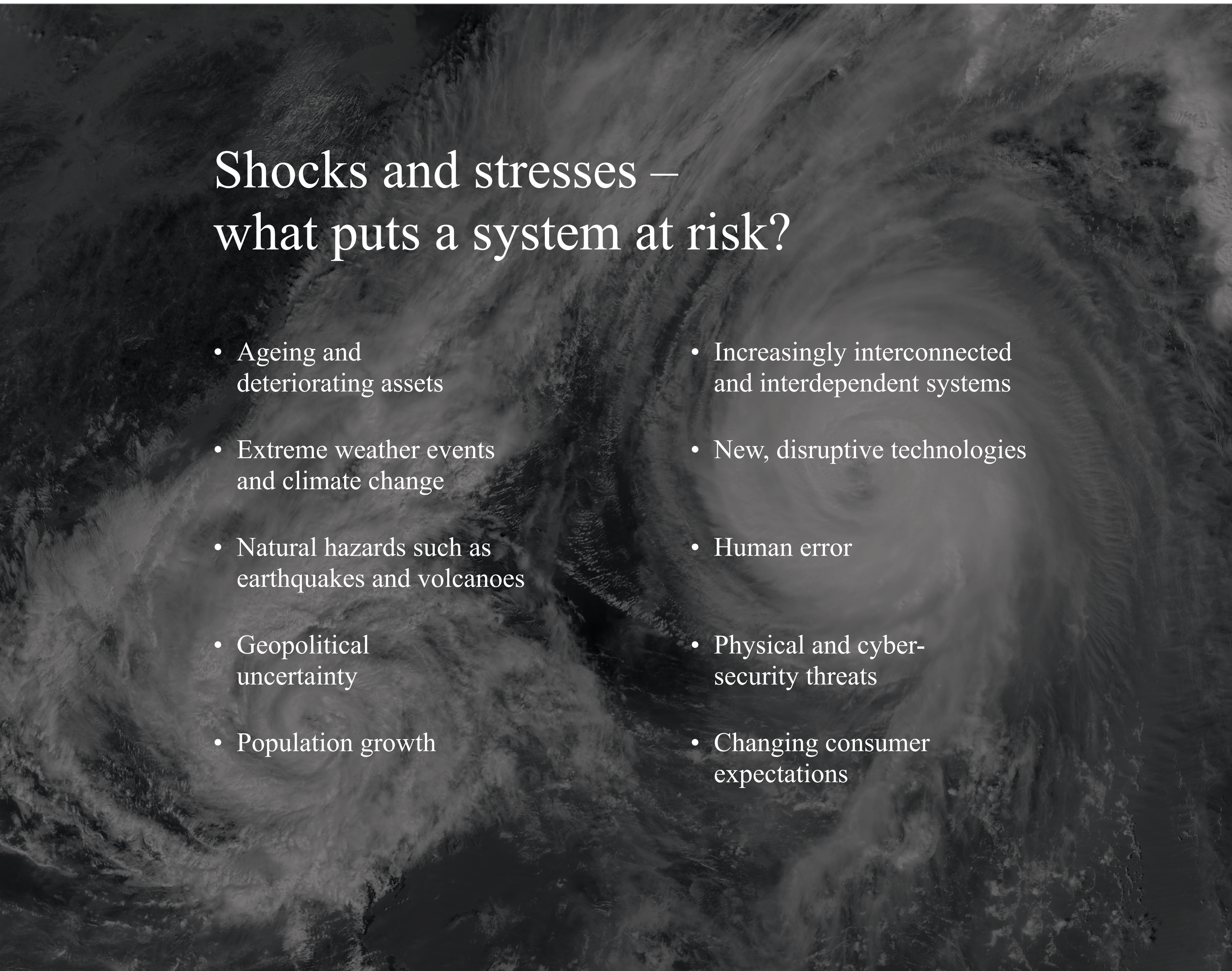
ALAN THOMSON
Global Energy Systems Leader

Understanding energy resilience

WHAT IS ENERGY RESILIENCE?

Resilience in an energy system can be defined as its ability to reduce the impact of shocks and stresses, including the capacity to anticipate, absorb, adapt to, and rapidly recover from such events and to transform where necessary.

Resilience must consider social, technical and organisational components. Our framework evaluates the resilience of a system not only by considering physical assets but also by acknowledging the equal importance of leadership, policies, institutions and social factors.



Shocks and stresses – what puts a system at risk?

- Ageing and deteriorating assets
- Extreme weather events and climate change
- Natural hazards such as earthquakes and volcanoes
- Geopolitical uncertainty
- Population growth
- Increasingly interconnected and interdependent systems
- New, disruptive technologies
- Human error
- Physical and cyber-security threats
- Changing consumer expectations

IDENTIFY CHALLENGES AND OPPORTUNITIES

Applying the energy resilience framework helps private and public organisations achieve a safer and more secure energy supply, and meet the ambitious targets for the coming decades.

What is the Energy Resilience Framework?

In our increasingly interconnected world, communities, businesses, industry and infrastructure systems all rely on energy. Without it, we could not keep trains moving, the lights on, data servers running and water supply flowing. It is essential energy systems continue to function under both natural and man-made pressures.

Devised by Arup, the Energy Resilience Framework (ERF) is a tool to help energy system owners, as well as operators, generators, consumers, investors and regulators, assess how resilient a business and energy system is to challenges ranging from climate change to digital disruption. Operators can use the framework to identify how to become more resilient, assessing their business against the indicators.

The framework can diagnose – for any energy system – where resilience performance meets best practice, and where challenges and opportunities for improvement lie. It also enables system managers to prepare for the coming decades.

FACTORS INCLUDED IN THE FRAMEWORK

Technical	Financial	Organisational	Social
Planning *Design* *Delivery* *Operation* *Maintenance*		*Regulations* *Governance* *Decision making*	

The framework draws heavily on our expertise in resilience in the built environment. This includes the City Resilience Index (CRI), which we developed with support from the Rockefeller Foundation, and the City Water Resilience approach, developed in collaboration with the Rockefeller Foundation and the Resilience Shift.

Applying this to your organisation

WHO IS THE FRAMEWORK FOR?

The framework can be used by any decision maker across the energy value chain across the world. From governments, regulators, generators, customers, owners, investors, transmission and distribution companies.

Its flexibility and range means it can be applied to different scales of energy systems. For example, it works as well for a single facility, city energy network or national energy system. And it can also be used for components of these systems, including generation assets or regulations.

The assessment of 'what matters' produced by the framework informs decisions about policy, regulation, industrial standards and investments. Individual organisations can use the tool to improve their own resilience and to define and prioritise actions.

While no single organisation can improve in every aspect of the framework, its use will ensure their decisions recognise dependencies on other actors in the wider system. Some organisations – such as government, regulators, system operators – can influence many elements of this framework, and the importance of their role in energy system resilience should always be considered.

Energy supply can't be separated from other infrastructure systems that depend on it, nor from the individuals and communities rapidly affected by any disruption or failures of the energy system. This is why the framework is intentionally broad in scope, allowing users to 'step back' and consider all determinants of a resilient energy system, before focussing on specific indicators of resilience. It is also designed to highlight interdependencies which might not be apparent on the surface.

"Arup's Energy Resilience Framework can diagnose – for any energy system – where resilience performance meets best practice, and where challenges and opportunities for improvement lie. It can be uses to consider how to improve resilience and define and prioritise actions. Through a thorough consideration of social, technical and organisational factors, any energy system – anywhere – can gain the resilience it needs to best serve society."

