

ANTICIPATE, REACT, RECOVER

Resilient infrastructure systems

NATIONAL
INFRASTRUCTURE
COMMISSION

May 2020

Contents

The Commission	3
Foreword	5
Infographic	6
In brief	8
Executive summary	9
1. The framework for resilience	14
2. Setting clear standards for resilience	20
3. Demonstrating resilience	30
4. Achieving resilience over the long term	38
Glossary	46
Acknowledgements	49
Endnotes	51

The Commission

The Commission provides the government with impartial, expert advice on major long term infrastructure challenges. Its remit covers all sectors of economic infrastructure: energy, transport, water and wastewater (drainage and sewerage), waste, flood risk management and digital communications. While the Commission considers the potential interactions between its infrastructure recommendations and housing supply, housing itself is not in its remit. Also out of the scope of the Commission are social infrastructure, such as schools, hospitals or prisons, agriculture, and land use.

The Commission's objectives are to support sustainable economic growth across all regions of the UK, improve competitiveness, and improve quality of life.

The Commission delivers the following core pieces of work:

- a *National Infrastructure Assessment* once in every Parliament, setting out the Commission's assessment of long term infrastructure needs with recommendations to the government
- specific studies on pressing infrastructure challenges as set by the government, taking into account the views of the Commission and stakeholders, including recommendations to government
- an *Annual Monitoring Report*, taking stock of the government's progress in areas where it has committed to taking forward recommendations of the Commission.

While the Commission is required to carry out its work in accordance with the remit and the terms of reference for specific studies, in all other respects the Commission has complete discretion to determine independently its work programme, methodologies and recommendations, as well as the content of its reports and public statements.

The Commission's binding fiscal remit requires it to demonstrate that all its recommendations for economic infrastructure are consistent with, and set out how they can be accommodated within, gross public investment in economic infrastructure of between 1.0 per cent and 1.2 per cent of gross domestic product each year between 2020 and 2050. The Commission's reports must also include a transparent assessment of the impact on costs to businesses, consumers, government, public bodies and other end users of infrastructure that would arise from implementing the recommendations.

When making its recommendations, the Commission is required to take into account both the role of the economic regulators in regulating infrastructure providers, and the government's legal obligations, such as carbon emissions reduction targets or making assessments of environmental impacts. The Commission's remit letter also states that the Commission must ensure its recommendations do not reopen decision making processes where programmes and work have been decided by the government or will be decided in the immediate future.

The Commission's remit extends to economic infrastructure within the UK government's competence and will evolve in line with devolution settlements. This means the Commission has a role in relation to non devolved UK government infrastructure responsibilities in Scotland, Wales and Northern Ireland (and all sectors in England).

The Infrastructure and Projects Authority (IPA), a separate body, is responsible for ensuring the long term planning carried out by the Commission is translated into successful project delivery, once the plans have been endorsed by government.

The Commission's members

Sir John Armitt CBE (Chair) published an independent review on long term infrastructure planning in the UK in September 2013, which resulted in the National Infrastructure Commission. Sir John is the Chair of National Express Group and the City & Guilds Group. He also sits on the boards of the Berkeley Group and Expo 2020.

Professor Sir Tim Besley CBE is School Professor of Economics and Political Science and W. Arthur Lewis Professor of Development Economics at the LSE. He served as an external member of the Bank of England Monetary Policy Committee from 2006 to 2009.

Professor David Fisk CB is the Director of the Laing O'Rourke Centre for Systems Engineering and Innovation Research at Imperial College London. He has served as Chief Scientist across several government departments including those for environment and transport, and as a member of the Gas and Electricity Markets Authority.

Andy Green CBE holds several Chair, Non-Executive Director and advisory roles, linked by his passion for how technology transforms business and our daily lives. He chairs Lowell, a major European credit management company and has served as Chair of the Digital Catapult, an initiative to help grow the UK's digital economy.

Bridget Rosewell CBE is a director, policy maker and economist. She served as Chief Economic Adviser to the Greater London Authority from 2002 to 2012 and worked extensively on infrastructure business cases. She is a Non-executive Director at Network Rail, Chair of the Atom Bank and Non-executive Chair of the Driver and Vehicle Standards Agency.

Professor Sadie Morgan OBE is a founding director of the Stirling Prize winning architectural practice dRMM. She is also Chair of the Independent Design Panel for High Speed Two and one of the Mayor of London's Design Advocates. She sits on the boards of the Major Projects Association and Homes England.

Julia Prescott is a co-founder and Chief Strategy Officer of Meridiam and sits on the Executive Committee of Meridiam SAS. She has been involved in long term infrastructure development and investment in the UK, Europe, North America and Africa. Since 2019 she has sat on the board of the Port of Tyne.

Foreword

This report comes at a time when the fragility of our way of life has been brought into sharp focus. At Budget 2018, the government asked the National Infrastructure Commission to undertake a study on the resilience of the nation's economic infrastructure. Now, at publication, we find ourselves in a remarkably different world.

In addition to the tragic human cost, the coronavirus pandemic will have a profound social and economic impact on the UK and across the globe. The Commission pays tribute to all those who are helping to minimise the impact to infrastructure during this period, often at significant personal risk. Throughout the country, people are working day and night to ensure our infrastructure networks remain resilient and I thank each of them for their continued efforts.



While this report draws on evidence collected before the pandemic, this study can inform thinking about the recovery and help ensure that we can be resilient to future challenges.

Over recent years, the UK's economic infrastructure has broadly been able to withstand shocks and stresses. However, it would have been imprudent to find reassurance in this relative success. There will always be new problems on the horizon, which may be more acute or unfamiliar.

To safeguard the systems our businesses and communities rely on, we need to anticipate and prepare for forthcoming challenges. This report sets out a framework for resilience that faces up to uncomfortable truths, values resilience properly, tests for vulnerabilities and drives adaptation before it is too late.

Events over the past year, including major floods and the UK's worst loss of power to the grid for a decade, have offered a glimpse of the damaging disruption that is possible when something goes wrong. While the flooding was localised and the power cut short term, both caused chaos for families and businesses. And we know that these are risks that will be exacerbated by climate and other changes.

It would be unreasonable to suggest that we can stay a step ahead of all the obstacles our infrastructure will face. But we can engineer a trajectory to prepare for disruptions and failures and make sure we can cope when things do go wrong. This should be achieved by establishing clear standards, ensuring systems are tested regularly and that operators take action to deliver resilience both now and in the future.

This report sets out a vision for a resilient UK – equipped and ready to respond to whatever an uncertain future may hold.

Sir John Armitt
Chair, National Infrastructure Commission

A PROACTIVE APPROACH IS NEEDED TO MAKE THE UK'S INFRASTRUCTURE RESILIENT TO FUTURE CHALLENGES

The UK's water, energy, digital, road and rail infrastructure has, for the most part, proved resilient to shocks and stresses over recent years. But there may be different or harder challenges in the future.

RECENT EVENTS HAVE EXPOSED VULNERABILITIES



The 'Beast from the East' in 2018 left **200,000** people without water for 4 hours and **60,000** people without water for 12 hours across the UK



A power outage in August 2019 led to **1.1 million** customers being disconnected from the grid



In December 2018, over **30 million** of O2's mobile network users were unable to get online for almost a whole day



In May 2018, rail timetabling changes disrupted Northern Rail and Govia Thameslink passengers' travel plans for **several weeks**

THE COMMISSION RECOMMENDS:

The system architecture needs to...



ANTICIPATE

Face uncomfortable truths

RESIST, ABSORB, RECOVER

Test for and address vulnerabilities

ADAPT, TRANSFORM

Drive adaptation and value resilience properly

The Commission recommends that...



