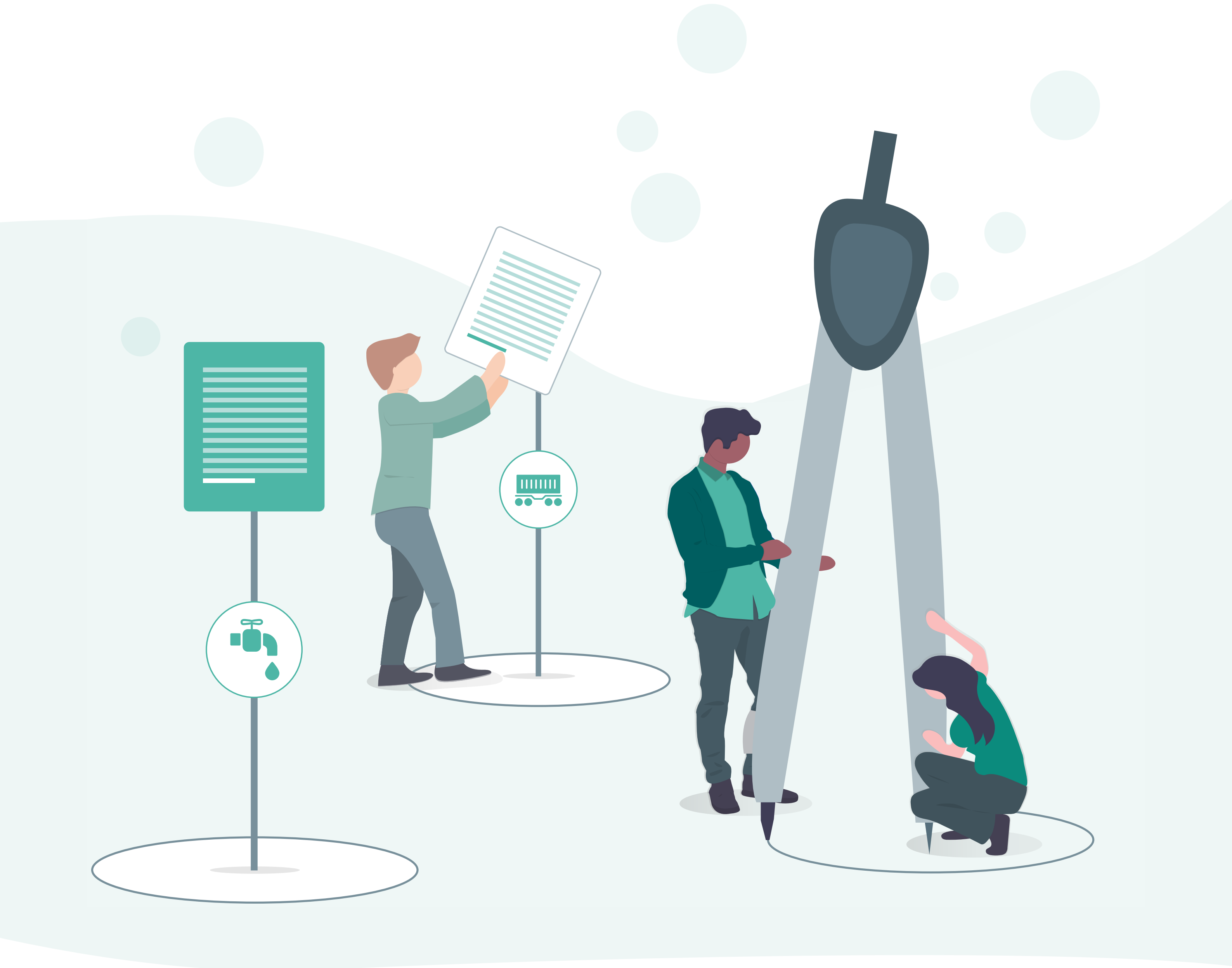
RESEARCH REPORT

The role of public policy in critical infrastructure resilience



THE UNIVERSITY OF MELBOURNE

THE RESILIENCE SHIFT

ABOUT THE RESILIENCE SHIFT

The Resilience Shift exists to inspire and empower a global community to make the world safer through resilient infrastructure. More people than ever depend on the critical infrastructure systems that provide essential energy, water, transport and communications services, and underpin food, healthcare and education. When this infrastructure fails the consequences can be catastrophic.

Supported by Lloyd's Register Foundation and Arup, the Resilience Shift provides knowledge and tools for those responsible for planning, financing, designing, delivering, operating and maintaining critical infrastructure systems. Our aim is to ensure infrastructure systems are able to withstand, adapt to, and recover quickly from anticipated or unexpected shocks and stresses - now and in the future.

DEFINING RESILIENCE

Resilience is the ability to withstand, adapt to changing conditions, and recover positively from shocks and stresses. Resilient infrastructure will therefore be able to continue to provide essential services, due to its ability to withstand, adapt and recover positively from whatever shocks and stresses it may face now and in the future.

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The Resilience Shift is a global initiative launched in 2016 to address the recommendations of the Lloyd's Register Foundation's 'Foresight review of resilience engineering'. It aims to inspire and empower a shift in critical infrastructure resilience thinking and practice so that engineered structures and infrastructure will be not only safer but also better. The Resilience Shift is funded by Lloyd's Register Foundation, and hosted by Arup working with a diverse range of grantees.

As part of its work on incentivising resilience, the Resilience Shift aims to answer questions on what we think is important in terms of moving the needle for the resilience of critical infrastructure, what we should do, why is it important and how do we put it into practice?

This report is concerned with the role that public policy instruments, like regulation and standards, can play in embedding resilience in critical infrastructure systems. It provides clarity in the use of key terms including 'public policy' and 'policy instruments' and highlights early innovations in critical infrastructure resilience policy.

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The Resilience Shift is delighted to have supported the authors in producing this report. It is an invaluable read for those involved in the planning, design, delivery, operation and maintenance of infrastructure systems, to build understanding of the workings, importance and impact of public policy in improving the resilience of critical infrastructure.

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1. Introduction

Critical infrastructure refers to the large socio-technical systems such as energy and water supply, or transportation of people or goods that are considered essential for a society and economy to function, and whose failure would create significant impact to human life, economic activity and/or national security. Critical infrastructure is often referred to as a socio-technical system in recognition of the interdependence of technological components (poles, wires, generators, trains, pipes etc.) and social components (including expert knowledge, user behaviour, social acceptance of technologies and the wider regulatory and policy landscape).[1]

Considering the importance of these systems, there are international efforts underway to embed resilience into the design, provision, operation and maintenance of critical infrastructure. In this context, resilience refers to **the ability of a complex system to absorb, recover from and adapt to shocks and stresses with minimal loss of functionality and a rapid return to normal service**.

Why is public policy important?

Public policy, which refers to actions undertaken by governments and guided by decision-making principles, is an important mechanism for embedding resilience in critical infrastructure because it articulates how public resources will be deployed to incentivise and restrict investment, design, construction and operation of critical infrastructure systems. Public policy is also a forum for resolving competing interests, coordinating actions across sectors and jurisdictions, and acting in the interests of diverse stakeholder groups and future generations. Crucially, the dynamic processes of policymaking, implementation and learning are pathways for driving change in critical infrastructure systems and a source of institutional resilience.

Critical infrastructure is a complex area of policymaking, and policymakers around the world are already facing several challenges to meet the infrastructure demands of a growing population, rising urbanisation, rapid technological change and sustainable development. The growing complexity and interdependence of critical infrastructure systems coupled with the increasing, and increasingly unpredictable, impacts of extreme weather events, climate change and social and economic instability introduce additional challenges for policymakers to adapt policy – and indeed policymaking – to enhance resilience.

[1] Infrastructure can also be referred to as a socio-ecological-technical system in recognition of the interdependencies between technical and social infrastructure components with ecological components (for example geographical terrain, climate and non-human species). Others refer to critical infrastructure as 'systems of systems' to capture the complexity and interdependency of sub-systems that must function together to deliver critical infrastructure services.

2. Operationalising resilience in critical infrastructure

A renewed focus on critical infrastructure systems

Infrastructure systems work to provide services such as energy and water, to protect things we value such as our built and natural environments, and to connect us through the movement of people, goods and information. Infrastructure has traditionally been thought of in terms of fixed assets, such as roads, bridges or ports, that are designed to fixed thresholds of performance. Infrastructure can also be seen as a socio-technical system that integrates technological and social components in such a way to deliver services that support community wellbeing, economic activity and sustainable development (Chappin & van der Lei, 2014; O'Rourke, 2007).

Ecological dependencies – on geographical terrain, climate and non-human species for example – are also recognised as important to infrastructure systems (**Figure 1**). Well-functioning infrastructure can often seem to become an invisible part of daily life – something we only notice when it is disrupted or fails. At other times, infrastructure is a highly visible symbol of a nation's hopes and aspirations whose ongoing function is valued for more than its economic benefits (Larkin, 2013).