—Alan Thomson, Arup

The seven qualities of resilient systems

FUTURE PROOFING FOR RELIABILITY

What is it that enables resilient systems to withstand, respond and adapt more readily to shocks and stresses? We have defined seven qualities that are either important in preventing the breakdown or failure of a system, or for enabling the right action to be taken at the right time. Hazard agnostic, these qualities are a useful reference point for deciding on specific actions: Do the actions enhance one or more of these qualities?

1 **REFLECTIVE**
Ability to understand the impact of internal and external conditions on assets.

2 **FLEXIBLE**
Can adapt to changing circumstances and deliver energy via various pathways.

3 **INTEGRATED**
Essential for optimising efficiency and performance of multi-vector systems.

4 **ROBUST**
Built on well designed, constructed and managed physical infrastructure.

5 **RESOURCEFUL**
Having a range of resources and infrastructure to meet critical demand.

6 **REDUNDANCY**
Spare capacity or duplicated infrastructure to accommodate disruption.

7 **INCLUSIVE**
The need for broad consultation and engagement of energy users.

REFLECTIVE

Reflective energy systems are able to understand the impact of internal and external conditions on assets, the supply chain and consumption patterns by learning from past experiences through human or digital monitoring. This understanding can assist decision making and enable energy systems to adapt to uncertainty and change in the energy supply chain, such as modifying standards or norms in response to emerging technologies.

FLEXIBLE

A *flexible* energy system can adapt to changing circumstances, as well as deliver energy to end users via various pathways. A multi-vector energy system is inherently flexible owing to its range of energy sources. Decentralised and modular approaches to infrastructure (e.g. microgrids) can also enhance flexibility. Flexibility can also be achieved by using traditional technologies in new ways, and through the way the system is managed.

INTEGRATED

Integration is essential for energy systems, particularly for optimising the efficiency and performance of multi-vector energy systems. Aligning different energy vectors promotes consistent decision making and ensures that investment in infrastructure supports a common outcome. Exchanging information and energy among different energy vectors can foster integration that enables rapid response to and recovery from disruptive events.

ROBUST

Robust energy systems are built on well-designed, constructed and managed physical infrastructure. This enables them to withstand hazardous events without significant damage or loss of function. Robust design anticipates potential failures of infrastructure in the energy supply chain and adopts design thresholds to minimise the risk of infrastructure collapsing catastrophically.

RESOURCEFUL

Resourcefulness means that energy system planners and operators have a range of energy resources and infrastructure at their disposal to meet demand in times of shock or stress. This may include investing in infrastructure across energy vectors based on anticipated future conditions. It may also include the capability to mobilise and coordinate wider human, financial and physical resources to respond rapidly (e.g. mobilising back-up generators during a crisis).

REDUNDANCY

Redundancy refers to spare capacity or duplicated infrastructure within energy systems so they can accommodate disruption, extreme pressures or surges in demand. Systems with redundancy can normally tolerate some infrastructure failures without it affecting their overall function. This may include interconnection to external systems (e.g. country-to-country electricity interconnection), as well as duplication of assets (e.g. dual-circuit transmission lines). Redundancies should be intentional, cost-effective and prioritised in each energy vector as well as at a whole-system level.

INCLUSIVE

Inclusivity emphasises the need for broad consultation and engagement of energy users, including vulnerable users such as those in fuel poverty. An inclusive approach contributes to a sense of shared ownership or a joint vision to build energy system resilience. Because energy is increasingly a global issue, this inclusivity needs to be developed on a national and international level.

Seven steps to achieve energy resilience

DE-RISKING ENERGY SYSTEMS

Define the system

Energy systems are complex, so it is important to define boundaries and the scope – whether that is a country, a city or a group of assets. Then identify the interdependencies of the system to understand the potential causes and consequences of a system failure.

Engage with stakeholders

A core team needs to engage with stakeholders to gather the background data needed to model and assess the resilience of the system. As a minimum, the interdependencies between key stakeholders should be identified.

Model the system

Create a multi-level model of the system – including assets, the causes and the consequences of possible failures, and their relative criticality. The level of detail in the model will depend on the complexity of the system, the purpose of the assessment and the budget available.

Assess energy resilience

Analyse the model and gather data, following the Energy Resilience Framework, to provide a qualitative indication of the system's resilience and identify areas for improvement. For a more useful output, the assessment should be validated by key stakeholders.

Develop an action plan

Interpret the assessment results to identify improvement actions. Consider their effectiveness and the predefined risk appetite to prioritise these actions and reach agreement on a plan.

Implement the action plan

Roll out the action plan by establishing a team to manage the implementation, and by tracking the baseline. This will increase the likelihood of realising the desired benefits.

Evaluate, learn and adapt

Evaluate the resilience measures, using this evaluation and stakeholders' input to identify changes. Reassess objectives for the next improvement period.

The Energy Resilience Framework

ESTABLISHING KEY IMPROVEMENTS

The framework uses three dimensions to analyse resilience.

LEADERSHIP AND STRATEGY

The alignment of policy, practices, and informed decision making within and between public and private sector organisations. This ensures the stability and sustainability of the energy supply, especially to support critical services such as healthcare.

ECONOMY AND SOCIETY

The social and economic systems that enable the formation and operation of energy systems and connect their function to economic and social outcomes.

INFRASTRUCTURE AND ECOSYSTEMS

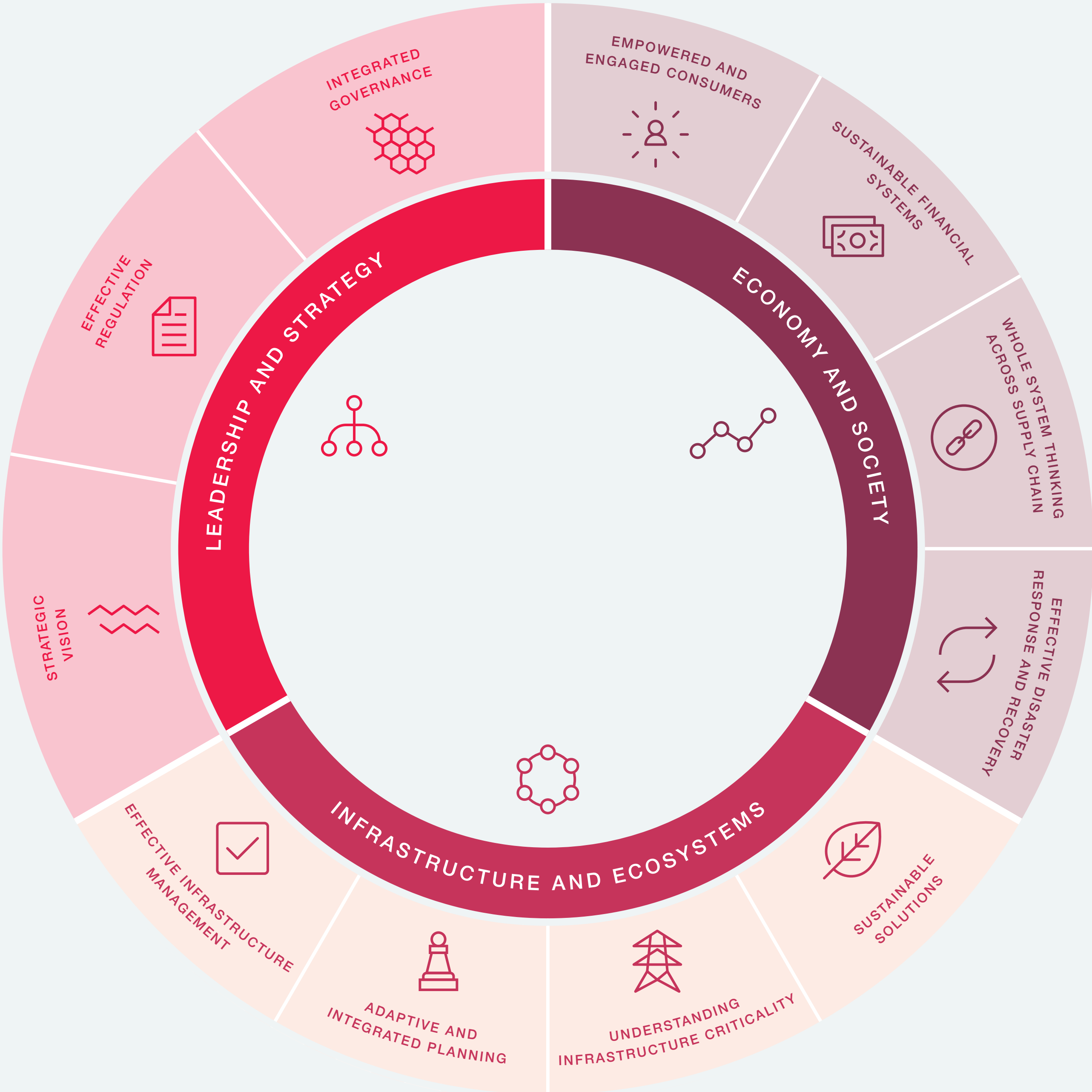
The quality of the built and natural systems that enables energy transformation and ensures supply to end users.