Government sets resilience standards

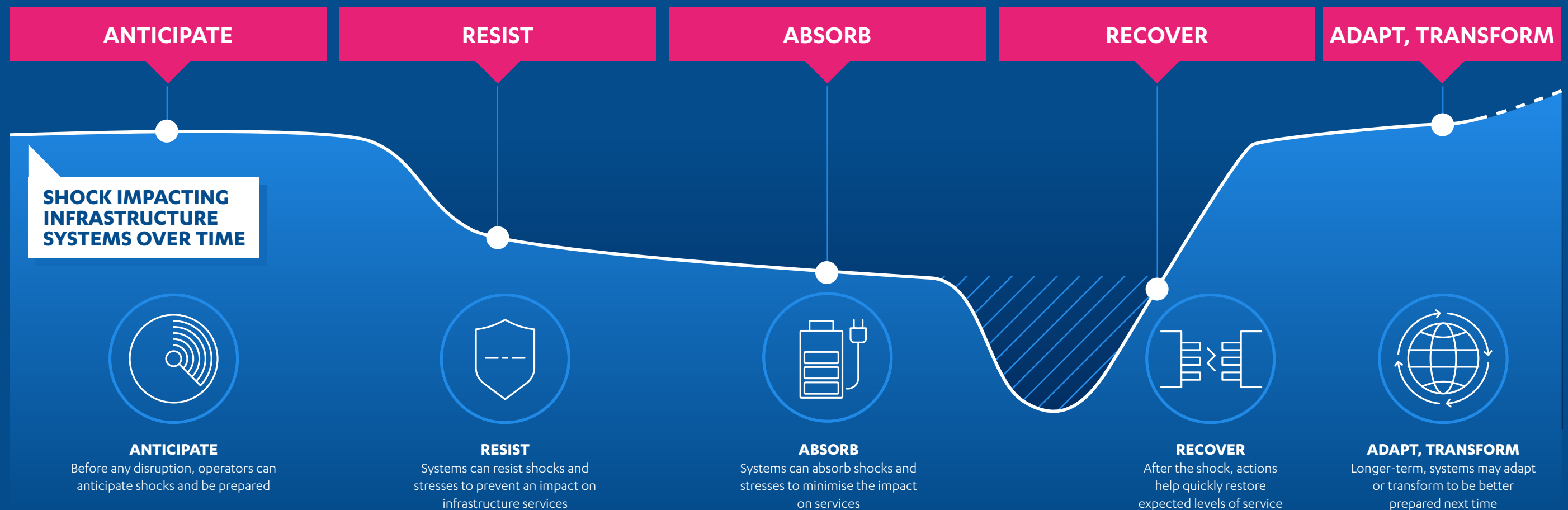
Regulators oversee regular stress testing

Infrastructure operators address vulnerabilities

Infrastructure operators produce long term resilience strategies

Regulators value resilience in decisions to support investment

THE COMMISSION HAS DEVELOPED A NEW FRAMEWORK FOR RESILIENCE



In brief

The UK's economic infrastructure has, for the most part, proved resilient to shocks and stresses over recent years. However, over the past year, major floods and the UK's worst power cut for a decade have offered a glimpse of the disruption that can happen when something goes wrong. While the flooding was localised and the power cut short term, both had significant impacts on families and businesses. The risks of disruption will be exacerbated by climate and other changes.

Resilient infrastructure can continue to provide the services the UK relies on despite shocks and has the capacity to adapt and transform to longer term chronic stresses, risks and opportunities.

To deliver resilient infrastructure, a framework for resilience is required that:

- **better anticipates future shocks and stresses by facing up to uncomfortable truths**
- **improves actions to resist, absorb and recover from shocks and stresses by testing for vulnerabilities and addressing them**
- **values resilience properly**
- **drives adaptation before it is too late.**

Much of what is needed is already in place, but improvements can still be made:

- **government should publish a full set of resilience standards every five years, following advice from regulators, alongside an assessment of any changes needed to deliver them**
- **infrastructure operators should carry out regular and proportionate stress tests, overseen by regulators, to ensure their systems and services can meet government's resilience standards, and take actions to address any vulnerabilities**
- **infrastructure operators should develop and maintain long term resilience strategies, and regulators should ensure their determinations in future price reviews are consistent with meeting resilience standards in the short and long term.**

Executive summary

The UK’s economic infrastructure has, for the most part, proved resilient to shocks and stresses over recent years. But maintaining a resilient system requires a proactive approach to resilience, facing up to the possibility of different or harder challenges in the future. This requires a framework for resilience that faces uncomfortable truths, values resilience properly, tests for vulnerabilities and drives adaptation before it is too late.

The coronavirus outbreak has shown that significant, high impact disruptions can and do happen. Much of this study was undertaken before the pandemic and it is too early to fully assess and learn lessons from the ongoing crisis. Instead, this report focuses on lessons learnt from previous disruptions and failures and the response of the UK’s energy, water, digital, road and rail infrastructure.

Many disruptions and failures of the UK’s economic infrastructure in recent years have led to moderate impacts, rather than extreme or catastrophic ones. Few have led to prolonged or widespread loss of energy or water. And the public has largely been able to cope with disruptions to digital, road and rail infrastructure. This is fortunate for citizens, but government, regulators and infrastructure operators must continue to adapt and face up to coming challenges.

A framework for resilience should deliver infrastructure that is resilient to a range of future challenges:

- government should publish a full set of resilience standards every five years, following advice from regulators, alongside an assessment of any changes needed to deliver them
- infrastructure operators should carry out regular and proportionate stress tests, overseen by regulators, to ensure their systems and services can meet government’s resilience standards, and take actions to address any vulnerabilities
- infrastructure operators should develop and maintain long term resilience strategies, and regulators should ensure their determinations in future price reviews are consistent with meeting resilience standards in the short and long term.

This requires the following actions over the coming years:

2021	<p>Government to ensure that Ofwat, Ofgem and Ofcom have resilience duties (as recommended in the Commission’s regulation study), and consider whether to extend this to road and rail.</p> <p>Government to introduce a statutory requirement for Secretaries of State to publish resilience standards every five years, starting in 2022, alongside an assessment of where changes are needed to existing structures, powers and incentives to support the delivery of these standards.</p> <p>Regulators to set out initial plans for stress tests.</p>
2022	<p>Regulators to advise government on costs and benefits of different resilience standards.</p> <p>Secretaries of State to publish the first set of resilience standards and assessment of changes to structures, powers and incentives.</p>

2023	Regulators to introduce new obligations on infrastructure operators, to ensure they: <ul style="list-style-type: none"> – meet government’s resilience standards – undertake regular stress tests – develop and implement plans to address vulnerabilities identified by stress tests – develop and maintain long term resilience strategies from 2023 onwards.
2024 (at the latest)	Regulators to ensure the first round of the new stress tests are complete.
Future price reviews	Regulators to ensure their determinations in future price reviews are consistent with meeting resilience standards in the short and long term.

Background

On 29 October 2018, the Chancellor asked the Commission to undertake a study on the resilience of the UK’s economic infrastructure. The terms of reference for the study excluded issues relating to foreign ownership, specific critical national infrastructure assets, industrial relations, national security concerns, the security of supply chains, and issues relating to the UK’s withdrawal from the European Union. Analysis of malicious threats, skills and the financial stability of infrastructure operators were limited to the scoping stages of the study, and so are not considered in this report.

The Commission published a scoping report and call for evidence in September 2019. While the Commission’s remit also covers solid waste and flood management, the scoping report explained the decision to focus the study on the digital, water, power, road and rail sectors. Flood risk has been considered within the study, but as a crosscutting hazard, rather than a separate infrastructure sector. The scoping phase also included an earlier public consultation, which received feedback from a wide range of different organisations and individuals and bilateral discussions with practitioners from a range of sectors such as infrastructure operators, regulators, consultants, banking, actuaries and academia. The full terms of reference for the study and the scoping report can be found at www.nic.org.uk/resilience/

In the main phase of the study, which concludes with this report, the Commission has undertaken further analysis, developed a framework that can be used to better deliver the resilience of economic infrastructure systems including three recommendations to improve the resilience of the UK’s energy, water, digital, road and rail infrastructure.

The framework for resilience

Resilient infrastructure can continue to provide the services businesses and communities rely upon despite short term shocks. It can also adapt and transform to longer term chronic stresses, risks and opportunities. The Commission has identified six key aspects of resilience: **anticipate, resist, absorb, recover, adapt** and **transform**. The framework for resilience should improve the approach to each of these aspects.