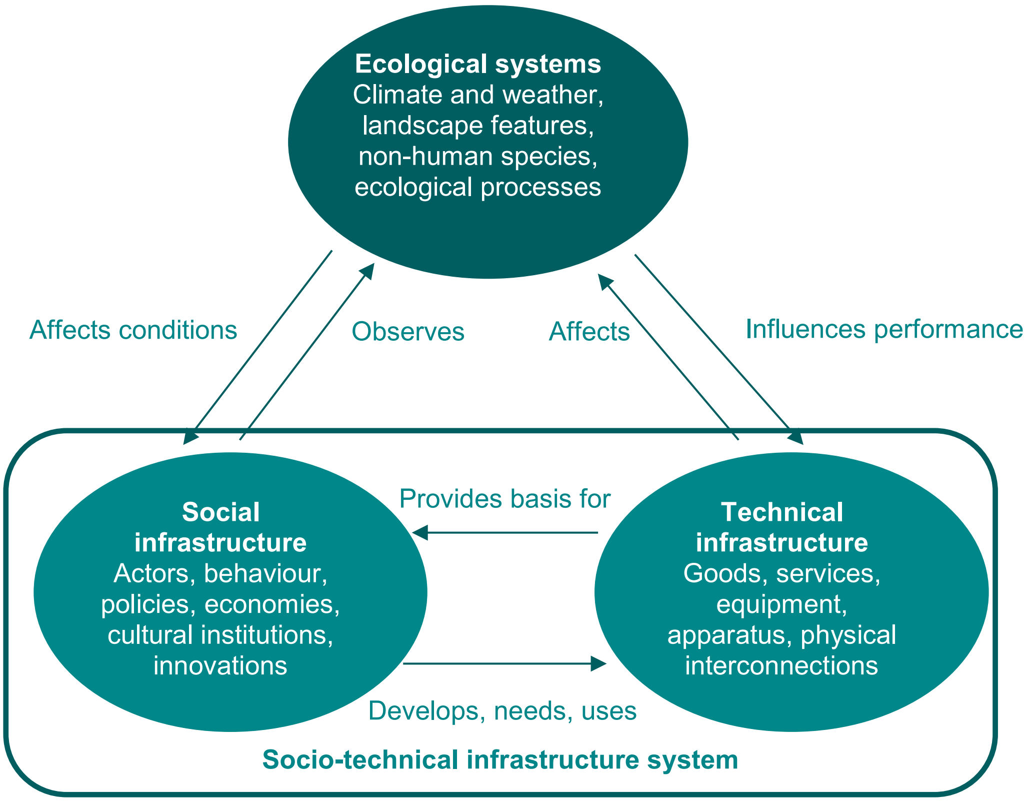

Figure 1. Illustration of infrastructure as a socio-technical system (edited from Chappin & van der Lei, 2014)

The Resilience Shift defines critical infrastructure on the basis of the services that it enables and on the consequence of failure, which would "create a significant impact to human life, economic activity and/or national security" (Resilience Shift, 2018).[2] The specific infrastructure systems that are included within the definition of 'critical infrastructure' vary from place to place but typically include transport, energy, telecommunications, water, waste and health-related infrastructure (see **Table 1**) (The Critical Five, 2014).

Table 1. Infrastructure systems commonly denoted as 'critical' (from from Larkin, 2013)

Critical infrastructure system	Key functions	Examples of key network components
Transportation systems	Circulation of people and goods, access and egress e.g. by emergency services	Roads, railways, airports, ports, signalling
Energy systems	Power supply	Nuclear plants, coal and gas power stations, wind farms, solar farms, hydroelectric facilities, waste-to-energy plants, distribution poles and wires, transformer stations, battery storage
Telecommunications	Circulation of information, cybersecurity, remote control	Broadcast media, communications towers, fibre optic cable, satellites
Water systems	Drinking water supply, removal/treatment of wastewater, flood control	Dams, treatment facilities, desalination plants, irrigation channels, pipes, pumps, levees, dikes, barriers
Healthcare systems	Primary healthcare and blood supply	Hospitals, blood banks, ambulances, drug supply
* Other systems that are considered by some countries as 'critical' include banking and financial services, critical manufacturing, emergency services, food and agriculture, government facilities and information technology		

Trends in critical infrastructure provision

There are converging imperatives to rethink the way we plan, fund, design and operate critical infrastructure. These are characterised briefly here into two types: the changing scale and nature of critical infrastructure systems, and the changing pattern of shocks and stresses experienced by these systems.

On the one hand, more critical infrastructure is being built globally and thus there is a greater potential for loss. McKinsey&Company (2016) estimated that the world spends in the order of US$2.5 trillion a year on transportation, power, water, and telecom systems. This infrastructure tends to be more expensive and the majority is being built in 'at-risk' locations, partly driven by urbanisation. These critical infrastructure systems are also increasingly interdependent such that disruption to one infrastructure system has cascading impacts or a 'domino effect' on other systems (O'Rourke, 2007). Examples of these interdependences arise from *tighter coupling* of physical and cyber systems (as

[2] A failure in this context should be understood as a system which is prevented from continuing to perform its function - as opposed to the failure of a physical asset, which is understood as a damage or loss (RESILIENCE SHIFT 2018).

seen in ‘smart’ grids), *along supply chains* (as seen in global food industries), or *between infrastructure systems* (as seen in the importance of reliable electricity supply to mass transportation systems). The rise of ‘just in time’ logistics, the imperative to access global markets and the importance of infrastructure for economic competitiveness all contribute to the growing dependency of economies on infrastructure.

These trends are set to deepen in coming decades. There is growing attention to ‘the infrastructure gap’, which refers to the vast amount of infrastructure investment that is projected to be needed globally (Oxford Economics, 2017). This gap – estimated to be around US$90 trillion over the next 15 years – arises in part from a multi-decadal lag in infrastructure investment by many developed countries who are experiencing the impacts of ageing infrastructure due to an over-reliance on the physical capital of the post- World War II infrastructure boom. It also arises from the substantial infrastructure requirements of emerging economies to enable sustainable and more equitable development (Global Commission on the Economy and Climate, 2017).

The nature of critical infrastructure systems will also continue to change. Underlying demographic trends such as urbanisation, an ageing population, increasing population mobility and growing inequality are key drivers. Technological change such as the ‘smart’ revolution, the ‘internet-of-things’ and the ‘fourth industrial revolution’ are additional drivers of change in critical infrastructure systems.

On the other hand, underlying patterns of shocks and stressors to critical infrastructure systems are changing and we are increasingly preoccupied with managing the new and pervasive risks of modernisation – we are living in a ‘risk society’ (Beck, 1992). Critical infrastructure systems are being exposed to more frequent and more severe weather events such as storms and heatwaves, shifts in rainfall and temperature patterns, and other climate change impacts such as sea level rise (IPCC, 2014). Many of these hazards are also correlated, placing stress on economic activity, community safety, public resources and infrastructure insurability (Macintosh et al., 2013).

Social unrest and vulnerabilities to economic shocks and cyber-attacks are also producing new landscapes of risk (World Economic Forum, 2018). Consequently, prevailing paradigms of probabilistic risk calculations and engineering based on past performance – which have served us well for many decades – are being challenged. It is becoming increasingly difficult to predict risks in time and space, calculate social impacts, and to isolate one hazard from another (Linkov et al., 2014).

Transitioning to a resilience-based approach

Transitioning to more resilient critical infrastructure systems is required to address the fundamental challenges posed by expanding infrastructure systems, complex interdependencies and growing uncertainty. This does not necessarily mean abandoning traditional risk analysis and management, but rather complementing these with frameworks and practices that support system-wide resilience.

Resilience is a broad concept that can be deployed for multiple uses, but it has emerged as a powerful framing concept in recent decades across diverse sectors such as disaster management, ecological conservation, urban planning and psychological wellbeing (Brown, 2014; Meerow & Newell, 2016). Resilience is associated with how socio-ecological or socio-technical systems respond to and overcome uncertainties and disruptions. The UN, for example, defines resilience as:

The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the *preservation and restoration of its essential basic structures and functions (UN Resolution 69/283 2015: 2).*

More recent evolutionary approaches to resilience also emphasise the importance of learning from disruptions and adapting to change: not merely ‘bouncing back’ but ‘bouncing forward’ (Simmie & Martin, 2010). This is particularly important in places and communities where the status quo may not be adequate or equitable (Davoudi, 2012).

For critical infrastructure systems, this means transitioning from a ‘fail-safe’ and managerial approach, towards a ‘safe-to-fail’ approach that accepts some disruptions are unavoidable, ensures an adequate level of service provision during compromised functioning, supports the rapid restoration of normal operations and is capable of learning from disruptions (Ahern, 2011; Vallejo & Mullan, 2017).

Resilient critical infrastructure systems are therefore those that can prepare, plan, absorb, recover from and adapt to hazards (Linkov et al., 2014; Marchese et al., 2018). Resilience in infrastructure means both minimising the loss of function that occurs during a disruption and a rapid recovery curve. Resilient engineering approaches include multifunctionality, modularisation, distributed decision-making, flexible responses, redundancy and ensuring the independence of component interactions (Ahern, 2011; Linkov et al., 2014).