11 goals

Each of these three dimensions has proposed goals, which define what is needed to achieve energy system resilience. The relative importance of each goal will be different for different systems and sub-systems.

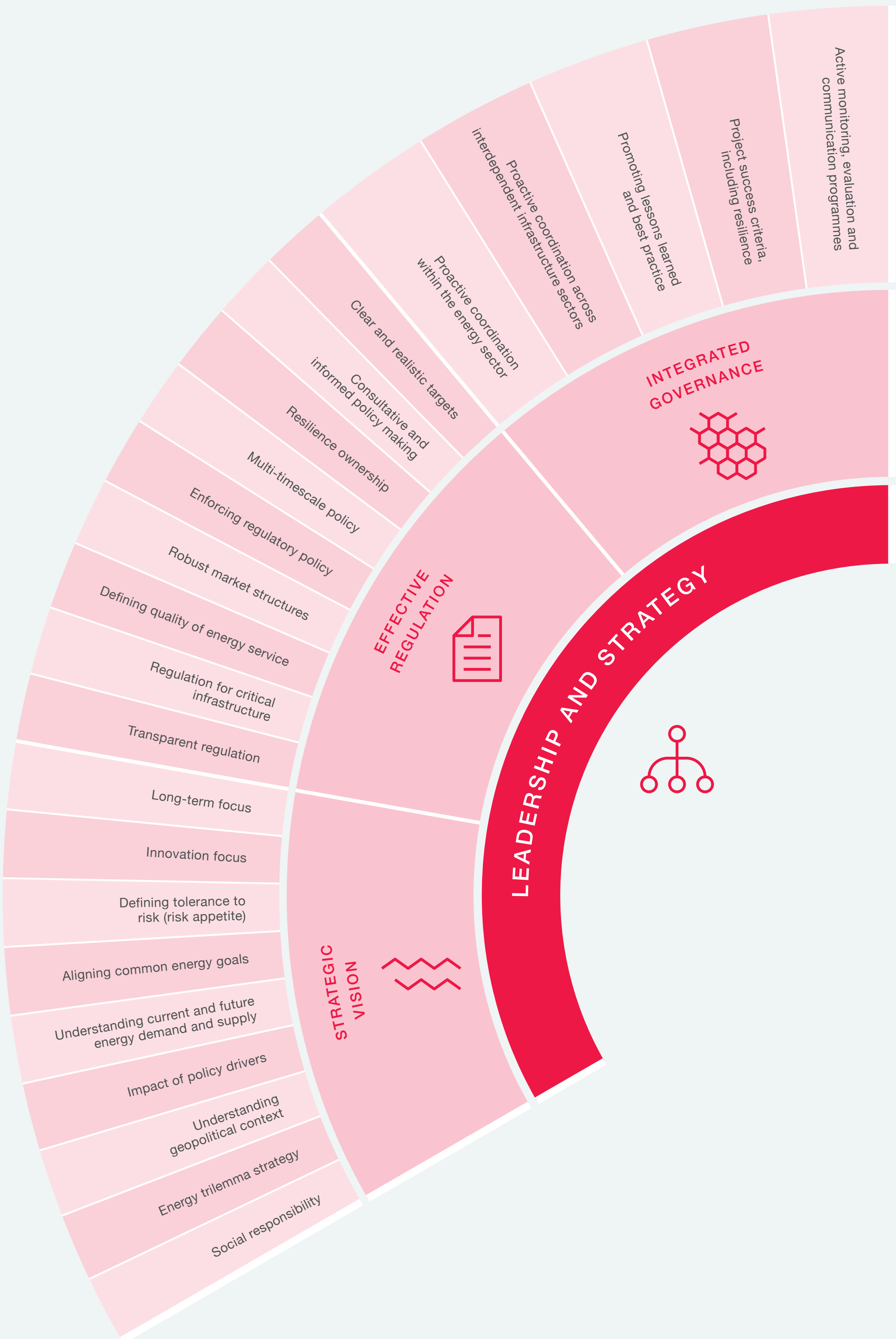
66 indicators

We have identified 66 indicators that add further definition to the goals and indicate the critical factors that contribute towards energy resilience. Some indicators are relevant to more than one goal but are applied in different ways (e.g. defining vs implementing).


LEADERSHIP AND STRATEGY
ECONOMY AND SOCIETY
INFRASTRUCTURE AND ECOSYSTEMS
INTEGRATED GOVERNANCE
EFFECTIVE REGULATION
STRATEGIC VISION
EMPOWERED AND ENGAGED CONSUMERS
SUSTAINABLE FINANCIAL SYSTEMS
WHOLE SYSTEM THINKING ACROSS SUPPLY CHAIN
EFFECTIVE DISASTER RESPONSE AND RECOVERY
SUSTAINABLE SOLUTIONS
UNDERSTANDING INFRASTRUCTURE CRITICALITY
ADAPTIVE AND INTEGRATED PLANNING
EFFECTIVE INFRASTRUCTURE MANAGEMENT

Leadership and strategy

Achieving energy resilience requires effective leadership with a clear strategic vision, enforced by effective regulation. This requires inclusive governance involving government, regulators, planners, network owners and operators.



LEADERSHIP AND STRATEGY
STRATEGIC VISION
EFFECTIVE REGULATION
INTEGRATED GOVERNANCE
Social responsibility
Energy trilemma strategy
Understanding geopolitical context
Impact of policy drivers
Understanding current and future energy demand and supply
Aligning common energy goals
Defining tolerance to risk (risk appetite)
Innovation focus
Long-term focus
Transparent regulation
Regulation for critical infrastructure
Defining quality of energy service
Robust market structures
Enforcing regulatory policy
Multi-timescale policy
Resilience ownership
Consultative and informed policy making
Clear and realistic targets
Proactive coordination within the energy sector
Proactive coordination across interdependent infrastructure sectors
Promoting lessons learned and best practice
Project success criteria, including resilience
Active monitoring, evaluation and communication programmes

Goal

STRATEGIC VISION

Choices must be made about how to sustain supply and reduce the potential for disruption. Decisions on how to balance resilience and affordability must be constantly reviewed to factor in new challenges and opportunities. Energy stakeholders must work closely together to set common goals.

1 – Long-term focus: an established shared vision to guide resilience programmes, taking into consideration the expected evolution of the energy sector including new and emerging shocks and stresses.

2 – Innovation focus: a predisposition to explore alternative ways to tackle challenges and respond to the unexpected.