Resilience can be hard to get right. Infrastructure presents complex challenges. Infrastructure systems are complex, and infrastructure in one sector may have dependencies on, or interdependencies with, other sectors that can exacerbate failures. Infrastructure operators do not always have the right incentives for resilience. And there can be a failure to acknowledge resilience challenges, which may be due to optimism, denial, or a lack of challenge or scrutiny of plans and assumptions.

These factors mean that government, regulators or infrastructure operators sometimes fail to **anticipate** predictable events or fail to prepare effectively for events that are anticipated. When preparing for disruptions and failures, there can be a failure to invest enough to **resist, absorb** and **recover** from shocks. And opportunities to **adapt** and **transform** infrastructure to meet new challenges and maintain resilience can be missed.

Addressing these issues requires a framework for resilience that faces uncomfortable truths, values resilience properly, tests for vulnerabilities and drives adaptation before it is too late. The three recommendations the Commission has developed can deliver this.

Setting clear standards for resilience

Government, regulators and infrastructure operators all take decisions about what disruptions and failures to protect the public against either explicitly or implicitly, as part of the 'anticipate' phase of resilience. Society and the economy are reliant on many infrastructure services continuing to function, and so it is important that there are realistic standards that clarify the resilience outcomes that government wants to see achieved. But these resilience standards cannot be left entirely to the market. Government will always get involved when there are serious failures. And resilience is not properly valued in the market: often consumers cannot choose different levels of resilience, and infrastructure failures do not just affect consumers. Infrastructure operators do not therefore always have the right incentives to invest in resilience. While government does set some resilience standards for infrastructure services, there are still gaps, they are not always regularly reviewed, and some existing standards are unclear or out of date.

Setting standards for resilience will help government, regulators and infrastructure operators and users face up to the shocks and stresses the system might come under and the actions required to deal with them. Transparent standards will also ensure operators understand what level of resilience they are expected to deliver as they anticipate potential events. However, setting these standards can be an uncomfortable process, with difficult choices to make.

Government will need to be supported by the energy, water, and digital regulators, who should all have resilience duties as recommended in the Commission's regulation study, *Strategic investment and public confidence*, alongside other experts. Resilience duties may also be appropriate in the road and rail sectors. Regulators should provide advice on the costs and benefits of different resilience standards, dependencies with standards in other sectors, and the range of shocks and stresses that infrastructure services should be resilient to. This should draw on a wide range of expertise and set out where there are areas of disagreement among experts, as well as consensus. Government will also need to consider the capacity for response of different locations or systems, and explore methods for understanding public views on resilience, as it can be hard to understand how the public would respond to a crisis in advance.

These resilience standards should allow regulators to drive infrastructure companies to improve levels of resilience where required. However, current structures, powers and incentives may constrain operators from meeting resilience standards. Government will need to assess these and address any constraints.

Recommendation 1: Government should introduce a statutory requirement by 2022 for Secretaries of State to publish:

- **clear, proportionate and realistic standards every five years for the resilience of energy, water, digital, road and rail services**
- **an assessment of how existing structures, powers and incentives enable operators to deliver these standards or where changes are needed.**

Regulators should introduce obligations on infrastructure operators to meet these resilience standards by 2023.

Demonstrating resilience

The infrequency of extreme events, while fortunate for citizens, means there may be vulnerabilities and impacts that government, regulators and infrastructure operators are unaware of until a disruption occurs. For example, it was only following the August 2019 power cuts that the issues restarting trains after disturbances to the power supply were identified, meaning customers were left stranded for hours.

Stress testing, through simulating how systems would react to shocks and stresses, can help infrastructure operators identify and address vulnerabilities in advance of an event. It can also help infrastructure operators test decision making processes, preparing operators for disruptions other than those in the scenarios set out in the stress tests. To ensure the stress tests address resilience vulnerabilities, regulators should set out scenarios and scope for stress tests – and provide guidance for developing bespoke tests where necessary – and oversee them, scrutinising outcomes and requiring operators to develop and implement plans to remedy any vulnerabilities identified. To ensure these stress tests are carried out as effectively as possible, the UK Regulators Network should promote sharing of best practice in stress testing across relevant regulators, including learning lessons from the financial sector and other stress testing already in operation.

Operators undertaking stress tests across the sectors can support regulators and government to gain a better overall understanding of the resilience of infrastructure. Regulators can use the stress tests to develop an overview of resilience in their sector and assess any actions needed. And the Civil Contingencies Secretariat of the Cabinet Office could use the reports to develop an overview of systemic and cross-cutting resilience issues arising across sectors.

Recommendation 2: Regulators should require a system of regular stress testing by 2024 for energy, water, digital, road and rail infrastructure operators, to ensure that infrastructure operators' systems and decision-making can credibly meet resilience standards for infrastructure services.

Regulators should introduce obligations by 2023 on infrastructure operators to require them to participate in stress tests and to require remedial action in case of failure of stress tests.

Achieving resilience over the long term

Circumstances change, and therefore the best approach to resilience may change too. Infrastructure operators should proactively adapt, and where necessary transform, their infrastructure systems or services over time to enhance resilience. Sometimes, in infrastructure, adaptation and transformation only occur after disruptions and failures. Operators should not wait for a disruption to improve resilience.

Social, environmental, technological, economic and other changes and uncertainties could impact the ability of infrastructure operators to meet government's resilience standards over the long term. Developing long term strategies that consider these factors can support improved approaches to resilience. For the strategies to be delivered effectively, they will need to identify governance, decision points, and options to manage and adapt infrastructure systems and services proactively. Regulators can provide oversight and guidance to this process, to ensure that the operators use the strategies effectively to drive improvements in resilience.

Long term resilience strategies can have benefits wider than the individual operator. Alongside opportunities to enhance resilience, infrastructure operators should use the strategies to identify potential trade-offs, dependencies or other factors, including decisions that need to be made by others. Regulators can use these strategies to develop a sector wide view of resilience, and address any issues raised. The UK Regulators Network could promote the sharing of best practice in developing long term strategies for resilience so that different operators and sectors learn from each other. And the sectors' and operators' resilience strategies can also help inform government decisions.

At least in some cases, improved resilience will require new investment. In competitive markets, clear standards will ensure a level playing field with firms able to pass costs to consumers, who will capture many of the benefits of resilience. In regulated markets, regulators will also need to ensure that, in future price reviews, their determinations are consistent with meeting government's resilience standards in both the short and long term.

Recommendation 3: Energy, water, digital, road and rail infrastructure operators should develop and maintain strategies to ensure infrastructure services can continue to meet resilience standards in the long term. To ensure this, regulators should:

- **introduce obligations by 2023 on infrastructure operators to require them to develop and maintain long term resilience strategies (where there is no current requirement)**
- **set out, in future price reviews, how their determinations are consistent with meeting standards of resilience in both the short and long term.**

1. The framework for resilience

Resilient infrastructure can continue to provide the services the UK relies on despite short term shocks. It also has the capacity to adapt and transform to longer term chronic stresses, risks and opportunities. The Commission has identified six aspects of resilience – anticipate, resist, absorb, recover, adapt and transform – that government, regulators and infrastructure operators need to consider for resilient infrastructure. Although some resilience challenges are hard, many techniques have been developed to address the challenges. But there needs to be a framework in place to identify and address coming challenges and existing vulnerabilities to avoid preventable disruptions and failures and meet future needs.

There needs to be a framework for resilience that improves the approach to each of these aspects. Government, regulators and infrastructure operators need to: better anticipate future shocks and stresses by facing uncomfortable truths; improve their actions to resist, absorb and recover from shocks and stresses by stress testing their systems for vulnerabilities in advance and taking actions to address them; and drive adaptation and, where necessary, transformation, including by setting out long term strategies for resilience, and valuing resilience properly. Much of what is needed is already in place, but improvements can still be made. Later chapters set out how to deliver an improved framework for resilience.