However, operationalising resilience-based approaches must extend beyond resilient engineering approaches to include resilient management, policy and regulation. An adaptive approach is needed along the value chain of infrastructure – in planning, design, construction and operation of critical infrastructure (see **Figure 2**) – to meet the challenges of managing risk to known hazards as well as to deep uncertainty and emerging risks. The Resilience Shift seeks to support this transition in decision-making:

One of the biggest challenges for critical infrastructure is breaking down the silos between infrastructure providers and customers along the supply chain so that everyone is focused on delivering resilience value where they can. We have found that a value chain is extremely useful for connecting the concepts of resilience and value in a context that will be familiar to everyone working on the design, delivery, operation of infrastructure systems (Resilience Shift, 2018).

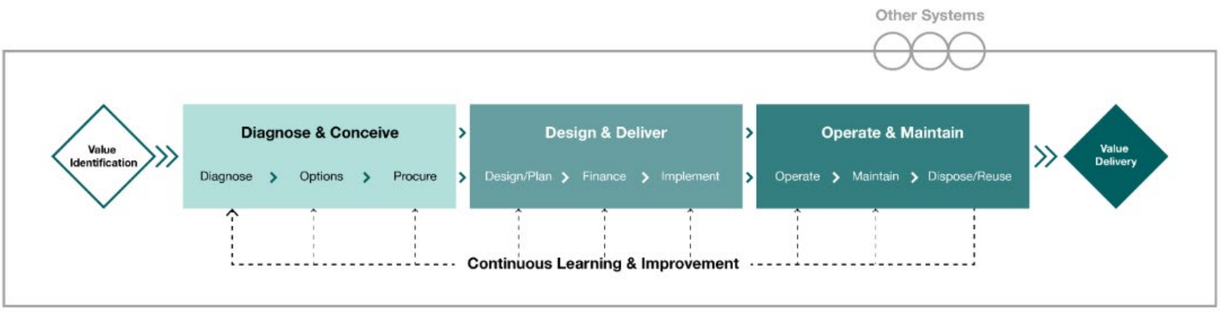

Figure 2. Value-chain approach to critical infrastructure provision (from Resilience Shift, 2018)

3. Public policy in infrastructure governance

Key elements of public policy

The Resilience Shift has identified that critical infrastructure provision depends strongly on incentives emerging from social structures and processes. These include: standards-setting bodies, public policy and regulation, insurance and financial industries, and the views of the public (Resilience Shift, 2018). This section reviews how public policy and its implementation instruments shape the landscape of incentives and restrictions that may enable or hinder resilience.

Public policy is most often associated with what governments do (or do not do).[3] Public policy can be defined as a framework for action that is guided by decision-making principles, undertaken by governments and carries authority (see **Box 1**). Examples of public policy include economic policy, housing policy, energy policy and foreign policy.[4]

Public policy is an important mechanism for driving resilience in critical infrastructure because it articulates how public resources will be deployed to incentivise and restrict investment, design, construction and operation of critical infrastructure systems. Public policy and its implementing instruments are also a forum for resolving competing interests (for example between alternative infrastructure options, between siting options, or between stakeholder groups). Furthermore, it provides a means to coordinate actions across sectors and jurisdictions and may promote the interests of future generations. Public policy sits within broader governance frameworks that collectively oversees critical infrastructure provision.

Box 1. Examples of some commonly used definitions of policy (edited from edited from Maddison & Denniss, 2013)

Policy is:

'what governments do, why they do it, and what difference it makes' (Dye 1972: 2).

'a purposive course of action followed by an actor or a set of actors in dealing with a problem or matter of concern' (Anderson 1984: 3).

'a political agreement on a course of action (or inaction) designed to resolve or mitigate problems on the political agenda' (Fischer 1995: 2).

'an authoritative statement by a government about its intentions … relying on hypotheses about cause and effect, and … structured around objectives' (Althaus, Bridgman & Davis 2007: 5).

'an action which employs governmental authority to commit resources in support of a preferred value' (Considine 1994: 3).

'a set of interrelated decisions taken by a political actor or groups of actors concerning the selection of goals and the means of achieving them within a specified situation where those decisions should, in principle, be within the power of those actors to achieve' (Jenkins 1978: 15).

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[3] It is worth noting that inaction can also be an expression of policy, for example a government taking no action on reducing greenhouse gas emissions is itself a statement of policy towards climate change.

[4] Public policy is only one type of policy; other examples include organisational and corporate policy, which address human resources, procurement and sustainability for example. This report will focus principally on the potential for public policy to embed resilience in critical infrastructure. However, it is worth remembering the potential for organisational policy (made by investors, professional bodies and infrastructure operators for example) to support government policy.

A policy is typically made up of policy objectives, statements of principles, policy instruments and administrative statements (**Figure 3**). Public policy also typically has delivery and enforcement arrangements.

Policy objectives
Articulate what the policy hopes to achieve in terms of change

Policy principles
Establish the values that underpin decision-making in this area e.g. fairness, value for money, participation or the precautionary principle

Policy instruments
Implementation tools to shape behaviour and achieve policy objectives

Administrative statements
Define the scope, targets, lifetime or limits of the policy

Delivery and enforcement arrangements
Outline the (new or existing) institutions and organisations that will deliver and oversee policy implementation

Figure 3. Components of public policy

Policies can be *distributive* (granting benefits to a group of beneficiaries such as federal spending on local infrastructure projects), *redistributive* (changing the allocation of wealth or rights among social groups such as taxation policy), or *regulatory* (governing the conduct of private activities).

Regulatory policies encompass competitive regulatory policy, as is often applied to monopolistic infrastructure systems like water or electricity or regulation of the professions, and protective regulation that protects the public from negative effects as in environmental protection regimes (Birkland, 2011).[5]

Policy instruments

Policy instruments are the implementation tools to shape behaviour and achieve policy objectives (Maddison & Denniss, 2013).

Policy instruments can be *coercive* e.g. legislation, regulation, licensing, administrative directions, reporting or taxation, or *non-coercive* e.g. communications, contracts, expenditure, loans and subsidies (Althaus et al., 2007). These instruments are described further in the next section.

[5] Infrastructure (and other) public policy is made up of several policy objectives but it is useful to distinguish between different goals because they presume different allocation of costs and benefits amongst social groups (including over time and in different places). This speaks to questions of policy justice and policy legitimacy.

Direct government provision	Regulatory instruments 'Sticks'	Economic instruments 'Carrots'	Information instruments 'Sermons'	Voluntary actions by businesses
Public assets Public land management National defence Social security Education Policing Emergency services Census, geological survey Compulsory acquisition **Public enterprises** State-owned corporations	Acts Regulation • Prescriptive • Performance • Principles • Process Executive orders Administrative decisions Zoning Mandatory standards Mandatory disclosure Fit for purpose obligations	Taxes and user charges Levies and fines Market-based instruments Subsidies, grants, loans Government insurance Government bonds PPPs and contracting out Market-based regulation Co-operative regulation	Public information Advertising Speeches and events Consultative boards Capacity-building activities Knowledge-sharing Voluntary disclosure Research	Voluntary standards Codes of practice Rating tools Insurance **Community-based actions and services** Volunteering Remittances NGOs Charities Churches

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More coercive instruments, less reliant on voluntary action, less discretion, more government involvement

Instruments more reliant on voluntary action, more discretion, less coercion, less government involvement

Figure 4. Five main types of policy instruments (modified from Howlett and Ramesh 2003; Althaus, Bridgman et al. 2007; Salamon, 2002 and Birkland 2011; Maddocks 2011)

Carrots, sticks and sermons: instruments of policy

Most policy objectives are pursued using a mixture of different policy instruments. Virtually all types of policy instruments are found in the infrastructure policy landscape (Vallejo & Mullan, 2017). **Figure 4** shows the policy instruments most commonly found in the infrastructure policy toolbox. These instruments have been classified into five main types and placed along a spectrum, from instruments that are the most coercive with the highest level of intervention by government and least amount of discretion, through to instruments that are less coercive and instead rely on voluntary action with minimal intervention by government (Althaus et al., 2007; Birkland, 2011; Howlett & Ramesh, 2003; Maddocks, 2011; Salamon & Elliott, 2002).[6]

On the far left are infrastructure policy instruments where government, or other institutions of the state,[7] pursue policy goals through *direct provision* of assets and services. In many countries, and for most of the 20th century, direct provision was the principal policy instrument for delivering critical infrastructure. It includes the provision of national defence, emergency services, public land management and critical infrastructure such as dams, electricity networks, ports and railways. Direct provision remains a viable policy instrument for critical infrastructure.

A closely-related policy instrument is the creation of *public enterprises* that sell goods and services. This, too, remains a widely used policy instrument for infrastructure, such as in the cases of state-owned electricity corporations or water corporations.

The three groups in the middle are often referred to as 'sticks, carrots and sermons', which refer to a basic typology of penalties, incentives and information.

Regulatory instruments, or 'sticks', prescribe actions which must be complied with; failure to do so usually involves penalties. Regulation includes acts, enabling legislation, rules, administrative procedures, executive orders, zoning, mandatory standards (see **Box 2** on standards) and mandatory disclosure requirements. Regulation is a widely used policy instrument for critical infrastructure provision and is typically justified on the basis that more coercive instruments are required when the risk of failure is high, when the public interest must be protected, or where there is market failure. Maddocks (2011) identifies four main types of regulation important for infrastructure:

- *Prescriptive regulation*: this prescribes activities that can be undertaken and/or how they are to be undertaken and may include prohibitions or obligations to comply with particular requirements or standards. Land use planning regimes are typically based on prescriptive

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[6] The typology of policy instruments presented in Figure 4 has been synthesised from policy literature and guidance documents. It reflects the underlying logic of most typologies of policy instruments, which are organised around the degree of coercion implied in bringing about a desired change in behaviour – this is sometimes expressed as the level of intervention by government, or the type of state activity being employed. This is a common way of organising policy instruments, but other typologies may emphasise the resources that governments can draw upon to shape behaviour (such as the NATO typology by Hood and Margetts 2007 which identified nodality or information resources (N), authority (A), treasury or money (T) and organisation or personnel (O)).