3 – Defining tolerance to risk (risk appetite): a clear understanding of the impacts and uncertainty levels that stakeholders will tolerate, and where these risks best sit, is fundamental to defining investment and improvement programmes.

4 – Aligning common energy goals: to provide clarity across the industry about priorities and guidance on prioritising investment.

5 – Understanding current and future energy demand and supply: monitoring energy supply and demand trends and data-driven forecasts of energy consumption.

6 – Impact of policy drivers: policy requirements could temporarily reduce the flexibility of the system and require specific, constrained actions e.g. decarbonisation.

7 – Understanding geopolitical context: understanding energy reliance between nations to inform decision making and maintain maximum policy freedom.

8 – Energy trilemma strategy: clear guidelines to ensure energy security and the expected level of compromise on affordability and sustainability.

9 – Social responsibility: the system collaborators awareness of their business/ infrastructure's role in enabling local communities to survive and thrive.

Goal

INTEGRATED GOVERNANCE

To succeed, programmes that address the standard of energy supply (e.g. stability, quality, sustainability, affordability) require bodies to align their policies, practices and decision making.

1 – Active monitoring, evaluation and communication of programmes: understanding external or internal programmes that could affect the resilience of the energy system, identifying opportunities for collaboration and avoiding gaps and/or duplication of efforts.

2 – Project success criteria, including resilience: criteria for evaluating projects' business cases to consider the total value contribution of the project, including resilience.

3 – Promoting lessons learned and best practice: mechanisms and culture in place for identifying and communicating energy resilience best practice across the supply chain.

4 – Proactive coordination across interdependent infrastructure sectors: inclusive and coordinated collaboration between government, academia, regulators, planners, owners and operators across urban systems e.g. regulators, utilities, energy transmission, transport operators and emergency services.

5 – Proactive coordination within the energy sector: inclusive and coordinated collaboration between government, academia, regulators, planners, owners and operators within the energy sector e.g. generation, transmission and distribution.

Goal

EFFECTIVE REGULATION

Energy regulations set out rules for users of the energy networks while providing guidelines to shape and manage urban systems. They are also essential for safeguarding the public and users' interests. Clear directives for balancing the trilemma (energy security, sustainability and affordability) are needed to ensure energy systems improve, longer term goals are set, and the system is resilient. Similarly, mechanisms for enforcing these guidelines are paramount for an effective regulatory framework that fosters resilient energy systems.

1 – Clear and realistic targets: expected benefits, objectives and key performance indicators as well as clear positioning on wider political, regulatory or policy commitments e.g. climate change agreements and emissions targets.

2 – Consultative and informed policy making: based on feedback from the industry and consumers, lessons learned and awareness of strategic opportunities and constraints e.g. geopolitical context.

3 – Resilience ownership: identifying and communicating the roles, responsibilities and interfaces among energy stakeholders – including responsibility for providing resilience to a system with a focus on protecting vulnerable users.

4 – Multi-timescale policy: clear separation between short, medium and long-term objectives, with sufficient flexibility to enable efficient delivery, and the difference between goals and practical implementation.

5 – Enforcing regulatory policy: designing mechanisms to monitor, implement and adapt the defined regulatory framework, and ensure efficient, realistic performance.

6 – Robust market structures: implementing strategy to stimulate investment that builds resilience and is aligned with priorities e.g. decarbonisation, decentralisation.

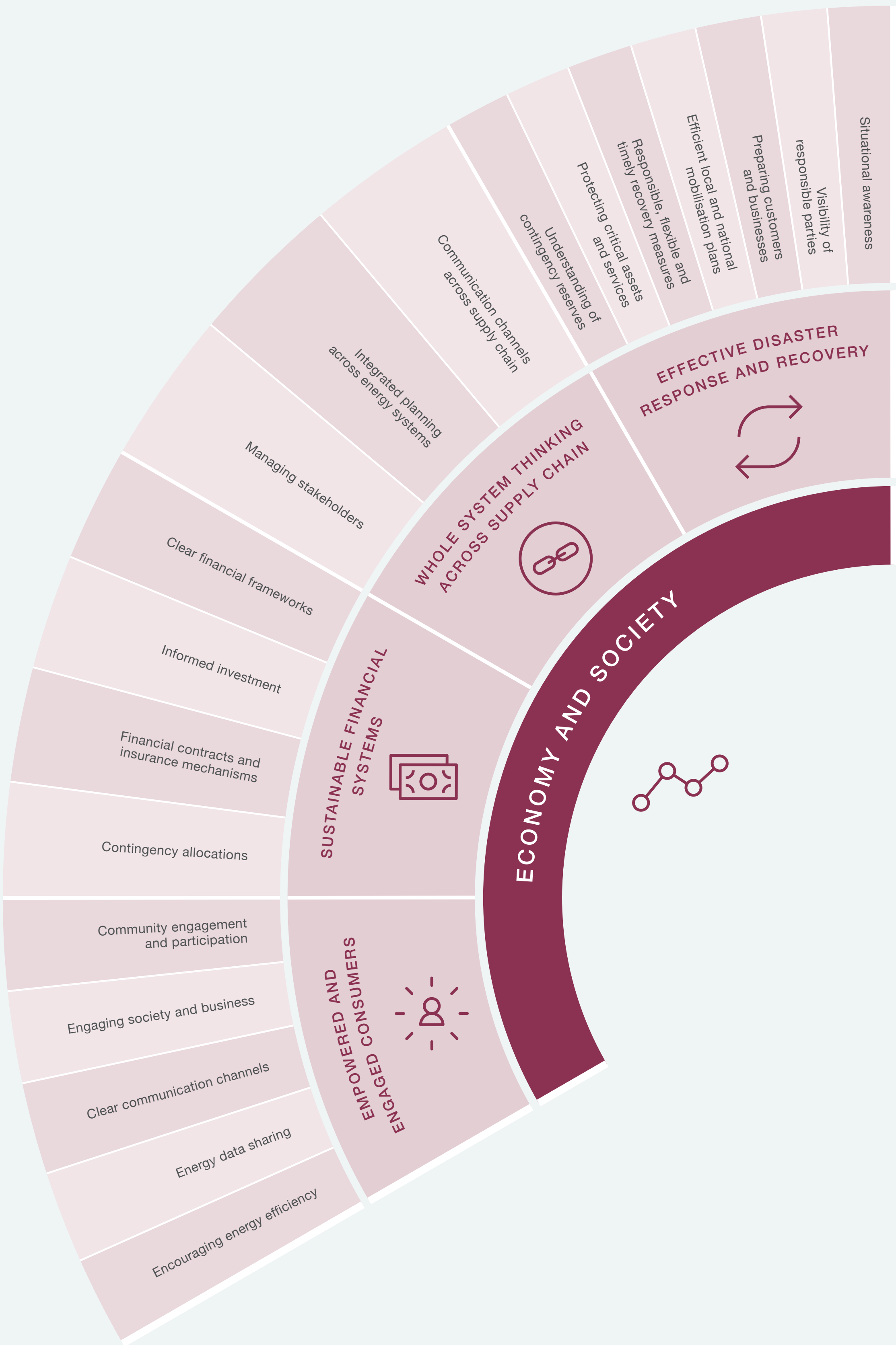
7 – Defining quality of energy service: clear and explicit definition of acceptable standards for energy services e.g. minimum level of service during interruptions.

8 - Regulation for critical infrastructure: acknowledging and identifying different levels of criticality of energy supply within a system and defining special considerations associated with them e.g. provision of redundancy.

9 – Transparent regulation: clear and effective mechanisms for using resources effectively, ensuring traceable decision making and preventing corruption.