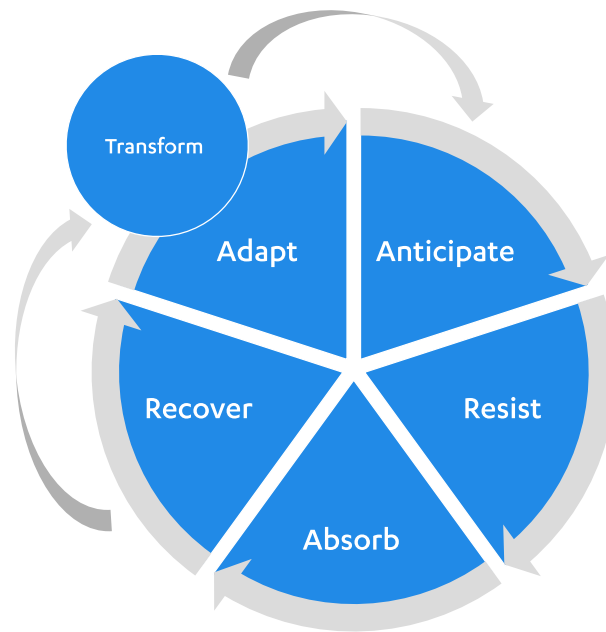
1.1 Aspects of resilience

The Commission has considered six aspects of resilience, which together capture the range of possible actions to take to deliver resilient infrastructure systems:

- **anticipate** – actions to prepare in advance to respond to shocks and stresses, such as collecting data on the condition of assets
- **resist** – actions taken in advance to help withstand or endure shocks and stresses to prevent an impact on infrastructure services, such as building flood defences
- **absorb** – actions that, accepting there will be or has been an impact on infrastructure services, aim to lessen that impact, such as building redundancy through a water transfer network to prepare for future droughts
- **recover** – actions that help quickly restore expected levels of service following an event, such as procedures to restart services following an event such as a nationwide loss of power
- **adapt** – actions that modify the system to enable it to continue to deliver services in the face of changes, for example using storage in the electricity system to support renewable generation
- **transform** – actions that regenerate and improve infrastructure systems, for example transforming infrastructure to meet the net zero target.

Figure 1.1 illustrates the six aspects of resilience. While the aspects are presented as a cycle here, not every aspect will be relevant to every infrastructure system or service.

Figure 1.1 The six aspects of resilience



1.2 Resilience in infrastructure

Many disruptions and failures of the UK's economic infrastructure in recent years have led to moderate impacts, rather than extreme or catastrophic ones. Few have led to prolonged or widespread loss of energy or water. And the public has largely been able to cope with disruptions to digital, road and rail services. However, maintaining resilient infrastructure systems requires constant attention. Shocks and stresses are inevitable, and the future may present different, or harder, challenges. The UK's track record on resilience is fortunate for citizens. But while government, regulators and infrastructure owners and operators should be proud of their successes, this cannot be allowed to lead to complacency. They must continue to adapt and face up to coming challenges.

Infrastructure presents complex challenges

Resilience is hard to get right in infrastructure. Infrastructure systems are complex, and infrastructure in one sector may have dependencies on, and interdependencies with, other sectors. These can lead to cascade and escalating failures, such as the cascade failure seen during the August 2019 power cut where some trains took hours to be restarted following a disruption to the power supply.¹ Increasing interdependencies can also lead to 'emergent' outcomes, which are not related to any specific aspect of the system but emerge from all the elements combined, and can be very difficult to foresee.² These vulnerabilities are not well understood.^{3,4}

As part of this study, the Commission worked with Oxford University to pilot an approach to system of systems modelling using network analysis and system simulation to understand the impact of dependencies and interdependencies, see box 1.1. The Commission has also carried out research on emergence to look at case studies of emergence in infrastructure and similar systems, which is published alongside this report.⁵

Box 1.1: Piloting an approach to understanding infrastructure interdependencies

Alongside Oxford University, the Commission piloted an approach to using modelling to understand the resilience implications of cross sector interdependencies in the UK infrastructure networks both now and in the future.

The pilot uses network modelling techniques to capture ‘functional dependencies’ – dependencies where one asset relies on another to function – between the assets in the water supply, rail, strategic road, electricity and digital sectors. The Commission did not use this model to analyse other types of dependencies, such as the risk of damage to an asset from being in close physical proximity to another. The modelling also did not consider risks from human error or behaviours.

This approach is intended to model how failures could cascade through the cross sector system. No model can represent all the complexity of the real world exactly, and so the model looks at one aspect of resilience and makes assumptions where there are data gaps. The results are illustrative. However, the model shows how this approach could help to understand cascade failures, how different ways to enhance resilience can be compared, and how opportunities for improving resilience could arise from planned changes to the networks. A key data gap is around the resistance of individual infrastructure assets and cross sector dependencies, which will need to be addressed if this work is to progress. A paper on the pilot is published alongside this report.⁶

Further characteristics of infrastructure systems make resilience difficult, for example:

- it is difficult to test infrastructure systems for vulnerabilities, or to understand the impact of changes, as they are in constant use
- many assets are long lived, and so uses and engineering standards may have changed since they were built
- data on asset condition and expected rates of decay is not always available – some data could be collected but is not, and other data is too hard to collect.

However, these problems can be overcome. Engineers and others have developed techniques to deliver resilience in infrastructure despite these challenges, including building spare capacity and backup systems into infrastructure networks, or ensuring that some infrastructure can fail safely. For example, telecoms and digital network companies use onsite backup generators in the event of a power outage, and flood defences can include systems which are safe to fail by diverting flood water to certain non-critical zones in the event of a failure. However, just having techniques available to improve the resilience of infrastructure doesn’t mean those techniques are always adopted in practice, especially when accountability is limited.

There are not always the right incentives for resilience

Government, regulators and infrastructure operators need to strike a balance between short term cost saving measures, which could mean having too little spare capacity to deal with shocks and stresses, and ‘gold plating’ – providing excess resilience at high cost (which would ultimately fall to consumers and taxpayers). Not effectively maintaining a system can have significant costs and impacts. For example, following flooding in 2019, during which over 1,000 people were instructed to evacuate their homes and

approximately 100 properties and 550 hectares of farmland were damaged,⁷ a total of £5.25 million in relief funding was made available to both Wainfleet and Whaley Bridge.⁸ Whilst the Environment Agency had spent £80,000 a year on planned maintenance on the River Steeping,^{9,10} reviewing the frequency of maintenance was one important recommendation made as part of the investigation following the flood.¹¹

Incentives for infrastructure operators are likely to lead to under investment in resilience measures.¹² The costs of providing resilience in advance fall to infrastructure operators, and ultimately, consumers. The benefits do not just fall to consumers, but to other dependent systems, and, more widely, to society and the economy. If a serious failure happened, government would step in to support the public (as seen with recent floods, and at Toddbrook dam), and taxpayers would foot at least part of the bill.

There can also be little accountability when infrastructure systems fail, particularly as the causes can be so complex that it is hard to prove who was at fault. Government setting clear, proportionate and realistic standards for resilience, and regulators using obligations to ensure infrastructure operators meet these, see Chapter 2, can ensure that responsibilities for resilience, and therefore accountability in the event of disruption and failure, is clear.

There can be a failure to acknowledge resilience challenges

As set out above, while there are many techniques that can be used to deal with resilience challenges, these need to be adopted in practice. And for them to be used, potential vulnerabilities need to be identified in advance. This can be difficult. There can be a natural, but flawed, tendency to assume that if there has not been a disruption or failure so far, there won't be one in future. And there can be an assumption that low probability disruptions and failures won't happen, and such events can be hard to assess and responses hard to evaluate. Even government and experts find it difficult to face up to known risks. For example, the 2010 volcanic eruptions at Eyjafjallajökull in Iceland were known to be overdue, but volcanic ash did not appear on the UK's National Risk Register.¹³ And financial deregulation in the 2000s did not account for the risk of financial crisis despite centuries of experience.¹⁴ Groupthink and a desire for consensus mean dissenting voices are often filtered out.

The disruptions and failures seen in recent years demonstrate that this way of thinking extends to infrastructure. Government, regulators or infrastructure operators sometimes fail to anticipate predictable events or fail to prepare effectively for events that are anticipated.¹⁵ For example, whilst it is not owned by a water company, the poor design and maintenance of Toddbrook dam was flagged months in advance of the partial failure in 2019, but urgent action was not taken until the partial failure occurred,¹⁶ and nearby residents had to be evacuated.¹⁷

There is a wide body of work, both in the UK and internationally, that is looking at how infrastructure resilience can be improved, see box 1.2.