[7] These include parliaments, the bureaucracy, courts of law and the military

regulatory frameworks, as are technical and reliability standards for electricity infrastructure, for example.

- *Performance-based regulation*: this specifies desired outcomes or objectives but not how this ought to be achieved. Examples include building codes that establish requirements for the thermal or structural performance of buildings but allow flexibility for designers or builders in how these are achieved. Other common examples include environmental pollution regimes that regulate the performance of industrial facilities (e.g. in terms of emissions) but do not specify the technologies or processes to achieve these, or contractual 'fit-for-purpose obligations' to deliver infrastructure that meets its intended purpose.
- *Principles-based regulation:* this relies on high-level principles to drive the desired outcome. Examples include regulation using sustainable development principles to guide or evaluate infrastructure projects;
- *Process-based regulation:* this controls the process of provision rather than specifying the outcome. Environmental impact assessment regulations are an example of process-based regulation widely used in critical infrastructure delivery.

Economic instruments, or 'carrots', use fiscal measures to induce the desired behaviour but ultimately leave the final choice to private actors. These instruments include taxes and user charges, levies and fines, market-based instruments, subsidies, grants, loans and benefit payments. These instruments also include government insurance, government bonds (such as infrastructure bonds), public-private partnerships (PPPs) and other forms of contracting out as well as market-based regulation and cooperative regulation (for example a blend of industry standards that are enforced by a regulatory agency – see **Box 2** on standards).

Economic instruments are widely used in critical infrastructure policy where infrastructure services have been marketized such as in the unbundling of electricity or telecommunications, the establishment of water markets, or the competitive leasing of airports and ports (Klein, 2016).[8] Other examples include user charges to manage road congestion, (Börjesson et al., 2012), government bonds to fund investments in sustainable infrastructure (Carbon Bonds Initiative, 2017), and public-private partnerships to procure, deliver and/or operate critical infrastructure (World Bank, 2018).

Box 2. Standards

Standards are used extensively in the design and delivery of critical infrastructure systems, yet the term encompasses a range of instruments in policy terms. A 'standard' refers to a voluntary document that establishes agreed principles or criteria so that users can make reliable assumptions about a product, service or practice. ISO/IEC (2016) defines a standard as:

A document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context. Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits.

[8] Note that there are numerous challenges to creating markets in critical infrastructure systems, arising in part from their networked character, which introduces barriers to competition and tends to favour monopolies (see Klein, 2016 for further discussion).

Standards are often developed by standards organisations at the international level (e.g. by the International Standards Organization), regionally (e.g. the European Union's EN Standards) or nationally (e.g. by Standards Australia). They can also be developed by groups (such as industry associations or trade unions) or even by individual companies.

Types of standards include product and design standards, codes of practice, safety standards, test methods and management system standards (Standards Australia, 2016). On their own, standards are voluntary, have no legal status and no requirement for compliance. However, a standard may be cited in legislation or written into a commercial contract and thus become mandatory (Standards Australia, 2016). It is for this reason that 'standards' appear as policy instruments under Regulatory, Economic, Information and Voluntary categories.

Information-based instruments, or 'sermons', seek to influence behaviour by raising awareness and/or shaping preferences (for example shifting social norms around water consumption during a drought). These tools include public information campaigns, targeted advertising, cabinet speeches, consultative boards, capacity-building activities and knowledge-sharing. These tools are less common in the provision of critical infrastructure, but are nevertheless used to support the direct provision, regulation and economic instruments described above. This is particularly true for demand-side management and disaster preparedness initiatives that seek to alleviate pressure on critical infrastructure systems: for example, public information campaigns to reduce water use during a drought, early warning information systems to notify people of impending flooding or alert systems informing people of transport disruptions (e.g. Dolnicar et al., 2012; Lowe et al., 2011). Governments also increasingly use information-based instruments to fulfil their role as knowledge-brokers and to build capacity; this is evidenced by the proliferation of climate projection websites and hazards mapping.

On the far right of the spectrum in **Figure 4** are infrastructure policy instruments where very little involvement by government is required, and instead the desired behaviour is achieved through *voluntary action* by private actors including businesses, families or charities according to self-interest, ethics or emotion. This includes voluntary activity by businesses and industry, for example through voluntary standards (see **Box 2**), codes of practice, rating tools or purchasing insurance. It also includes voluntary activity by communities such as volunteering, remittances, the work of non-governmental organisations, charities and churches. These are widely used in many parts of the world, for example volunteer efforts after a disaster or community-based disaster mapping (Cadag & Gaillard, 2012; Rivera & Nickels, 2014), and governments can act to expand the role of these in achieving policy goals, such as withdrawing government-funded services or actively promoting voluntary action.

Choosing policy instruments

Infrastructure policy instruments operate within several complex systems – social and cultural, political and economic, and built and natural environment systems. These interact and influence each other to drive the selection and effectiveness of policy instruments. A range of considerations contribute to selecting policy instruments to achieve infrastructure policy objectives. How this is best dealt with to create critical infrastructure resilience is further discussed in Section 4, but some general reflections are included here.

Each infrastructure policy instrument has its own strengths and weaknesses, as summarised in Table 2. A preference for one type over another – regulation over information for example – will depend on specific policy issues, institutions and routines, and the prevailing political-economic context. More coercive instruments like regulation might be preferred where the risk of failure is very high (as in the case of many critical infrastructure systems) or where an outcome is required quickly. Information or persuasion may be preferred where a market failure is driven by information asymmetry or if enforcement is difficult. Liberal democracies like the USA or New Zealand have shifted from preferring regulation and direct government provision of infrastructure towards more incentive-based instruments such as markets and information, whereas social democracies like Sweden or Germany have retained a preference for redistributive policies.

The choice of policy instruments will also be influenced by the way they allocate roles and responsibilities across government jurisdictions (Parsons, 1995). For example, in federated states like Australia or the United States, constitutions limit the powers of the federal government with sub-national levels of government (such as states and provinces) having wide-ranging responsibilities for infrastructure provision; on the other hand, national governments often have higher revenue-raising capabilities through taxation or royalty payments.

Table 2. Potential advantages and disadvantages of policy instruments (Howlett & Ramesh, 2003)

	Regulatory instruments	**Economic instruments**	**Information instruments**
Advantages	Administratively efficient if all factors known Potentially all-encompassing Predictable Rapid Politically appealing in their visibility	Allows private actors to express preferences voluntarily and choose level of service Can involve less direct administration Can be rapid and effective Can foster innovation and diversity	Norm-shaping Potentially all-encompassing Politically appealing in their visibility Can generate 'deep' understanding and embed high levels of legitimacy for policy and social change
Disadvantages	Can generate social inequity and economic distortions, e.g. setting barriers to entry Can inhibit innovation Inflexible and lack nuance	Can generate social inequity and economic distortions Politically difficult to initiate because of their visibility Less predictable	Relatively unpredictable in terms of uptake & outcomes Time-frame for change uncertain

	Sometimes limited in scope and range Problems of legitimacy associated with coercion	Sometimes limited in scope and range Problems of legitimacy associated with commercial and equity impacts	Sometimes limited in scope and range (segmented audiences)

Individual policy instruments are also assessed for feasibility and comparative merit. Criteria used to compare or evaluate infrastructure policy instruments vary, because they reflect what is deemed to be important to communities and decisionmakers, but commonly used criteria are listed in **Table 3** (Birkland, 2011; Howlett & Ramesh, 2003; Maddocks, 2011).

Table 3. Criteria commonly used to compare infrastructure policy instruments

Criterion	**Explanation**
Workability	Taking into account technical and political feasibility, administrative requirements, resources required for implementation and enforceability.
Effectiveness	The ability of an instrument to effect the desired change based on the behavioural assumptions of target population.
Efficiency	This is often calculated based on cost-benefit analysis or cost-effective analysis.
Equity	Based on the distributive effects of policy, both in time and in space, such as the allocation of benefits and risks, the possibility of entrenching or reducing disadvantage and who bears the cost of externalities.
Appropriateness	Taking into account proportionality, as well as the broader cultural context of the policy.
Timeliness	How quickly the tool works relative to the urgency of the problem.
Flexibility	Whether the tool is sufficiently flexible to adjust to changing circumstances.
Accountability	The extent to which those implementing the instrument can be held accountable for their actions
Choice	The degree to which citizens have choice in the policy.

Understanding how infrastructure policy instruments allocate roles and responsibilities to non-government actors such as the private sector and civil society also matters (Parsons, 1995). Preferences for this are closely linked to the prevailing political-economic-cultural context such as the strength of a country's market economy or the visibility and freedom of the voluntary and non-governmental sector or the extent to which day-to-day life is governed by customary institutions like tribes. In some countries, for example, the provision of critical services is dominated by international NGOs who may not respond to domestic policy initiatives in the same way as a local actor; in other places, there has been little privatisation of infrastructure and thus economic instruments may be less effective than long-term behaviour-change programs supported by information instruments.