Economy and society

Achieving energy resilience will require action not just by the energy sector but by society as a whole. This socio-economic domain of energy resilience includes understanding societal requirements, the structures required to manage the resources to realise these requirements and the collective approach needed to respond to critical events.


ECONOMY AND SOCIETY
EFFECTIVE DISASTER RESPONSE AND RECOVERY
Situational awareness
Visibility of responsible parties
Preparing customers and businesses
Efficient local and national mobilisation plans
Responsible, flexible and timely recovery measures
Protecting critical assets and services
Understanding of contingency reserves
WHOLE SYSTEM THINKING ACROSS SUPPLY CHAIN
Communication channels across supply chain
Integrated planning across energy systems
Managing stakeholders
SUSTAINABLE FINANCIAL SYSTEMS
Clear financial frameworks
Informed investment
Financial contracts and insurance mechanisms
Contingency allocations
EMPOWERED AND ENGAGED CONSUMERS
Community engagement and participation
Engaging society and business
Clear communication channels
Energy data sharing
Encouraging energy efficiency

Goal

EMPOWERED AND ENGAGED CONSUMERS

Collaboration with the end users is paramount. Active consumers provide a better understanding of real requirements and ensure decision making is more robust. Bilateral communication between consumers and the energy community is fundamental to managing expectations and satisfying future supply and demand. As the energy system moves from a historically centralised, passive system, to a more dynamic and decentralised one, there is a greater need to engage more market players and understand their impact on the system.

1 - Community engagement and participation: actively engaging communities in energy and climate issues and understanding how community-level solutions enhance energy resilience.

2 - Engaging society and business: policy and future mitigation or response should consider the energy needs of society and business – the requirement for end users to pay for the energy system has a large impact on its financial sustainability.

3 - Clear communication channels: define and implement mechanisms for effective communication with customers.

4 - Energy data sharing: bi-directional sharing of energy data enables consumers to make better-informed decisions and system operators to better manage demand and increase flexibility. Data protections are required (see cyber security) to ensure trust between parties and guarantee long-term resilience.

5 - Encouraging energy efficiency: liaising with consumers to manage demand and consumption e.g. household-based initiatives.

Goal

SUSTAINABLE FINANCIAL SYSTEMS

Sustainable financial environments increase certainty and protect energy stakeholders. Creating a robust and safe environment is vital for stimulating and sustaining the investment required to update and maintain physical assets and plan and operate risk control strategies. This investment makes the system better prepared for shocks, including changing economic conditions.

1 - Clear financial frameworks: distributing risks fairly provides investor certainty and promotes investment while protecting consumers. It assures affordability and avoids price spikes from supply/demand imbalances or poor market operation.

2 - Informed investment: using data to quantify the added value of increasing energy resilience.

3 - Financial contracts and insurance mechanisms: defining strategy to protect energy stakeholders against the financial exposure and putting safety nets in place where financial risks are identified.

4 - Contingency allocations: acknowledging, understanding and quantifying unmitigable risk exposure to allocate moneys for the response and recovery of the energy system.

Goal

WHOLE SYSTEM THINKING ACROSS SUPPLY CHAIN

A standard energy supply chain (e.g. generation, transmission, distribution and retail) tends to be fragmented and relies on independent but interconnected actors. To build a resilient system, they need to work together as a single system – through ownership of roles and responsibilities, integrated planning and effective communication.

1 - Communication channels across supply chain: defining and implementing channels for continual liaison across the energy supply chain.

2 - Integrated planning across systems: sharing opportunities such as energy efficiency, issues and constraints and reducing the risk of gaps and/or inefficient use of resources. Joining efforts across the supply chain is also fundamental to tackling major common goals such as climate change or the energy trilemma.

3 - Managing stakeholders: understanding stakeholders within the energy system and defining and implementing a strategy to manage them.

Goal

EFFECTIVE DISASTER RESPONSE AND RECOVERY

Even stable and resilient systems may fail due to exceptional unavoidable shocks and stresses. Having predefined, tested plans for response and recovery makes a significant difference to how severely an event affects a system. A resilient system has proactive, flexible and integrated approaches to identifying threats, responding to the failure and recovering the system. This guarantees the system is safe to fail.

1 - Situational awareness: identify vulnerabilities through continual monitoring, and using forecasting tools and modelling to obtain timely reliable data to inform decision making and future investment.

2 - Visibility of responsible parties: understanding who is responsible for the different elements of disaster response and recovery plans and ensuring that there is clear communication between them.

3 - Preparing customers and businesses: a predefined strategy for energy producers and users to ensure that they have an effective response to critical events.

4 - Efficient local and national mobilisation plans: cross-sector, detailed, tested and flexible plans including warning protocols and continual communication with customers.

5 - Responsible, flexible and timely recovery measures: cross-sector, integrated, flexible, tested and collaborative mechanisms to provide short-, medium- and long-term recovery of the system.

6 - Protecting critical assets and services: proactive response plans that clearly prioritise recovering infrastructure needed for human survival and essential services.

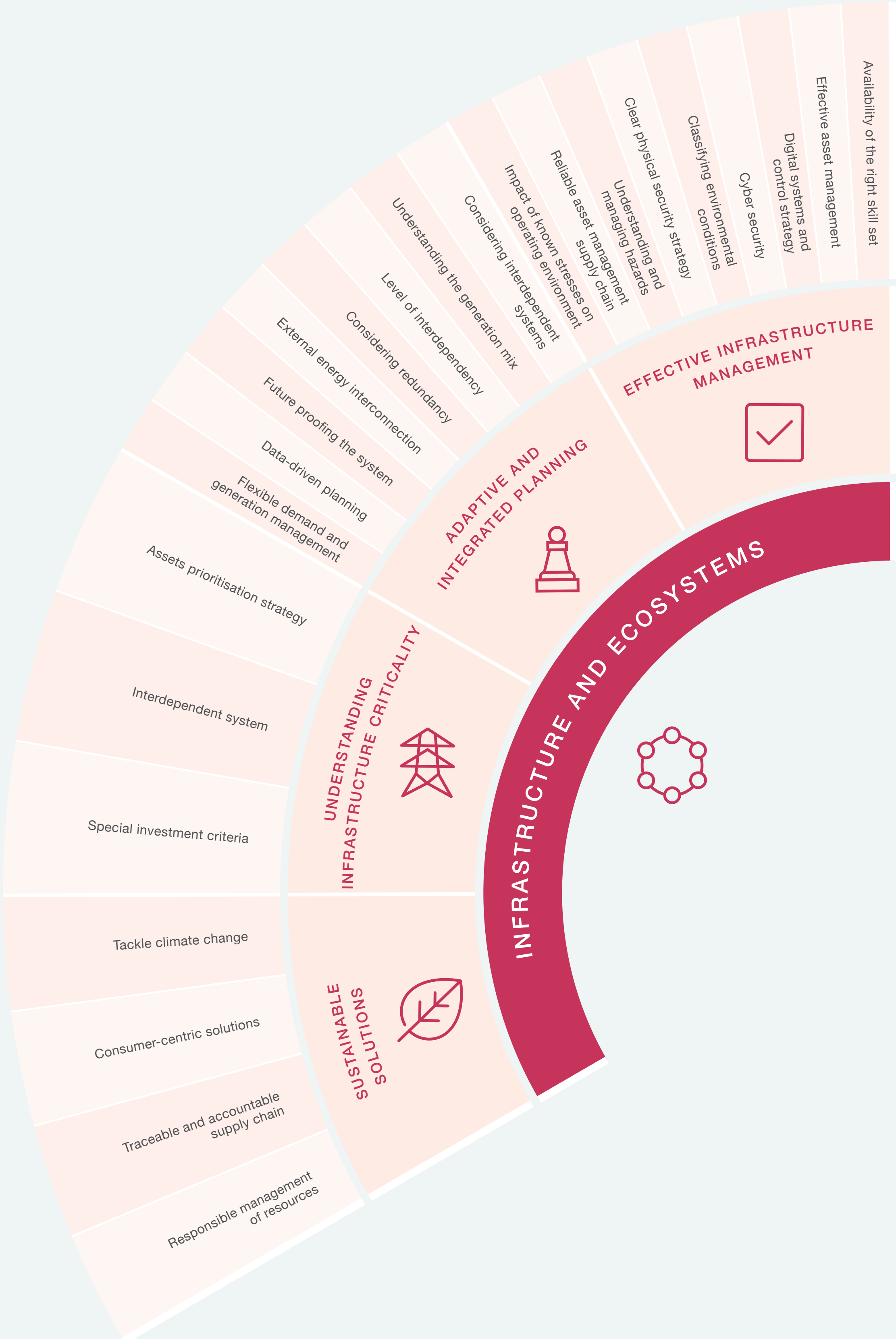
7 - Understanding of contingency reserves: awareness of existing contingency reserves, their purpose and how to mobilise them.