Box 1.2: Approaches to resilience in infrastructure

The list below provides an overview of some notable reports, reviews and recommendations covering resilience of critical infrastructure:

Good Governance and Critical Infrastructure (2019), OECD¹⁸ provides a policy toolkit to help governments address challenges facing infrastructure in a more “complex, digitally interconnected environment” and considers the shift of critical infrastructure policy from asset protection to system resilience.

The role of public policy in critical infrastructure resilience (2019), Resilience Shift¹⁹ considers the role that public policy instruments, such as regulation and standards, play in embedding resilience in critical infrastructure systems. It identifies four key challenges for embedding resilience in critical infrastructure policy: risk allocation, market failures, interdependencies, and adaptive policy.

Resilience in the round (2017), Ofwat²⁰ considers resilience as the ability to cope with, and recover from, disruption and anticipate trends to maintain services and protect the environment now and in the future. It provides practical guidance for water companies and others.

Keeping the country running (2011), Cabinet Office²¹ is a guide to support government and infrastructure sectors improve the resilience of critical infrastructure and essential services. It frames resilience as the ability to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event.

Engineering the Future: Infrastructure, Engineering and Climate Change Adaptation – ensuring services in an uncertain future (2011), Royal Academy of Engineering²² examines the vulnerabilities of different sectors and the changes required to enhance resilience to climate change. The report acknowledges system vulnerabilities that emerge from interdependencies and highlights the roles of governance and regulation, planning for adaptation, learning lessons and public engagement.

1.3 The framework for resilience

All the issues set out above can be addressed. But that requires ensuring the right framework is in place to test operators’ resilience assumptions and provide external challenge. The framework should enable government, regulators, and infrastructure operators and owners to face uncomfortable truths, test for vulnerabilities, value resilience properly and drive adaptation before it is too late.

Much of what is needed is already in place, but improvements can still be made. This report sets out recommendations to help deliver an improved framework for resilience.

Anticipate – facing uncomfortable truths

The framework should ensure there are the right incentives and accountability for resilience. This is part of the anticipate phase of resilience. While government does set some resilience standards for infrastructure services, there are still gaps, they are not always regularly reviewed, and some existing standards are unclear or out of date. Government needs to face up to future possibilities and set out clear, proportionate and realistic standards for the resilience of energy, water, transport and telecoms services against a wide range of shocks and stresses. This will support infrastructure operators to face up to uncomfortable truths and understand what is expected of them under the different scenarios.

To facilitate this, government should also assess how standards will be delivered by infrastructure systems, ensuring that the right structures, powers and incentives are in place. This is set out in more detail in Chapter 2.

Resist, absorb, recover – testing for vulnerabilities

The framework should tackle the potential failure to acknowledge resilience challenges by requiring energy, water, digital, road and rail infrastructure operators to undertake regular stress testing. The stress tests will assess the systems' ability to resist, absorb, and recover from shocks and stresses, and identify vulnerabilities. The stress tests should be overseen by regulators, and infrastructure operators should demonstrate that their systems and decision-making can credibly meet resilience standards for infrastructure services against a wide range of shocks and stresses. The regulators should also require infrastructure operators to address any vulnerabilities identified. More detail on stress testing is set out in Chapter 3.

Adapt and transform – driving adaptation and valuing resilience properly

The framework should support continued action on resilience by requiring energy, water, digital, road and rail infrastructure operators to develop and maintain strategies to ensure infrastructure services can continue to meet resilience standards in the long term. Developing long term strategies can encourage operators to look towards future challenges, and invest to adapt, and where necessary transform, their infrastructure systems to meet them. Regulators will also need to assess whether the long term strategies are being carried out. More detail on setting long term strategies is set out in Chapter 4.

At least in some cases, improved resilience to meet government standards over the short and long term will require new investment. That requires that resilience is valued properly. In competitive markets, clear standards for resilience will ensure a level playing field with firms able to pass costs to consumers, who will capture many of the benefits of resilience. In regulated markets, regulators will also need to ensure that, in future price reviews, their determinations are consistent with meeting government's resilience standards in both the short and long term.

2. Setting clear standards for resilience

Government needs to set out clear, proportionate and realistic standards for the levels of infrastructure resilience it expects under different circumstances, as part of the ‘anticipate’ phase of resilience. It is important to have standards for the resilience of essential services, to help anticipate potential shocks and stresses, and prepare for disruptions or failures. But there is significant variation in whether, how, and how effectively this is currently done. It is up to government to ensure infrastructure resilience standards are set effectively on behalf of the public.

Making these decisions can be difficult, and so government must be supported with expert advice convened by the regulators. This chapter sets out the principles for setting resilience standards, and a new process for setting them, which should lead to better resilience outcomes across the sectors. Government should review these standards every five years and publish reports setting out the full set of resilience standards, highlighting where these have been amended or new standards added. Resilience standards should drive regulators and infrastructure operators to improve levels of resilience. Government will need to ensure that the right policies are in place to support this.

2.1 Resilience standards are important

Setting and meeting target resilience standards help government, regulators and infrastructure operators to anticipate potential shocks and stresses, face up to the disruptions or failures these could cause, and prepare for these eventualities. Setting these standards can be an uncomfortable process, with difficult choices to make. Therefore, there need to be clear timeframes for setting and reviewing these standards to ensure these decisions get made.

Setting standards has other benefits, including:

- **transparency:** the process of setting standards transparently allows assumptions to be scrutinised and tested, which can help mitigate groupthink and manage public expectations of achievable service levels
- **reducing coordination costs elsewhere in the economy:** infrastructure users who rely on services will know what service they should expect under what circumstances, and so most will be able to rely on it with limited contingency planning, while those that need a higher standard (such as hospitals, or dependent infrastructure operators) can put in place contingency plans
- **supporting testing:** infrastructure resilience is too important to only address when problems arise, so systems need to be tested for vulnerabilities in advance – a clearer understanding of what constitutes failure, or even a near miss, makes it easier to identify where action is needed

- **providing accountability:** responsibility for delivering and paying for the standards will be allocated, leading to greater accountability when things do go wrong
- **incentivising resilience upgrades:** the standards may require operators to make upgrades to improve their existing levels of resilience.

2.2 Resilience standards are government's responsibility

The energy, water, digital, road and rail sectors all provide services that society and the economy rely on to continue to function. These services are generally provided by the private sector. Private sector companies are, and should be, responsible for ensuring the services they offer are resilient. But resilience cannot be left entirely to the market, because it is likely to under invest in it:

- **Government will always get involved when there are serious failures or risks are too high for the private sector:** Government must protect citizens and will get blamed for any serious failure of essential services.²³ Government's role becomes most obvious where lives are at risk,²⁴ but it is also frequently reflected through financial interventions, such as taking ownership of a rail franchise,²⁵ or underwriting insurance schemes like Flood Re and Pool Re,^{26,27} where the costs are too high for the private sector to take the risks.²⁸ Infrastructure operators are rarely exposed to the full costs of serious failures. This weakens infrastructure providers' incentives to provide expensive resilience measures.
- **Resilience is not properly valued in the market:** Often, consumers do not have real choices about the level of resilience they receive. Most infrastructure companies cannot offer different standards of resilience to different people. And there aren't usually realistic alternatives for consumers to the resilience standard offered by the incumbent infrastructure provider: while backups, like generators, exist, they are often expensive solutions to low probability events.²⁹ Even if there were more choices for consumers, most don't have experience of failures, so find it hard to know how much they would pay to avoid it.^{30,31} Therefore, infrastructure providers don't often have the right financial incentives from consumers to provide resilience to lower probability events.
- **Infrastructure failures do not just affect consumers of that service:** For example, failures in the rail network will affect not only commuters, but the businesses they work for and the firms and customers that, in turn, rely on those businesses. Because infrastructure is integral to so much of society and the economy, these secondary effects can be large.³² But as the costs of this do not only fall on consumers, infrastructure providers do not have strong incentives to avoid them.
- **Markets focus on those who can pay:** For the most part this is publicly accepted for infrastructure services.³³ However, in a crisis, the public view tends to be that protection should be based on need, rather than who can pay, with the most vulnerable supported the most.³⁴ Markets cannot reflect these kinds of concerns about fairness.³⁵

Therefore, it is government, not infrastructure providers, who need to determine resilience standards on behalf of society, just as government sets out rules for consumer protection, or health and safety standards. Government inevitably takes a share of responsibility for resolving serious disruptions, and can look across sectors, and take into account the value of resilience, the effects of failure on the economy and society, and concerns about fairness.