The allocation of roles and responsibilities between the public and private sectors is of importance in infrastructure policymaking. It is relevant to embedding resilience because in recent decades a growing proportion of infrastructure in both emerging and developed economies has been delivered by the private sector and it is seen as an important source of future investment capital to meet the widening infrastructure funding gap. By contrast, there is a trend towards re-municipalisation of infrastructure in some parts of the world whilst some countries have found it difficult to attract private capital due to economic or political instability.

Infrastructure policy instruments are based on assumptions about behaviour change and the allocation of resources and risks (or costs and benefits). Information-based policy instruments often assume a knowledge-deficit decision-making model whereby it is assumed that providing more information to individuals will lead to different choices (for example, in public health messaging). Market-based policy instruments tend to assume that behaviour will be shaped by rational and self-interested actors revealing their preferences through supply, demand and price. Alternatively, coercive instruments like regulation operate under the assumption that fear of punishment can bring about behaviour change more rapidly than other instruments.

There is evidence that these assumptions hold true in certain cases. On the other hand, there is also significant evidence that these assumptions are over-simplified, and that behaviour is far more complex and context-dependent. Behavioural psychology, for example, has clearly established that more information does not necessarily lead to behaviour change (sometimes known as the ‘knowledge-action gap’) (e.g. Finighan, 2015) whilst economic geography has similarly shown that participation in so-called competitive markets is shaped and constrained by a range of factors that contradict rational choice theory (e.g. Harvey, 2005).

4. Policy for critical infrastructure resilience

Challenges in infrastructure policy

Critical infrastructure is a complex area of policymaking, and it is beyond the scope of this report to review the policy landscape across all countries, infrastructure types and hazards. However, general themes can be identified in existing policy regimes for infrastructure; as discussed below and summarised in **Table 4**.

Table 4. Key challenges for critical infrastructure policy

Challenge
Cross-sectoral policy integration
Coordination across levels of government
Making the political and economic case for long term investments
Optimal balance of public and private involvement
Integrating with existing infrastructure

Challenges of cross-sectoral policy integration

The provision of infrastructure is rarely addressed as a single sphere of policymaking, but rather spans many policy areas: economic policy, for example, shapes the demand for logistics infrastructure for market access; national security policy may influence the location and ownership possibilities for major ports and airports; and climate policy affects investment in and operation of energy infrastructure. Land use policy, competition policy and environmental policy are other key areas that shape the policy framework for critical infrastructure. Social welfare policy is also important to protect vulnerable groups' and individuals' access to the essential services that critical infrastructure provides (such as water and power). The broader policy framework for disaster risk management also provides incentives for the infrastructure sector. Critical infrastructure policymaking therefore demands a high level of policy integration across sectors, but also across government departments and agencies that might otherwise operate in policy silos.

Challenges in coordination across levels of government

Critical infrastructure tends to cross multiple scales of policy and regulation, leading to challenges of coordination with existing policy frameworks. Due to the size and nature of critical infrastructure, national governments make infrastructure policy to further the national interest and to achieve coordination between subnational regions and across sectors; national governments also typically have substantial revenue-raising capabilities (for example through taxation). Many countries (for example federations like Australia, the United States, Germany, Brazil and India) also have strong regional layers of government (e.g. states or provinces) that have responsibilities for the provision of infrastructure services like hospitals or roads. Critical infrastructure interacts with local communities, and their natural and built environments, enmeshing it with local politics. . Costs may be disproportionately borne by a local community with benefits distributed widely in the economy, or vice versa, further complicating infrastructure policymaking. Cooperation between countries on international trade, environment and migration may also create a mis-match between the infrastructure costs and benefits

Challenges in making the political and economic case for long term investments

Infrastructure usually requires large fixed investments of financial and physical capital to build, and it typically has a long productive life, ranging from 20 years for a data centre to more than 100 years for a major transport route (DEFRA, 2011). The 'lumpy' nature of infrastructure investment and long lifespans pose challenges for policymaking held accountable to electoral cycles and to cost-benefit calculations in which the future is discounted. There has also been a broad shift away from equity and effectiveness criteria towards cost effectiveness criteria in evaluating critical infrastructure priorities. Uncertainties in our ability to forecast infrastructure requirements – driven by demographic change, environmental change, urbanisation and migration, technologies change etc – exacerbate the difficulties associated with making long term policy for critical infrastructure.

Challenges in securing sufficient finance and seeking the optimal balance of public and private involvement in infrastructure delivery

The challenges of closing the infrastructure gap, introduced in Section 2, are set amidst a broader shift in the balance of infrastructure provision between public and private actors. This is a key focus of policy and regulation. During the 20th century, governments were the principal providers of infrastructure in most OECD countries whilst international development assistance was the principal source of funding in developing countries (Coombs & Roberts, 2007). In recent decades a growing proportion of infrastructure in both developed and emerging economies has been delivered or financed by the private sector, although this trend has reversed in some places and there are new policy challenges emerging to create sufficient stability to attract private investment (World Bank, 2016). With many countries shifting towards the privatisation and marketisation of infrastructure services, such as electricity or water or telecommunications, and the increased use of public-private partnerships and other types of contracting, there has also been increased participation of the private sector in infrastructure design, delivery and operation.

Challenges in integrating with existing infrastructure

Critical infrastructure policymaking must integrate new infrastructure within existing infrastructure systems that often create physical, financial, political and institutional path dependencies for future investment and construction (Maddocks, 2011). This poses a significant hurdle for transitioning to more resilient infrastructure systems, such as decentralising energy supply or retreating infrastructure from hazardous coastal environments. There is also an enormous amount of critical infrastructure around the world that is partially finished, derelict or decommissioned that must also be considered in building critical infrastructure resilience.

Additional challenges for policy seeking to drive critical infrastructure resilience

Enhancing resilience in critical infrastructure systems under conditions of increased uncertainty and complexity translates into several policy challenges *additional* to those outlined above. Although this issue has received far less attention than the technical challenges of achieving engineering resilience, the potential for policy and regulatory frameworks to be crucial levers for enhancing infrastructure resilience is now being acknowledged (e.g. ACCRN, 2008; Cabinet Office, 2011; DEFRA, 2011; EU Council, 2008; Global Commission on the Economy and Climate, 2017; Maddocks, 2011; National Infrastructure Advisory Council, 2009; NCCARF, 2013; OECD, 2018; Rockefeller Foundation, 2013; Sundararajan & Suriyagoda, 2016; Vallejo & Mullan, 2017). Some of the key policy challenges – many of which are interconnected – are summarised below and outlined in **Table 5**.

Table 5. Some policy challenges for embedding resilience in critical infrastructure

Policy challenge	Examples
Risk allocation	Definition and allocation of risk between public and private actors in infrastructure contracting Allocation of risks, costs and benefits between generations and across places Moral hazard arising from government intervention
Market failures	Information asymmetries e.g. climate change projections, scenario modelling, overcoming proprietary or commercial disincentives to share information Providing market signals for adaptive behaviour, coordinating and scaling up adaptive actions, correcting for maladaptive action Managing externalities and distributive costs of adaptive actions, and managing risks associated with retreat / stranded assets Acting in the public interest such as shifting performance-based requirements for critical infrastructure Providing public goods such as disaster preparedness, response and recovery
Interdependencies	Overcoming path dependencies from existing infrastructure systems Modelling and scenario planning of failure pathways Valuing resilience – modularity, decentralisation, smart, independent
Adaptive policy	Policy learning approaches and policy capabilities Flexible regulation and standards Pathways and triggers Changed procurement practices

Challenges in the allocation of risks

Shifting risk profiles and rising uncertainty where historical datasets (e.g. historical climate data or performance data) are no longer reliable indicators of the future generate new difficulties in the allocation of risk between actors involved in critical infrastructure provision. There are several dimensions to this policy challenge. One is the definition and allocation of risk between public and private actors through contracting of critical infrastructure (Sundararajan & Suriyagoda, 2016), create complex challenges for public private partnerships.

Another dimension is the allocation of risk over time and space, which is compounded by the long lifespans of most critical infrastructure. This generates policy challenges for valuing resilience; for example, should the costs of providing more robust infrastructure be borne by current generations when the benefits will be realised by future generations. It also creates policy challenges for deciding when to intervene to improve resilience: wait for infrastructure to fail and replace; through ongoing repair and incremental change; or through significant investment and replacement (NCCARF, 2013).

A third, and related dimension, is the moral hazard that may be created with government intervention. If government acts as the 'insurer of last resort', for example, this can create a moral hazard to private adaptation actions (Macintosh et al., 2013).

Challenges in correcting market failures

Under conditions of systemic uncertainty and interdependencies, there are new policy challenges for government to correct market failures. These include a need for new information-based policy instruments to overcome information asymmetries, such as investment in climate change projections, collation of infrastructure condition databases, publication of socio-economic modelling, facilitation of scenario planning and/or investing in trust-based networks that help to redress commercial or proprietary disincentives for market actors to share information (Vallejo & Mullan, 2017). There are significant market risks associated with informational policy instruments, particularly in relation to pursuing 'retreat' options from hazardous areas and the creation of stranded assets (Gibbs, 2016; Macintosh et al., 2013).