Infrastructure and ecosystems

This dimension relates to infrastructure and its interdependencies. Infrastructure should not be thought of as only physical assets. It should include production systems, control networks and the interactions between them, the natural environment and their operators.

A resilient energy infrastructure system has assets that are effectively managed and have adequate capacity. A forward-looking approach that accounts for the increased pace of climate change and other environmental challenges (e.g. air quality) and enables adaptive planning in response is also important.

Solutions for energy resilience should aim for sustainability and provide transitions to alternative energy sources, technologies and processes where these offer improvements and benefits to users.


INFRASTRUCTURE AND ECOSYSTEMS
EFFECTIVE INFRASTRUCTURE MANAGEMENT
ADAPTIVE AND INTEGRATED PLANNING
UNDERSTANDING INFRASTRUCTURE CRITICALITY
SUSTAINABLE SOLUTIONS
Availability of the right skill set
Effective asset management
Digital systems and control strategy
Cyber security
Classifying environmental conditions
Clear physical security strategy
Understanding and managing hazards
Reliable asset management supply chain
Impact of known stresses on operating environment
Considering interdependent systems
Understanding the generation mix
Level of interdependency
Considering redundancy
External energy interconnection
Future proofing the system
Data-driven planning
Flexible demand and generation management
Assets prioritisation strategy
Interdependent system
Special investment criteria
Tackle climate change
Consumer-centric solutions
Traceable and accountable supply chain
Responsible management of resources

Goal

EFFECTIVE INFRASTRUCTURE MANAGEMENT

Best-practice approaches to infrastructure management are needed. This includes a focus on people, new technologies and data, adaptive processes for managing assets and a robust and modern security strategy.

1 - Availability of the right skill sets: understanding role profiles and defining and implementing strategy to train and retain the right people.

2 - Effective asset management: integrated asset management strategy, including coordinated operations and maintenance, to optimise the performance of assets throughout their lifecycle.

3 - Digital systems and control strategy: for implementing technology to monitor assets and increasing access to reliable data and technical information.

4 - Cyber security: ensuring that relevant factors are embedded at every stage of the assets' lifecycles.

5 - Classifying environmental conditions: identify interdependencies between systems and their environment (e.g. floodplains, which are changing dynamically with the increased pace of climate change).

6 - Clear physical security strategy: define and implement physical security requirements (including environmental protection) to guarantee the integrity of assets.

7 - Understanding and managing hazards: identify shocks and stresses that could interact with the system, understanding how natural and anthropogenic hazards might change over a system's lifetime and proactively planning how to manage them.

8 - Reliable asset management supply chain: reliable means of procuring energy and non-energy services from network or non-network suppliers (e.g. maintenance, voltage control or grid stability).

9 - Impact of known stresses on operating environment: the increased pace of climate change requires operational standards to be reviewed constantly – events that were considered unlikely are quickly becoming normal (e.g. increased summer temperatures).

Goal

ADAPTIVE AND INTEGRATED PLANNING

Integrated and adaptive planning aligns efforts towards a common goal and ensures they sufficiently address the uncertainty in emerging challenges. This approach increases the system's flexibility and ability to respond to a potentially critical change.

1 - Considering interdependent systems: electrification of other major infrastructure sectors (e.g. transport, utilities, communications) is increasing cross-sector dependencies, requiring integrated and inclusive planning across sectors (e.g. transport and energy strategy are mutually dependent).

2 - Understanding the generation mix: consider supply sources such as oil, gas, hydrogen and nuclear. Identify how diverse these and the generation mix are, such as wind, solar and gas. Include technical challenges associated with high shares of wind and solar power generation.

3 - Level of interdependency: consider carefully how decentralised and independent the energy system is (e.g. a centralised system vs a microgrid) and the magnitude of knock-on effects in case of failure.

4 - Considering redundancy: consider incorporating redundancy into energy sources, important components of networks and assets to increase resilience.

5 - External energy interconnection: interconnection between independent energy systems (e.g. cross-border flows of gas and electricity).

6 - Future proofing the system: monitoring trends and planning the system to new and future requirements, modern technologies and materials.

7 - Data-driven planning: make accurate data available to key decision makers, planners, owners, and operators to inform programmes, policies and research as well as to establish the current baseline and make an attractive business case for resilience actions.

8 - Flexible demand and generation management: having the means to tackle changes in energy demand and load type.

Goal

UNDERSTANDING INFRASTRUCTURE CRITICALITY

Communities rely on infrastructure systems to function, but some components of the system are more important than others to survivability. Efforts to improve the resilience of energy systems must be prioritised based on an understanding of criticality.

1 - Assets prioritisation strategy: identify and understand criticality levels for energy and energy-dependent infrastructure and prioritise investment, response and recovery accordingly.

2 - Interdependent system: see and understand internal and external interdependencies between systems and their physical and non-physical interfaces.

3 - Special investment criteria: acknowledge the added importance of critical infrastructure and special considerations for providing resilience (e.g. redundancy) and assess the business case – including where additional funding might be justified to provide increased resilience.

Goal

SUSTAINABLE SOLUTIONS

Mechanisms for improving some of the resilient qualities of an energy system can actually increase the risk exposure of the system (e.g. the climate impact of using fossil fuels for electricity capacity management). To ensure the implemented solutions are effective, sustainability factors must be considered. The United Nations Sustainable Development Goals provide an excellent benchmark. Actions must align with the goals or, at the very least, not undermine them.

1 - Tackle climate change: implement green, circular solutions or alternatives that support the journey towards decarbonisation.

2 - Consumer-centric solutions: ensure health and wellbeing and protect vulnerable customers.

3 - Traceable and accountable supply chain: ensure the end-to-end responsibility/liability of the supply chain.

4 - Responsible management of resources: ensure by-products are disposed of responsibly. Incorporate circular economy principles during the design and implementation of strategies.

Applying the framework: A case study

South Australia Blackout, 2016

The South Australia blackout made headlines across the world, leaving many without power.

On Wednesday 28 September 2016, tornadoes with wind speeds up to 260 km/h occurred in South Australia. Two tornadoes damaged three major transmission lines, wind farms ceased power generation and the Heywood interconnector was disconnected. South Australia could not operate in 'islanded mode' - the system managed by Australian Energy Market Operator collapsed within one second and the entire state of South Australia - 1.7m people - lost power. Twenty four hours later, power was restored to 90% of households, yet 70,000 people were still without electricity. 50 hours after the blackout the grid was back to normal.

Using the Energy Resilience Framework, we have mapped out the events, existing practices and regulations, post-disruption investigations as well as recommendations in accordance with the official "Black System South Australia" report. In addition to the three dimensions and 11 goals of the Energy Resilience Framework, a new axis is introduced for chronologically describing what happened, exploring pre-disruption, during disruption and post-disruption, which sheds more light on how to tackle resilience.