The Commission has addressed the need for government led standards in previous reports: the first National Infrastructure Assessment recommended the government should set out a strategy to deliver a nationwide standard of resilience to flooding with an annual likelihood of 0.5 per cent by 2050, where feasible. There is currently no clear standard for flood protection, and too often flood defences are built following floods. The Commission’s recommendation aims to protect everywhere equally, only providing a higher standard in urban areas where the risks of emergency services being overwhelmed would be much greater than in rural areas.³⁶

The Commission’s regulation study, *Strategic investment and public confidence*, (see box 2.1) also looked at other ways in which resilience needs to be led by government. The report recommended that the government updates regulators’ duties to include promoting resilience of infrastructure systems.³⁷ Transport was not in scope of the regulation study and has a different regulatory model, but the government should consider whether a resilience duty would also be appropriate for regulators in the road and rail sectors.

Box 2.1: Strategic investment and public confidence

In October 2019, the Commission published its review of the economic regulatory framework for the energy, water and digital sectors.³⁸ The study concluded that an updated and strengthened regulatory system should:

Provide a strategic framework to deliver the UK’s long term infrastructure needs: government should produce Strategic Policy Statements for each sector in the first year of every parliament and introduce legislation which requires regulators to have regard to the Commission’s recommendations, if endorsed by the government.

Have statutory duties that support long term investments: all regulators should have a primary duty to ensure resilience in their sectors.

Use competition to drive innovation: wholesale competition outside of the ‘standard’ price control should be the default mechanism to deliver strategic investments, to improve affordability, transparency and innovation.

Ensure regulation acts fairly for all groups of consumers: regulators should be more proactive in addressing financial risk and corporate governance, to ensure that rewards reflect performance and risks that are genuinely taken by investors, and regulators should be able to prevent companies from engaging in price discrimination that does not provide an overall benefit to consumers.

2.3 There are gaps in current resilience standards

There is currently significant variation in whether and how government provides resilience standards for economic infrastructure. In the absence of clear government direction, regulators and infrastructure operators also take decisions about which disruptions or failures to protect the public against either explicitly or implicitly. In some cases, this means that standards are unclear, counterproductive, or are based on questionable assumptions. In other cases, the focus of standards only covers one aspect of resilience, or no standard is set out. Table 2.1 provides illustrative examples of current resilience standards, including examples of good practice and where improvement is needed.

Table 2.1 Illustrative examples of current standards

Sector	Expectation	Description
Energy and water	Restoration of supply - guaranteed standard (consumers)	The guaranteed standards for energy ³⁹ and water ⁴⁰ both set out how quickly members of the public should expect their service to be restored. Any failure by operators to meet these standards means consumers are eligible for compensation. Consumers are clear about how long disruptions may last and the means of redress if disruptions go beyond this.
Energy	Electricity system frequency - guaranteed standard - (system)	The Security and Quality of Supply Standard ⁴¹ sets out the system frequency that the electricity system operator is expected to maintain and how quickly frequency should be restored to the expected range if it falls outside of this. The operator is clear about the expected normal operation of the system, how quickly frequency should be restored, and what circumstances require further action.
Water	Drinking water quality	Drinking water quality standards for England are set out in legislation. ⁴² Standards are clear, specific and strongly enforced through fines as a result of prosecutions. ^{43,44}
Rail	Expected service during bad weather	Network Rail has clear definitions of both ‘adverse’ and ‘extreme’ weather. ⁴⁵ While both are linked to the potential for disruption, the magnitude of disruption is not defined. Network Rail has previously noted that public expectations of the level of service during ‘adverse’ weather may not be met. ⁴⁶
Road	Reliability of road journeys	Highways England uses a journey reliability indicator as part of its performance measures. ⁴⁷ However, there is no specified target. Without a target, measuring progress is not transparent and it is difficult to evaluate whether journeys are as reliable as expected.
Digital	Service availability	Ofcom’s general conditions require communications providers to maintain uninterrupted access to emergency organisations “to the greatest extent possible”. ⁴⁸ This is clear and strongly enforced , with significant fines for failures. ⁴⁹ This is a more strict obligation than the “appropriate steps” required to be taken to ensure general network availability. ⁵⁰

2.4 Principles for setting resilience standards

Government should ensure a full set of clear, proportionate, and realistic resilience standards are set out for energy, water, digital, road and rail services. It should also review existing standards to ensure they are clear, proportionate and based on realistic assumptions and up to date evidence. Government’s resilience standards should cover which potential disruptions and failures infrastructure is expected to resist or absorb and how disruptions that government deems tolerable are expected to be dealt with, including response and recovery plans.

For the resilience standards government sets to be effective, they should be:

- informed by a solid understanding of the resilience of the public and businesses
- mindful of the capacity for response of different locations or systems
- informed by the real cost of response
- transparent.

Standards also need to be clearly aligned with the government's broader policy priorities. For example, policies that encourage greater reliance on digital services ought to be supported by appropriate standards for the resilience of those services.

Understanding the resilience of the public and businesses

It will never be realistic to protect communities and businesses from all disruptions. They can absorb some impacts of disruption or failure by changing their behaviours. For example, many people can take an alternative route or work from home to avoid disruptions to road and rail networks (although this may not be sustainable over the long term). However, people and businesses cannot and should not be expected to cope with all disruptions. The government's resilience standards need to be informed by a solid understanding of both what standard of resilience the public and businesses expect and how they respond to disruptions.

Government needs to consider a range of methods for understanding public views and expectations. At present, much of the evidence comes from stated preference surveys which indicate service users' willingness to pay for or accept a certain level of service. These can obscure the reality of the public's willingness and capacity to cope with failure, as most of those asked will not have experienced the failures they are being asked about.⁵¹ This is reflected in the fact that the assumptions underpinning some current policies and objectives are unrealistic. An example of this is the significant lack of incentives for households to self-insure against flooding.⁵²

Ofwat has already suggested that more sophisticated triangulation of different engagement techniques and data sources, (such as revealed preference choice experiments and behavioural insights), may be required to ensure a more accurate understanding of public views and behaviour.⁵³ Another way might be to consider how the public has responded to disruptive events in the past. This is particularly the case for considering low probability events where the evidence base is limited. Effective public engagement and consideration of high impact, low probability events are both included in the Commission's principles for setting levels of service, which are summarised in box 2.2. In some cases, there will be no definitive answer, but assumptions about public views need to be subject to regular scrutiny to make the best judgement possible.

Box 2.2: Principles for setting levels of service

Standards required for resilience are necessarily broader than the level of service provided to consumers. However, levels of service are also important as they set the standards that the public should expect when using infrastructure services on a day-to-day basis.

Research the Commission carried out on levels of service,⁵⁴ highlighted that a range of approaches tend to be used across, and within, sectors to determine the right level of service. The Commission has developed a set of principles to follow when setting levels of service based on best practice found from the Commission's research and engagement with stakeholders.⁵⁵ These principles ensure that costs, impacts and public expectations are appropriately balanced when setting levels of service.

The principles for setting levels of service are:

- minimise costs and risks for potentially catastrophic events as far as practicable
- use a range of methods to understand consumer views on disruption
- consider the widest possible range of impacts of potential disruptions or failures
- the right discount rate should be used for assessing costs and benefits of resilience, which might be lower for extreme cases where lives or irreversible socio-economic changes are at risk
- consider wider social impacts and any impacts on other dependent sectors qualitatively or quantitatively.