Economic and regulatory instruments can also be used to provide market signals for adaptive behaviour or to coordinate private adaptation actions to avoid maladaptation at the system level or to scale-up private efforts (Maddocks, 2011). A key policy challenge is how to address the externalities of adaptive action such as the distributional effects of building more robust coastal infrastructure and displacing the hazard (Macintosh et al., 2013).

Finally, driving resilience in critical infrastructure deepens the importance of public policy that acts in the public interest, such as engaging with communities to deliberate on the trade-offs between security of supply and cost of provision of critical infrastructure (NCCARF, 2013) and setting performance-based requirements for critical infrastructure, or that provides public good, such as disaster preparedness, response and recovery efforts (Chelleri et al., 2015).

Challenges in managing interdependencies

As already noted above, critical infrastructure policy requires a high degree of coordination and integration across sectors and jurisdictions and has typically prioritised cost effectiveness and robustness criteria with a fail-safe design logic. Increasing interdependencies within and between critical infrastructure systems exacerbates these challenges of integration, valuation and design. One example of this challenge is how to value the contribution of one critical infrastructure system to another (such as the importance of electricity supply to transportation systems) and conversely how to value attributes of a system that contribute to resilience (such as redundancy, modularity, decentralisation, independence and flexibility).

Related to this is a demand for public policy that supports national infrastructure condition reports, interdependency models and scenario planning for failure pathways (Pescaroli, 2018). A widespread shift to 'all-hazards' emergency preparedness and disaster planning is another way that policy can support resilience in infrastructure.

Challenges in adaptive policy

'Embedding' resilience in critical infrastructure draws our attention to processes of *change*. A final key challenge is the need to make policy, and policymaking, more adaptive (Maddocks, 2011; Rahman et al,, 2008; Yzer et al., 2014). There are two dimensions to this. The first is to make more *adaptive policy* where policy forms, mixes and instruments are capable to responding to changing circumstances such as demographic change, climate change or technological change. This might include incorporating trigger points into regulatory frameworks, or staging implementation of economic instruments, or creating policy 'sand boxes' to allow for regulatory innovation (e.g. Barnett et al., 2014; Enquist et al., 2005). The second dimension is to adopt a *policy learning* approach (Howlett & Ramesh, 2003), which is critical for 'wicked problems' (Head & Alford, 2013). This would include fostering the capacities of policy actors to innovate and experiment with new mixes of policy instruments, monitor and learn through policy implementation, circulate and share those experiences, and consult locally on how different policy lessons might or might not apply (Borrás, 2011).

5. Case studies

Many efforts are underway to change the policy environment to support resilience in critical infrastructure.

In addition to The Resilience Shift, these include global initiatives through the World Bank's Public-Private Infrastructure Finance initiative and Global Facility for Disaster Reduction and Recovery, the Rockefeller Foundation's 100 Resilient Cities program and Asian Cities Climate Resilient Network, the UN Office for Disaster Risk Reduction as well as through bilateral and multilateral Development Banks and the European Programme for Critical Infrastructure Protection.

Many countries are also investing in policy research and change at the national and subnational levels.

This section presents selected case studies to illustrate how policy instruments, policy mixes and policy making are experimenting to build resilience in critical infrastructure systems.

The case studies included below respond to the 'additional challenges for policy' outlined in Section 4 (**Table 6**).

- **Case Study 1** on Public-Private Partnerships highlights how changes in PPP structures and processes are grappling with the policy challenge of how to best allocate risk to enable resilience.
- **Case Study 2** on Transferable Development Rights highlights how changes in land use planning frameworks are trying to resolve market failures arising as properties become more hazardous under climate change.
- **Case Study 3** on Rating Tools and Technical Standards highlights how above-compliance holistic sustainability rating schemes are evolving to incorporate resilience into infrastructure projects.
- **Case Study 4** on Complex Systems Modelling highlights how investments in collaborative research networks and complex systems modelling is generating new knowledge about infrastructure interdependencies.

Table 6. Summary of case studies

Case study	Key Resilience Challenge	Stage(s) of Value Chain			Policy Instrument(s)
		Diagnose & Conceive	Design & Delivery	Operate & Maintain	
1. Public-Private Partnerships	Allocation of risk	✓		✓	Economic Instruments (PPPs and Contracting Out) combined with Prescriptive (Regulation) and Voluntary (Insurance) elements
2. Transferable Development Rights	Market failures	✓	✓		Economic Instruments (Market-based instrument) combined with Regulatory (Prescriptive Land Use Planning) and Information (Disclosure) instruments
3. Rating Tools and Technical Standards	Adaptive policy		✓	✓	Voluntary Instrument (Rating tools) aligned with Regulatory Instruments (e.g. Prescriptive or Performance legislation and Mandatory standards)
4. Complex Systems Modelling	Interdependencies	✓	✓	✓	Information Instruments (Research, Knowledge-sharing and Public Information)

Cade study 1: Public- private partnerships

Stage(s) of Value Chain:

Diagnose & Conceive and Operate & Maintain

Policy Instrument(s):

Economic Instruments (PPPs and Contracting Out) combined with Prescriptive (Regulation) and Voluntary (Insurance) elements

As noted in Section 2, a key trend in critical infrastructure worldwide has been the overall increase in private sector involvement in the design, financing, construction and operation of infrastructure systems. This is typically governed by public-private partnerships (PPPs), which refer to "contractual arrangements between a public entity or authority and a private entity for providing a public asset or service, in which the private party bears significant risk and management responsibility" (World Bank, 2018).

In countries with mature PPP markets, new shocks and stressors – including the global financial crisis and climate change – mean that there is a renewed focus on the structuring of these partnerships to manage these uncertainties appropriately, whilst in countries where PPPs are not routinely used, there is attention on the capability within public and private sectors to utilise such instruments.

PPPs are increasingly the object of policy innovation because risk allocation lies at the heart of these contracts and shocks/stresses such as climate change are shifting commonly-held beliefs about which contractual party is best able to manage risks. The National Emergency Supply Agency (NESA) in Finland has been instrumental in driving good practice use of PPPs for the continuity and security of critical sectors in the economy. In creating thematic clusters of key stakeholders for risk-assessment and resilience-planning, NESA demonstrates how traditional technical and financial measures such as maintaining reserve stockpiles, may be paired with incentivised private sector efforts to overcome vulnerabilities in supply and business continuity (OECD, n.d.).

A recent report by the multi-donor technical assistance facility, PPIAF, identifies a range of measures commonly found within PPPs that are (in)directly related to managing climate risk including those that address relief and compensation, *force majeure*[9] events, insurance and uninsurable events, changes in law and variations/renegotiations (Sundararajan & Suriyagoda, 2016). In response to these, and related, challenges, the World Bank's Global Infrastructure Facility and the Tokyo Disaster Risk Management Hub[10] have jointly funded a project on 'Resilient

[9] Force majeure refers to political or extreme weather events deemed to be unforeseeable circumstances beyond the control of the parties, that may inhibit the parties from fulfilling their duties and obligations under the project agreements (PPIAF 2015)
[10] The Tokyo DRM Hub refers a secretariat of the Japan-World Bank Program for Mainstreaming Disaster Risk

Infrastructure PPPs—Contracts and Procurement' to develop and disseminate knowledge about disaster-resilient infrastructure PPPs, particularly to low and middle-income countries. In 2017, the facilities published findings from six case studies in Japan (including three BOT and three Concession-style PPPs[11] for infrastructure ranging from health, education and research facilities to airports and major roads).

The report concludes that revised and more detailed standards that incorporate lessons from previous disasters are a key way that the policy environment for critical infrastructure can adapt and evolve. At the same time, the application of these standards in structuring project PPPs should be tailored to the characteristics of each project. The context-specific definition of Force Majeure was also found to be a key item of negotiation and there is work underway in Japan towards adopting numerical objective criteria for different hazards to more clearly delineate public-private responsibilities. Profitability risks and grace periods for (reduced) performance of services after disasters are also contractual levers to embed resilience. Japan has also established an information database on past natural disasters and anticipated risks to help private entities estimate long-term disaster risks and thus reducing uncertainty for private operators.

Additional PPP levers for embedding resilience included the specification and evaluation of disaster risk management (DRM) in the procurement process: specifications for DRM should cover emergency response, inspection and evaluation of damages, robust facility designs, and robust operation and maintenance systems and important areas of clarification were expectations for notifying public authorities about interrupted service provision or damaged infrastructure and clearly detailing the required functions or service delivery during/after a disaster. Similarly, monitoring and payment provisions were used as incentives for private companies to invest in DRM measures. Given that these enhanced DRM requirements can affect the cost competitiveness of bids, the report emphasised the need to include evaluation criteria that rewarded innovation in DRM. For some projects, where the market for potential private sector providers was limited, early screening and ongoing dialogue was required in the procurement process.