AEMO - Australian Energy Market Operator

NEM - National Electricity Market

AERNA - Australian Renewable Energy Agency

NER - National Electricity Rules

TNSP - Transmission Network Service Provider

DNSP - Distribution Network Service Provider

COAG - Council of Australian Governments

ESCOSA - Essential Services Commission of South Australia

DIMENSION	GOAL	PRE-DISRUPTION
LEADERSHIP AND STRATEGY	*Strategic Vision*	• AEMO's System Security Market Frameworks Review » Exploring new options to procure inertia • AEMO's Future Power System Security programme
	Effective Regulation	• Reviewing and updating technical standards for registered generators • Multi-timescale regulatory initiatives » Short-term focus areas » Medium-term focus areas • AER's regulation to maintain some minimum level of system strength, but it is unclear how this minimum level is specified.
	Integrated Governance	• Collaboration among AEMO, AER and AEMC. (proactive coordination within the energy sector) • COAG Independent Review into the Reliability and Security of the NEM, and ESCOSA to review technical licence conditions for generation in SA (proactive coordination interdependent infrastructure sectors)
ECONOMY AND SOCIETY	*Empowered and Engaged Customers*	Further research is needed on the customers' preparedness regarding possible interruption of electricity supply
	Sustainable Financial Systems	• Existing procedure is available for Electricity Market Suspension • Energy spot prices were determined in accordance with a pre-published "suspension pricing schedule" • Negative settlements residue management • Further research is needed on where energy infrastructure investment stands in the financial market and insurance mechanisms have been offered to businesses and generation companies
	Whole System Thinking across Supply Chain	
	Effective Disaster Response and Recovery	AEMO has clear restoration strategy in place, which sets out the roles and responsibilities of the different organisations involved, and details of AEMO's restoration strategy used to restore the power system and load in Southern Australia
INFRASTRUCTURE AND ECOSYSTEMS	*Effective Infrastructure Management*	• AEMO was unaware of protection settings for some wind turbines • TNSPs design standards and maintenance of their assets
	Adaptive and Integrated Planning	• Dramatic change in generation mix, i.e. high renewable and low conventional generation • UFLS scheme is in place to provide demand-side management to the system • Exploring new options for procuring non-energy services
	Understanding Infrastructure Criticality	• Classification/assessment of credible power system contingencies based on weather conditions • Lack of situation awareness in the control room • Staff not trained to properly interpret weather information
	Sustainable Solutions	Pre-event the wind generation is 883MW, close to 50% of the generation mix at the time.

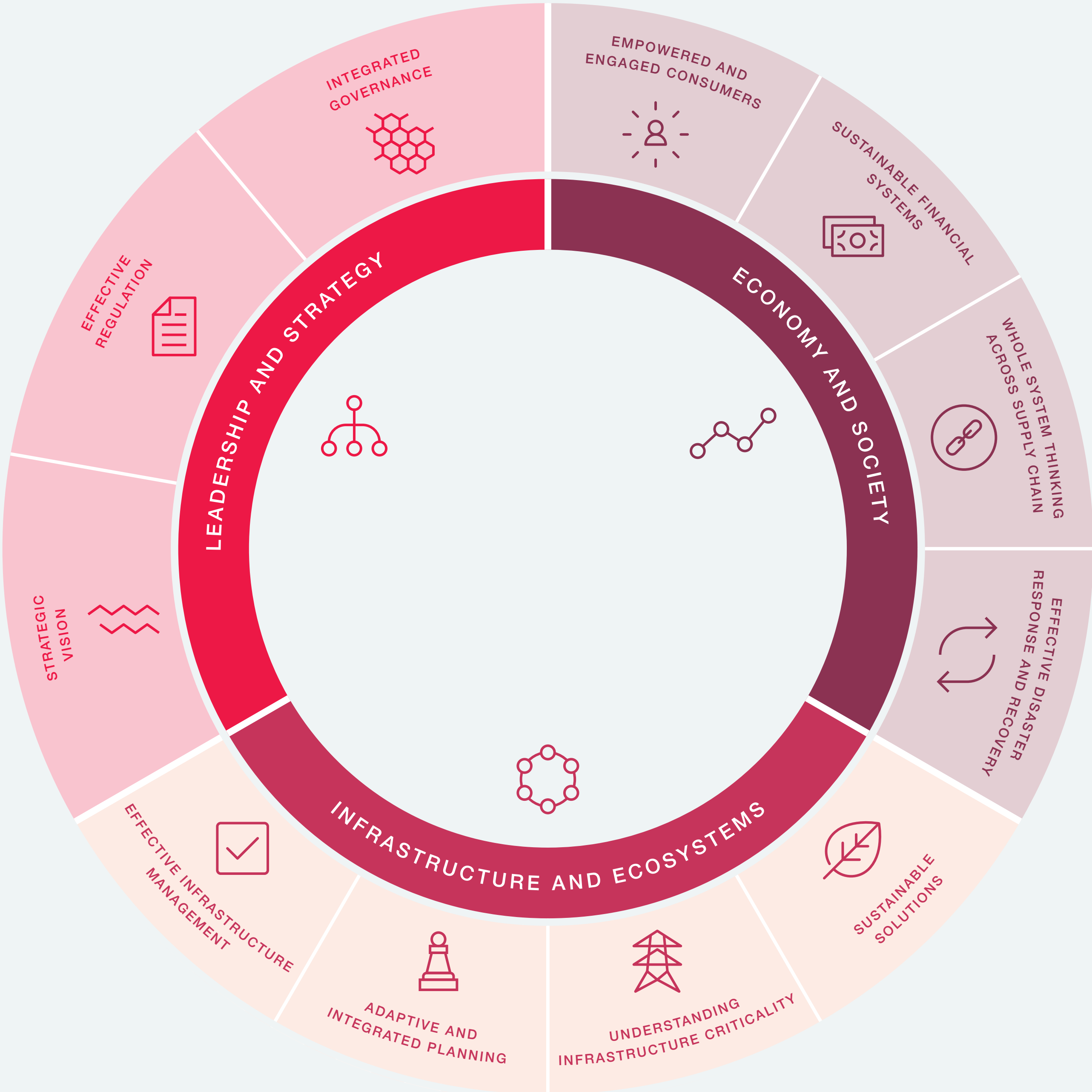
DURING DISRUPTION	POST-DISRUPTION
	• AEMO, with the SA System Restart Working Group, to review the system restart process • These learnings will then be shared with the Restart Working Groups in the other NEM regions, Western Australia, and the Northern Territory
• Robust energy market structure, in terms of having procedures for Electricity Market Suspension and Energy spot prices, were controlled in accordance with a pre-published “suspension pricing schedule”	• Multiple rule change proposals for standards.
Collaboration and coordination among different organisations: • AEMO • TNSPs • DNSPs • Generators	• Continue all the collaboration as outlined pre-disruption
Further research is needed on how the customers responded to the interruption of electricity supply and what they were able to do to minimise impact	Further research is needed on how the customers adapts or makes their own arrangement to be more prepared for this type of event
Further research is needed on whether any financial market responded to the event or any participants in any financial market (e.g. stock exchange) were affected by the black system	AEMO to review market processes and systems, in collaboration with Registered Participants, to identify improvements and any associated NER or procedure changes necessary to implement those improvements
	The technical challenges of the changing generation mix must be managed with the support of efficient and effective regulatory and market mechanisms, to ensure the most cost-effective measures are used in the long-term interest of consumers
Wind farms failed to provide effective disaster response and recovery in the presence of the storm and tornadoes: » In addition to 456 MW of sustained reduction in wind generation, 42 MW of transient reduction was experienced due to natural fault ride-through response of remaining wind farms which do not immediately recover active power to pre-event level • Lack of situational awareness in terms of detecting abnormal flows on the electricity network that might have prevented the system separation Electricity network interconnection was not able to sustain the system after the reduction in wind generation, leading to system separation	Proceeding without a clear understanding of the status of the network and what is available could result in safety risks to the public and industry personnel, and damage to the power system and generating units Once the status of the power system is assessed, preparation for system restoration may commence This includes making equipment safe prior to any restoration activities, through liaison with TNSPs, DNSPs, and generators
• Unable to reclassify the loss of multiple circuits under high wind conditions • Unable to reclassify multiple generating unit contingencies	Data related issues: • AEMO to develop, in consultation with Registered Participants, a more structured process to source and capture data after a major event in a timely manner and better co-ordinate data requests made to them • AEMO to investigate, with Registered Participants, the possibility of introducing a process to synchronise all high speed recorders to a common time standard • Establishing arrangements to get access to improved data on DER
Load shedding or generation response was not planned with a response time fast enough to prevent system separation	• AEMO to develop detailed procedures on the differences required in power system operations during periods of market suspension and identify if any NER changes are required to improve the process • AEMO to investigate the possibility of implementing a better approach for ensuring the minimum stable load of generating units is taken into account in the dispatch process • Increased modelling requirements • Power system modelling and simulation studies
All on-line wind farms successfully rode through faults, until a pre-set limit which allows a maximum number of successful ride-through events was reached or exceeded.	AEMO permitted the impacted Generators to implement the proposed new settings on-site, enabling successful ride-through for a larger number of successive faults.