The paper published alongside this report provides more detail on these principles, including where specific approaches are not applicable when setting out clear resilience expectations and when making the case for specific resilience investments.⁵⁶

The capacity for response of different locations or systems

When setting standards for resilience, government also needs to consider how the resources for response can best be allocated. Primarily this is about where impacts and therefore demand for response services is likely to be highest. But it is also necessary to consider where and in what circumstances, response measures can be most effective.

The density of cities means there tend to be more resources available. But density also means that disruptions will have a more severe impact than an identical disruption in a rural location. For example, if the emergency services in a city are overwhelmed in a disruption, and can no longer respond, the impacts will be greater and the loss of life will be much higher than if the disruption occurs in a rural area, and emergency services from a nearby city can be deployed to support local emergency response. The Commission recommended providing a higher standard of flood protection to urban areas in the National Infrastructure Assessment for this reason.⁵⁷ Standards should also consider where it is realistic that neighbouring areas could provide support. For example, if there were widespread flooding, it might not be possible to move resources such as temporary flood defences around due to flooded roads, or defences already being in use.

The real cost of response

When assessing costs and benefits of setting different resilience standards, government should consider the expected real costs of emergency response if no standard, or a different one, was in place. This should be informed by realistic assumptions about how government would react. Existing assumptions, which may be out of date, should be scrutinised.

For example, in *Preparing for a drier future*, the Commission highlighted that water companies plans assumed that, in the event of a serious or prolonged drought with a less than one per cent annual probability, normal water supplies would be cut off and limited supplies provided through standpipes or rota cuts. However, this is unrealistic: the report argued that rather than cut people off, government would take emergency measures to continue household water supplies for as long as possible, despite the high costs. The report recommended that government should ensure plans are in place to deliver additional supply and reduce demand to avoid this eventuality.⁵⁸

Transparency

Transparency about what resilience standards are expected, and why, should help better prepare infrastructure operators and the public for disruptions. Where disruptions do happen, having clear resilience standards can help avoid surprises, provide accountability, and explain and inform the government's response.

Transparency needs to be balanced with national security considerations, and there are examples of good practice that could be built on. The National Risk Register sets out a public summary of the key risks to infrastructure and society, based on the classified National Security Risk Assessment.⁵⁹ The public summary of Sector Security and Resilience Plans includes a high level summary of planning in each of the UK's critical sectors, again summarising more detailed classified documents.⁶⁰ While these documents provide a useful starting point, government should ensure that they contain enough detail to aid planning beyond critical infrastructure operators and inform the public appropriately.

Where resilience standards already exist, they tend to be public. However, they can be buried in legislation or obscure sources. Government should publish its resilience standards for each sector in easily accessible public reports to help support better outcomes, processes and accountability.

2.5 Process for setting resilience standards

Government ministers need to be responsible for making decisions on resilience standards, as set out in section 2.2, subject to devolution settlements, see box 2.3. There should be a statutory requirement for the relevant Secretaries of State to publish a report setting clear, proportionate and realistic standards for the resilience of energy, water, digital, road and rail services where government standards don't currently apply and lay these before Parliament. It should be for government to decide the appropriate level of detail of these standards, although the Commission does not intend this to cover technical engineering or component standards but focus on the resilience outcomes operators should provide for the public. The published reports should set out the full set of resilience standards for each sector, highlighting where these have been amended or new standards added.

Setting standards for which failures to protect the public against (and consequently, which failures not to), is complex and subjective and therefore politically difficult to decide. This means that, while only government can act on behalf of the public, ministers will need to be supported in setting resilience standards by a broad range of expert advice and evidence.⁶¹ This should include a wide variety of views from other levels of government (local and, where relevant, the devolved administrations), regulators, operators and users.

Government should require the relevant regulators to provide technical support to government in setting resilience standards. The Commission's regulation study *Strategic investment and public confidence* recommended that the government update regulators' duties to include promoting resilience of infrastructure systems.⁶² Regulators generally have the technical expertise about the sectors that government does not and can ensure infrastructure operators take appropriate actions to meet the resilience standards. Therefore, regulators should set out to government departments what resilience standards are possible, and at what cost.

Regulators should convene panels of experts to collate a broad range of views and input into setting resilience standards. Regulators have links to independent experts within and outside industry and often use a similar approach, for example during price review processes. Compiling this expertise can provide a broader range of evidence. But understanding a broad range of views can also help mitigate groupthink, which is vital to ensure that resilience standards are not overly optimistic or based on unrealistic, but accepted, assumptions. The panels should include minority views, provide challenge and spark debate.

Regulators should use the advice of the panels to inform expert, independent advice, provided to government, on the costs and benefits of different resilience standards, considering a comprehensive range of shocks and stresses against which infrastructure services should be resilient. Regulators should bear in mind that there may be further shocks and stresses that, despite best efforts, have not been considered. The advice should draw on a wide range of expertise and set out where there are areas of disagreement among experts, as well as consensus. Regulators should receive additional resources to carry out this advisory role where necessary.

Government departments should use this advice to set or reconfirm clear and realistic standards at least every five years for the resilience of energy, water, digital, road and rail services. Government should then review and, where necessary, update these standards every five years. Not all standards will need to change every five years. However, if appropriate, standards could be reviewed more regularly. Once government has published the standards, regulators should amend the obligations on infrastructure operators to meet these resilience standards where relevant.

At least in some cases, meeting these standards will require new investment. In competitive markets, clear standards will ensure a level playing field with firms able to pass costs to consumers, who will capture many of the benefits of resilience, both as consumers and as members of society. In setting standards, government will need to pay particular attention to the ability of consumers in vulnerable circumstances to pay the costs, but also be aware that the benefits may be greatest for people who are vulnerable. In regulated markets, regulators will also need to ensure that, in future price reviews, their determinations are consistent with meeting government's resilience standards in both the short and long term, to enable operators to recover the costs of improving resilience.

Box 2.3: Devolution in the UK

The current devolution of powers relating to digital, energy, transport and water is set out below. Devolved matters are outside of the Commission's remit.

UK nations

The table below sets out which matters are devolved to the legislatures of Scotland, Wales and Northern Ireland for areas relating to the matters covered in this report. Other relevant devolved matters (devolved to all three nations) include economic development, the environment, housing, and local government.

Sector covered in this report	Level of devolved responsibility		
	Scotland	Northern Ireland	Wales
Energy	Reserved, aside from energy efficiency	Devolved, aside from nuclear	Reserved, aside from energy efficiency
Water and sewerage	Devolved responsibility	Devolved responsibility	Devolved responsibility
Digital	Reserved	Reserved	Reserved
Transport	Largely devolved	Devolved responsibility	Devolved, aside from rail
Flood risk	Devolved responsibility	Devolved responsibility	Devolved responsibility

Metro mayors

There are now eight metro mayors.⁶³ None of them has devolved responsibility for energy, water or digital, but many do have some powers related to transport. Metro Mayors and local authorities in England are responsible for housing and planning decisions, which interact with regulators' decisions on network capacity.

Devolution and resilience

Responsibilities are split between administrations. While some relevant policy areas, such as the UK's security strategy, are reserved, the devolved administrations are responsible for policy and strategic direction on security and protection activity in devolved areas. This means there is significant cooperation and discussion on resilience issues across different levels of UK governance. The government and regulators should involve other levels of government as appropriate when carrying out the recommendations in this report, particularly where there are common issues or challenges.

2.6 Using standards to drive better outcomes

Resilience standards should drive regulators and infrastructure companies to improve levels of resilience. When setting out or reconfirming standards, government should make a public assessment of how the incentives, structures and powers for regulators and operators across the sectors are sufficient to ensure that the standards can be delivered. This should not entail a detailed review of decisions made by independent regulators, but a broad look across the system. If the current incentives, structures and powers are not sufficient to deliver the standards, government should amend those incentives. In some instances, this will require government itself to act, but in others government may need to provide strategic direction to the relevant regulator, including through Strategic Policy Statements.

Amendments to current powers, structures and incentives will not always be required, but it is important that they are at least considered. Where they are not needed, publicly explaining why will help to clarify to regulators and operators how the standards can be delivered. It may also help highlight where the standards cannot realistically be achieved by operators. Any amendments should not conflict with existing regulatory settlements. Resilience standards should be reviewed regularly, but they will not necessarily need to be changed regularly. The standards should be forward looking and as durable as possible. Updates should be based on changed circumstances, such as increased or reduced demand, technological developments, or responding to climate or environmental challenges. Government will need to prioritise standards and make any trade-offs required.