Finally, the report found that it was necessary to consider the value for money of infrastructure insurance as well as its availability for specific hazards in specific regions. For example, business operators may be required to add an earthquake rider to their fire insurance, but this may compromise the profitability of the infrastructure investment given the cost and low availability of earthquake insurance in Japan. Alternative risk management and transfer mechanisms (such as derivatives, cat bonds, captives, reserves or contingency funds) should be considered alongside

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Management in Developing Countries, administered by the Global Facility for Disaster Reduction and Recovery (GFDRR), World Bank Group. The Global Infrastructure Facility (GIF) is a partnership among governments, multilateral development banks, private sector investors, and financiers and provides a new way to collaborate on preparing, structuring, and implementing complex projects that no single institution could handle on its own. (Sundararajan & Suriyagoda, 2016)

[11] BOT = build-operate-transfer; Concession = gives a concessionaire the long term right to use all utility assets, including responsibility for operations and some investment. Assets typically revert to the authority at the end of the concession period. (World Bank 2018)

more conventional insurance. The report found that the main advantage of alternative risk transfer mechanisms was that payments can be made available more quickly than insurance as damage assessments are not required. The report concludes by considering cases where financial institutions have required private operators to provide business continuity and DRM plans, and technical due diligence reports, to secure finance. Insurance was not mandated to secure loans, but it was taken into consideration in credit assessment.

Case study 2: Transferable development rights

Stage(s) of Value Chain:

Diagnose & Conceive and Design & Delivery

Policy Instrument(s):

Economic Instruments (Market-based instrument) combined with Regulatory (Prescriptive Land Use Planning) and Information (Disclosure) instruments

The impacts of climate change represent a significant new source of shocks and stresses to critical infrastructure systems. Climate change will render areas of land more hazardous than under previous climatic regimes. Sea level rise combined with stronger storm systems producing new patterns of coastal flooding and erosion are a prime example of this phenomenon. Such changes to bring climate change on a collision course with well-established land tenure, property law systems and principles of private property rights (Sheehan et al., 2018). In Australia 85% of the population lives within 50km of the coast and it is estimated AU$266 billion of infrastructure is at risk from sea level rise (Sheehan et al., 2018). This is echoed elsewhere around the world and poses enormous challenges for the policy and regulatory frameworks that have governed prior development patterns; it also has profound implications for the efficient functioning of land markets in countries that have liberalised their property systems. These challenges are both retrospective and prospective: how can we build resilience into pre-existing critical infrastructure systems that are now located in more hazardous areas and how can we direct new critical infrastructure development away from higher-risk areas?

Innovations in land use policy are grappling with the difficult intersection between regulatory, economic and information-based instruments. Physical works like sea walls are often proposed in response to sea level rise, however there is increasing awareness about the consequences on coastal processes and the significant investment requirements. (Donner & Webber, 2014). Subsequently non-physical measures to incentivise and control changes in development are gaining popularity. Policy levers include disaster preparedness planning, building codes, land use zoning, land taxation and relocation strategies (Boatman et al., 2008). At the same time, states are wary about the potential costs to taxpayers where it is determined that property owners are due compensation or where it is deemed desirable to return coastal land to public ownership. A range of policy instruments are available to grapple with this issue. Transferable Development Rights (TDR) are blended policy instruments made up of regulatory elements within property law and planning schemes, market-based elements in land markets and property development, and sometimes information-based mechanisms like disclosure. These programs can be mandatory or voluntary.

TDR programs are designed to separate the ‘right to develop’ from the land itself; creating a new market in trading development rights. There are parallels with market instruments in natural resource policy such as carbon and water trading schemes (Linkous, 2017). TDR programs typically establish ‘sending sites’, i.e. parcels of land where development rights will be sold, and ‘receiving sites’, i.e. parcels of land that have been deemed more suitable for additional development. The price of the development credit reflects the difference between the developed and undeveloped value at the sending site (Fulton et al,, 2004) and once a development right is sold ‘a restrictive deed, covenant, or easement is recorded for the sending site property, specifying regulations for future permitted and prohibited activities’ (Nellermoe, 2016, p. 231). TDR Banks are often created to serve as a ‘clearinghouse’, helping to ensure liquidity and stability in the TDR market (Nellermoe, 2016).

TDR programs can thus be used to direct new development away from at-risk areas as well as to transfer the right to develop from existing developments that are now at greater risk, although they do not typically cover the cost of removing existing infrastructure from ‘sending sites’. If designed well, TDR programs can support the redistribution of development to achieve public goals and in a way that is economically efficient, helping to correct ‘windfalls and wipe-outs’ commonly seen in property markets (Linkous, 2017) particularly in relation to hazard information disclosure and post-disaster land value drops or speculations (Dharmavaram, 2013). These schemes have been used in different countries such as the Netherlands and the USA for almost a century, typically in heritage conservation and agricultural land protection (Sheehan et al., 2018). There has been some use of them for biodiversity conservation and open space protection also (Bruening, 2007). To date, TDR programs have had mixed success in terms of the amount of land protected and their efficiency (Bruening, 2007; Linkous, 2017; Pruetz & Standridge, 2008).

Nevertheless, they remain popular, most likely because TDR programs are consistent with prevailing preferences for market-based approaches to land use planning (Dolnicar et al., 2012). There is renewed interest in their potential to foster urban and infrastructure resilience by transitioning existing and new development activities away from at-risk areas. A World Bank report published in 2013 reviews the potential for land value capture schemes, including TDR programs, to facilitate effective disaster risk reduction particularly in emerging economies and developing cities where TDR programs have combined disaster risk reduction, environmental protection, infrastructure development and poverty alleviation goals (Burra, 2005; Dharmavaram, 2013). TDR programs use informal slums in hazardous areas as ‘sending sites’, in many cases recognising the development rights of the residents and securing majority support from local settlers. ‘Receiving sites’ are typically located in more built-up urban areas. The sending sites are then converted to uses more consistent with their hazard profiles, for example public open space. Numerous TDR programs operate in the USA too (Nellermoe, 2016). In their meta-analysis of American TDR programs, Pruetz and Standridge (2008) identified 10 success factors: there needs to be demand for bonus development, receiving areas must be customized to meet community needs, further development of sending areas must be strictly regulated, few or no alternatives to TDR available to secure extra development (e.g. height or floor space), the provision of market incentives such as enhanced transfer ratios (i.e. a more-than-one-to-one development right), certainty that bonus development will be approved, strong public support for preservation goals, simplicity in program design, promotion and facilitation, and a TDR bank.

Case study 3: Rating tools and technical standards

Stage(s) of Value Chain:

Design & Deliver and Operate & Maintain

Policy Instrument(s):

Voluntary Instrument (Rating tools) aligned with Regulatory Instruments (e.g. Prescriptive- or Performance-based legislation and Mandatory standards)

One of the major trends in built environment design and construction over the last two decades has been the proliferation and success of voluntary sustainability rating tools. These rating tools reward built environment projects for above-compliance design and operations and are seen as defining best practice in infrastructure design, construction and operation as well as fostering innovation. They are also an example of adaptive policymaking that (i) allows for flexibility in the way projects achieve an overall sustainability performance, (ii) continually push the envelope of best practice that interacts with (and in some cases influences) technical standards, and (iii) has a process of continuous review and improvement.

Rating tools are based on technical assessment methods that assess projects across economic, social, environmental and governance dimensions over the project's life cycle. Their assessment frameworks are typically made up of sustainability indicators organised into different categories (such as Leadership, Procurement, Energy, Heritage or Economic Benefits); specific performance or process requirements are outlined for each indicator and project teams are required to submit evidence of compliance with those requirements to be awarded credits against each indicator. Ratings are awarded to projects based on overall credit scores, and most rating schemes require that assessments are carried out by registered practitioners and that supporting evidence is independently verified.

Rating tools are typically classified as 'voluntary' policy instruments because most have been led by the built environment industry, albeit often with some level of financial support from governments, and do not in themselves establish mandatory or economic incentives for action. In some cases, the rating tools have been used in contractual documentation for the delivery of built environment projects or in land use planning policies, giving them additional weight.

Rating tools were first developed for buildings and then communities or precincts: well-established examples include the UK's *Building Research Establishment Environmental Assessment Method* (BREEAM), the USA's *Leadership in Energy and Environmental Design* (LEED), Australia's *Green Star* and Japan's *Comprehensive Assessment System for Building Environmental Efficiency* (CASBEE). Soon after, rating tools were developed infrastructure such as roads, bridges, energy and water infrastructure: including the UK's Civil Engineering Environmental Quality (CEEQUAL) in 2003, the USA's *Envision* tool in 2012, Australia's *Infrastructure Sustainability* (IS) tool in 2012, and Engineers Against Poverty/ARUP's *A Sustainability Poverty Infrastructure Routine for Evaluation* (ASPIRE).

These tools have increasingly turned attention to resilience as a core component of sustainable infrastructure delivery and have introduced or modified indicators accordingly. The IS tool, for example, has two indicators assessing Resilience and Climate/Natural Hazards and Envision has six indicators measuring Resilience.

There has been some debate within industry about the compatibility of ‘sustainability’ and ‘resilience’ approaches to assessing infrastructure projects (Bocchini et al,, 2013), and whether resilience-focussed rating tools are required.