Final thought on energy resilience

AN INTERCONNECTED WORLD

Truly resilient systems, including those relating to energy, require understanding, evaluation and provision across a wide range of technical and non-technical factors acting with and against one another.

Arup's Energy Resilience Framework facilitates a broader resilience discussion. It encourages an integrated approach which recognises precedent, whilst also guiding a thought process which reflects the evolving and increasingly complex place of energy in our built environment.


LEADERSHIP AND STRATEGY
ECONOMY AND SOCIETY
INFRASTRUCTURE AND ECOSYSTEMS
INTEGRATED GOVERNANCE
EFFECTIVE REGULATION
STRATEGIC VISION
EMPOWERED AND ENGAGED CONSUMERS
SUSTAINABLE FINANCIAL SYSTEMS
WHOLE SYSTEM THINKING ACROSS SUPPLY CHAIN
EFFECTIVE DISASTER RESPONSE AND RECOVERY
SUSTAINABLE SOLUTIONS
UNDERSTANDING INFRASTRUCTURE CRITICALITY
ADAPTIVE AND INTEGRATED PLANNING
EFFECTIVE INFRASTRUCTURE MANAGEMENT

References

CREATING THE FRAMEWORK

This framework has been developed leveraging Arup's resilience expertise and intellectual property, combined with insight from verified sources.

Numerous publications present frameworks, or detailed analytical approaches to assess energy system resilience. Typically, these focus on the ability of infrastructure to withstand, absorb or rapidly recover from disturbance. The current work in this sector is mainly focussed on the design, planning, operation and maintenance of electricity infrastructure and its operation. Resilience solutions (mainly technical) are being adapted and implemented across the world, and lessons are being learned through the implementation process. Solutions vary based on predicted hazards, community context, priorities, complexity, and available resources. Frameworks to assess the resilience of critical infrastructure and guidelines for policies and regulations required for a resilient energy system are also being addressed.

Evidence throughout the literature suggests that energy systems with particular features are more likely to be resilient. This aligns with Arup's work on city resilience, which proposed seven qualities of a resilient urban system.

LEARNING FROM OTHER SECTORS

The resilience of highly interconnected critical systems such as energy, water, transport, and digital communications, and of the social, agricultural and industrial infrastructure that depends on these (e.g. healthcare, finance, food, government) requires a common understanding across sectors.

Fragmented governance, where different stakeholders are involved in regulating, designing, delivering, owning, operating and maintaining the national energy infrastructure and interdependent systems, has emerged as a common theme linked to a lack of resilience.

Siloed approaches that respond to the resilience challenge within one sector, or one organisation are not the answer. The framework presented here has intentionally drawn heavily on the work done to develop the City Resilience Index. Cities are a lens through which all infrastructure performance should be considered, and a common acceptance of what matters should be developed. Therefore the CRI provides a valid starting point for this work. Further reference has been made to the City Water Resilience Approach, a catchment-scale approach for diagnosing and acting on the resilience of a city's water systems. The thousands of hours of research, collaboration and validation that has gone into that work have provided a robust launch pad for this work.

1. *Neil Greet and Paul Barnes, "Special Report The challenge of energy resilience in Australia Strategic options for continuity of supply", Australian strategic policy institute, August 2017.*
2. *House of Lords, "The resilience of electricity systems", UK government, June 2015.*
3. *Yoshikazu Kobayashi1, "Enhancing Energy Resilience: Challenging Tasks for Japan's Energy Policy", Centre of strategic and international studies Japan, April 2014.*
4. *U.S Department of Energy, "Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions", October 2017.*
5. *ICF international, "Electric grid security and resilience establishing a Baseline for adversarial threats", report prepared for U.S Government, June 2016.*
6. *Cambridge Econometrics, E3 modelling, "EU energy trends and macroeconomic performance: Case study - Energy resilience and vulnerability in the EU and other global regions", report prepared for European commission, February 2017.*
7. *Ove Arup & Partners International Limited, "City Resilience Framework", April 2014.*
8. *NREL, "City-level energy decision making: Data use in energy planning, implementation, and evaluation in U.S. Cities", report prepared for U.S Department of Energy, July 2015.*
9. *U.S Department of Energy, "Energy Resilience Solutions for the Puerto Rico Grid", June 2017.*
10. *Australian Government, "Critical infrastructure resilience strategy", June 2017.*
11. *NREL, "Guide to Cybersecurity, Resilience, and Reliability for Small and Under-Resourced Utilities", report prepared for U.S Department of Energy, July 2015.*
12. *NREL, "Alternative energy generation opportunities in critical infrastructure, November 2003.*
13. *Modassar Chaudry et al, "Building a Resilient UK Energy System", report prepared for UK energy research centre, March 2009.*
14. *Eliza Hotchkiss and Sherry Stout, "Best Practices in Resilience Planning", NREL, March 2019.*
15. *Ove Arup & Partners International Limited and UCL "Infrastructure and Digital Systems Resilience", report prepared for National Infrastructure Commission, November 2017.*
16. *NREL, "Federal Tax Incentives for Energy Storage Systems", January 2018.*
17. *AEMO, "SA (South Australia) region Black System event on 28th September 2016 - Final report", March 2017.*
18. *Royal Academy of Engineering, IET and Lancaster University, "Living without electricity", May 2016.*
19. *UCTE, "Final report system disturbance on 4 November 2006", April 2007.*
20. *Ofgem, "Preliminary report into the recent electricity transmission faults affecting South London and East Birmingham", September 2003.*
21. *Ove Arup & Partners International Limited, "City Water Resilience Framework", 2018.*
22. *IEEE Power and Energy Society: The Definition and Quantification of Resilience*
23. *CRIED Final Report: Resilience of Distribution Grids Working Group.*
24. *European Commission JRC Science and Policy Report: Risk Assessment methodologies for Critical Infrastructure Protection. Part II: A New Approach*
25. *UK Parliament House of Lords: The Resilience of the Electricity System*
26. *Energy Partner Research: Final Report on Future Resilience of the UK Electricity System*

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