There is a new generation of tools emerging (Meister Group, 2017) including: the *Resilience-based Earthquake Design Initiative* (REDi) rating system developed by Arup; the *SuRe Standard for Sustainable and Resilient, an* infrastructure global voluntary standard being developed by the Global Infrastructure Basel Foundation and Natixis; the *Building Resilience Rating Tool* developed by the Insurance Council of Australia; the *Community Resilience Assessment Methodology* (CRAM) developed by the US National Institute of Standards and Technology; and the *Performance Excellence in Electricity Renewal* (PEER) standard developed by the Electric Power Research Institute and Motorola.

The PEER standard is the first rating system dedicated to the sustainability, resilience and reliability of power systems, including cities, utilities, campuses and transit systems. It is part of the USA’s Green Building Certification Institute’s (GBCI’s) suite of rating tools (which includes LEED and others). PEER sets standards and evaluates performance across four key areas: reliability and resiliency; energy efficiency and environment; operations, management and safety; and grid services. It defines risks and threats to power systems including supply interruptions (e.g. from trees), unintentional damages (e.g. from animals or traffic accidents), and extreme weather (e.g. flooding or windstorms or earthquakes) and proposes resilience measures that are preventative, protective and operational (Sulthan, 2018).

A potential limitation of PEER is its emphasis on ‘hardening’ infrastructure to shocks, specifically within facilities or campuses. As at 2019, nine projects are showcased under the standard (GBCI, 2019).

In 2018, the Ameren Microgrid became the United States first micro-grid to be certified, receiving a PEER v2 gold rating. The US$5 million facility, located adjacent to the University of Illinois, was connected in May 2017 and has received international attention. The facility supports a 1-MW residential load through distributed generation sources including solar, wind and natural gas together with advanced automation and energy storage (S&C Electric Company, 2018). It is reported to be the only known microgrid in the nation capable of ‘seamlessly transitioning the power source for an entire distribution circuit from exclusively distributed generation sources to the traditional grid’ (GBCI, 2019).

PEER reports several resilience features. One being that even under normal conditions the microgrid uses diversified on-site generation sources to optimise the efficiency of the power system.

Additional cyber-secure controls determine whether the needed load exceeds the capacity of the renewables supply and shifts to energy storage or other systems to assist. In the event of a disruption (e.g. a power outage), the microgrid is 'islanded' from the grid. Another unique feature of the microgrid is its ability to seamlessly transition customers back to the utility grid after islanding (GBCI, 2019). Project proponents, St-Louis based utility company Ameren Corporation and S&C Electric Company, were jointly recognised at the US Green Building Council 2018 Leadership Awards for Excellence in Electricity Renewal (GBCI, 2019).

Case study 4: Complex systems modelling

Stage(s) of Value Chain:

Diagnose & Conceive, Design & Deliver and Operate & Maintain

Policy Instrument(s):

Information Instruments (Research, Knowledge-sharing and Public Information)

A key challenge to policymakers is the increasing complex interdependences between infrastructure – such as tighter coupling of physical and cyber systems, along supply chains or between infrastructure systems, heightening the risk of cascading failures. Using policy to coordinate public and private actors across critical infrastructures sectors, is central to responding to complex interdependent risks. Cost-benefit and risk analyses informing decisions on critical infrastructure must also account for the 'value' of resilience in other and between infrastructure systems (for example the value that energy resilience has for transportation infrastructure).

A policy initiative that is increasing in popularity is collaborations between government, industry and researchers that generate sophisticated, publicly available data on the interdependencies across infrastructure systems. The aim of these initiatives is to combine comprehensive and quality information on critical infrastructure systems with sophisticated data management, modelling and visualisation tools (Barr et al., 2013) and create buy in for decision making evidence.

The UK Infrastructure Transitions Research Consortium (ITRC) and the National Infrastructure System Models (NISMODs) is an independent consortium of seven UK universities and over 50 partners from infrastructure policy and practice. It was established in 2011 with funding from the Engineering and Physical Sciences Research Council (EPSRC), part of UK Research and Innovation (UKRI), a new body which works in partnership with universities, research organisations, businesses, charities, and government to create strong conditions for research and innovation (ITRC, 2019). UKRI operates with a combined budget of more than £7 billion, principally from the UK Government, and brings together seven research councils, Innovate UK and Research England (UKRI, 2019).

The remit of ITRC has been to provide concepts, models and evidence to inform the analysis, planning and design of national infrastructure (ITRC, 2019). They investigate infrastructure and its interdependencies in energy, digital communications, solid waste, transport, waste water, water supply and infrastructure governance (ITRC, 2019). In addition to developing new methods and models, it provides a virtual environment to test long-term investments and how they perform under changing conditions, whether they be political, economic, demographic or climatic.

In its first phase, from 2011-2016, the consortium developed tools and capabilities for the worlds-first national infrastructure system-of-systems model, NISMOD. The NISMOD platform includes (Barr et al., 2013; Hall et al., 2014; ITRC, 2016):

- NISMOD-DB, a national-scale spatial database, analysis and modelling system that combines information on infrastructure assets and networks with knowledge about the spatial and temporal patterns of infrastructure demand, supply and capacity.
- NISMOD-LP, which is a national model of the long-term performance of infrastructure systems to support modelling of the long-term capacity and demand requirements of infrastructure driven by high resolution demographic projects and regional multi-sectoral economic scenarios.
- NISMOD-RV, a model for infrastructure network risk and vulnerability. It embeds natural hazards in risk analysis framework to examine the robustness and vulnerability of current or hypothetical national infrastructure networks.

The NISMOD resources have been widely used in infrastructure policymaking in the UK. One example of their application has been in multi-modal multi-scalar transport modelling that explicitly considers cross-sectoral interdependencies with other infrastructure networks such as energy (where transport is the largest consuming sector), digital communications (which provide bandwidth to passengers and enable smart mobility), waste management (which requires transport services) and water supply (where flooding poses a major risk of transport disruptions) as well as vulnerabilities and resilience to risks (Lovrić, Blainey, & Preston, 2017). Information from the models have been used in the UK's National Infrastructure Plan and National Needs Assessment (Hall et al., 2017) as well as by the National Grid to help plan the integration of solar energy, defence company Lockheed Martin to analyse the risks of cyber attach on electricity substations, and the Committee on Climate Change in the 2017 Climate Change Risk Assessment (ITRC, 2016).

In its second phase, from 2016-2020, the ITRC has been awarded £5.3 million to conduct the Multi-Scale Infrastructure Systems Analytics (MISTRAL) work programme (ITRC, 2016, 2019). This builds on NISMOD to develop an integrated analytics capability to inform infrastructure decision-making across scales, from local to global. MISTRAL will extend infrastructure systems analysis capability in three scalar directions: downwards to look at the household and business level; upwards to address global interconnections in telecommunications, transport and energy; and laterally by applying the approach to other countries. It is intended that by 2020, the ITRC national infrastructure portal will be open to academia and industry as well as policymakers, providing access to infrastructure datasets, simulation and modelling results.

Similar large-scale research efforts to develop suites of infrastructure analysis and modelling tools are or have been underway in the USA (e.g. National Research Council report on Sustainable Critical Infrastructure Systems), the Netherlands (e.g. Knowledge for Climate), Australia (e.g. the Critical Infrastructure Protection Modelling and Analysis (CIPMA) programme) and globally (e.g. International Symposia for Next Generation Infrastructure) (Barr et al., 2013).

6. Conclusions

In recognition of the influence policy has on the infrastructure value chain, this report seeks to clarify what public policy is and what kinds of policy instruments are available to policymakers to promote resilience in infrastructure. The report has demonstrated the diversity of policy instruments that are available and utilised to prescribe or incentivise desired behaviours along the infrastructure value chain.

Importantly, this report has grounded the basic policy definitional work in the context of wider challenges in policymaking for critical infrastructure. Rather than seeing policy as static, or policy instruments as a toolbox of 'plug and play' levers, this report draws attention to the need to consider mixtures of policy instruments that evolve as we trial and implement and evaluate them. It also highlights the need for adaptive policy instruments that can respond to changing circumstances. At the same time, the report has highlighted that the benefits of developing common or standard approaches to infrastructure policymaking must be balanced against the need to contextualise these in different places and communities.

This report highlights examples of policy innovations seeking to foster best practice in infrastructure resilience. Policy developments for resilience are in the early stages of experimentation and implementation, and there is more work to be done to establish and assemble an evidence base for effective policy interventions. At the same time, these policy developments build on longer trajectories of policy work in disaster risk management, climate change adaptation and business continuity planning whose communities of practice and early pilot projects offer lessons that may be transferable to a wider 'all-hazards' and 'resilience' approach.

Finally, this report reiterates the important interplay between the technical and the political dimensions of policymaking. Within resilience scholarship and practice there is now a well-established awareness that resilience is not merely a technical descriptor of complex adaptive systems: it is also deeply and inherently social and we must continually ask 'resilience for whom and of what' (Meerow & Newell, 2016). Whilst decision-making should certainly be informed by the expertise and experience of infrastructure designers, builders, investors and operators it is also imperative that we give space to deliberative processes that allow for debate and participation from a wide range of stakeholders. In designing socio-technical systems for resilience, policy can and should be an asset: a public statement of priorities and principles, a forum for negotiating collective goals and trade-offs, and a vehicle to facilitate flexibility and evolution in infrastructure governance. Public policy not only enables the safety and resilience of our infrastructure systems, but gives legitimacy to the changes that communities experience in their daily lives.

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