Recommendation 1: Government should introduce a statutory requirement by 2022 for Secretaries of State to publish:

- **clear, proportionate and realistic standards every five years for the resilience of energy, water, digital, road and rail services**
- **an assessment of how existing structures, powers and incentives enable operators to deliver these standards or where changes are needed.**

Regulators should introduce obligations on infrastructure operators to meet these resilience standards by 2023.

This requires the following actions over the coming years:

2021	Government to ensure that Ofwat, Ofgem and Ofcom have resilience duties (as recommended in the Commission’s regulation study), and consider whether to extend this to road and rail. Government to introduce a statutory requirement for Secretaries of State to publish resilience standards every five years, starting in 2022, alongside an assessment of where changes are needed to existing structures, powers and incentives to support the delivery of these standards.
2022	Regulators to publish initial advice on costs and benefits of different resilience standards . This should draw on a wide range of expertise and set out where there are disagreements and consensus among experts. Secretaries of State to publish the first set of resilience standards and assessment of changes to structures, powers and incentives.
2023	Regulators to introduce new obligations on infrastructure operators, to ensure meet government’s resilience standards from 2023 onwards.
Future price reviews	Regulators to ensure their determinations in future price reviews are consistent with meeting resilience standards in the short and long term.

3. Demonstrating resilience

Few recent disruptions to the UK's energy, water, digital, road and rail services have led to extreme or catastrophic impacts. However, this relative success may have led operators to underestimate the likelihood of disruption or failure and left some infrastructure vulnerabilities to be exposed only when disruption occurs.

Carrying out a range of desk based stress tests of infrastructure systems can help identify resilience vulnerabilities in advance of a disruption or failure, and provide assurance that government's resilience standards can be met. Energy, water, digital, road and rail regulators should oversee proportionate stress testing of infrastructure systems. Operators should provide regulators with detailed, confidential accounts of the outcomes of stress tests and publish summary assessments.

Stress testing will improve the resilience of infrastructure over time within sectors. Operators who fail stress tests will need to develop and implement plans to remedy vulnerabilities identified, overseen by the regulators. Regulators can also use the outcomes of stress tests to gain an overview of the resilience of the sector.

Stress testing can also be used to improve resilience across sectors. The Civil Contingencies Secretariat of the Cabinet Office will be able to use the reports from stress tests to identify systemic and cross cutting resilience issues across sectors. And the UK Regulators Network can support sharing best practice and lessons learned between sectors to support improved stress testing and resilience.

3.1 Vulnerabilities can be invisible

Fortunately for the UK, many disruptions and failures of the UK's economic infrastructure in recent years have led to moderate impacts, rather than extreme or catastrophic ones. In the last ten years, electricity system frequency has only dropped below normal levels once,⁶⁴ since 2001, both the number and duration of power cuts have halved,⁶⁵ and compared to 20 years ago, the number of water quality incidents in England and Wales have fallen by 80 per cent.⁶⁶ There are few large scale outages in the telecoms sector (the last was the EE outage in May 2019),⁶⁷ and when these do occur, customers are often able to use Wi-Fi and landlines to stay connected despite mobile connectivity being lost. Road and rail disruptions are more frequent, however short term disruptions can usually be absorbed by the public at a lower cost than protecting against the disruption, as they can use other routes or modes of transport. Longer term disruptions, such as the recent issues on Northern Rail, Southern Rail and the May 2018 rail timetabling changes, can have significant impacts on passengers' lives.⁶⁸

While there have not been many major events, there have been some avoidable near misses, showing that resilience could still be improved. For example, the most likely cause of the partial failure of Toddbrook dam in 2019 was its poor design, exacerbated by intermittent maintenance over the years, leading to deterioration.⁶⁹ There have also been some extreme local disruptions, such as the cryptosporidium contamination in Lancashire.⁷⁰

There have also been issues due to a lack of available resources or equipment to respond to shocks. In 2007, floods in Bransholme caused a surface water pumping station to fail for 12 hours. Whilst there was minimal impact, a faster response was hampered because the temporary pumps allocated for this eventuality in Yorkshire Water's emergency plan were already being used to address an incident in the Ulley Dam in Rotherham.⁷¹ Following the 2015 and 2016 floods, the Environment Agency invested an additional £12.5 million in incident response equipment including flood barriers and pumps for future incidents.⁷²

Some vulnerabilities are only identified when a shock happens, and experience of failure can lead infrastructure operators to improve resilience. For example, during the August 2019 power cut, some trains took hours to be restarted following disturbances to the power supply, leaving customers stranded for hours. The workforce responded well and passengers were disembarked safely from stranded trains.⁷³ However, there should have been plans in place to cope with disturbances to the power supply.

In February 2018, the winter storm dubbed the 'Beast from the East' led to large scale disruptions in the water sector. Frontline staff of all water companies worked extremely hard in challenging conditions, sometimes making personal sacrifices.⁷⁴ However, the conditions were not unprecedented,⁷⁵ and Ofwat concluded that some companies that had experienced similar serious events in the past showed improvements in their management of incidents.^{76, 77, 78}

3.2 Current assessments of resilience leave some gaps

Chapter 2 recommends that government sets a comprehensive set of resilience standards for the energy, water, digital, road and rail sectors. If government is to set these standards, infrastructure operators, regulators, and government need to have some way of knowing if they can be met. Infrastructure operators will need to ensure that they can meet their obligations, regulators will need to check this too, and government will need to know that the standards it is setting on behalf of the public can be met.

Effective resilience assessments, followed by taking action to address identified vulnerabilities, will increase the likelihood that these standards are met. While some vulnerabilities can be invisible, most recent disruptions and failures do not appear to have arisen from complete unknowns. Many could have been prepared for. For example, extreme weather events such as the 'Beast from the East' are largely predictable, although it can be hard to predict when they will occur. And even planned events, such as the changes to the rail timetable in 2018, have produced unexpected system wide impacts, due to gaps in the assurance processes.⁷⁹ Although some good testing and assurance processes exist already, issues like these suggest current assurance processes are not comprehensive enough over all the sectors.

Effective, comprehensive resilience assessment processes should:

- **be carried out regularly:** too often assessments are only carried out following disruptions – after the 2015 floods, a national flood resilience review was launched that assessed the flood resilience of key local infrastructure,⁸⁰ after the August 2019 power cuts the rail sector was asked to make appropriate checks to ensure their systems are able to absorb and recover from power disruptions,⁸¹ and the 2014 Transport Resilience Review was conducted following extreme weather in 2013⁸²

- **cover a range of threats and hazards:** currently cyber threats are assessed and reported against in multiple sectors, in line with the framework for reporting developed by the National Cyber Security Centre;⁸³ this is an example of good practice for one risk, but a similarly rigorous approach should be used across a range of threats and hazards
- **be transparent and applied consistently across the sector:** in the transport sector there is limited transparency over how transport operators assess their abilities to meet targets, and the outcomes of these assessments
- **assess what it would take to cause a loss of service:** Ofwat guides operators to stress test their systems, but it is not specific that this should include assessing what it would take to cause a loss of service⁸⁴
- **enforce advance action to address vulnerabilities:** in many sectors, for example in the digital sector,⁸⁵ enforcement and assurance have a stronger focus on addressing resilience issues after an event has occurred, rather than pre-emptive action.

3.3 Stress testing can assess the resilience of systems

One way of carrying out assessments of the resilience of infrastructure in advance of events is through regular, comprehensive stress testing – thorough, desk based testing used to determine the stability of the system and determine its ‘breaking point’. This approach is used to identify vulnerabilities in the financial sector, see box 3.1.

Box 3.1: Financial sector stress tests

Since the global financial crisis, financial stress testing has become common globally. In the UK, the process is run annually by the Prudential Regulation Authority, the division of the Bank of England that supervises financial institutions to ensure they act safely and reduce their chances of getting into financial difficulties.

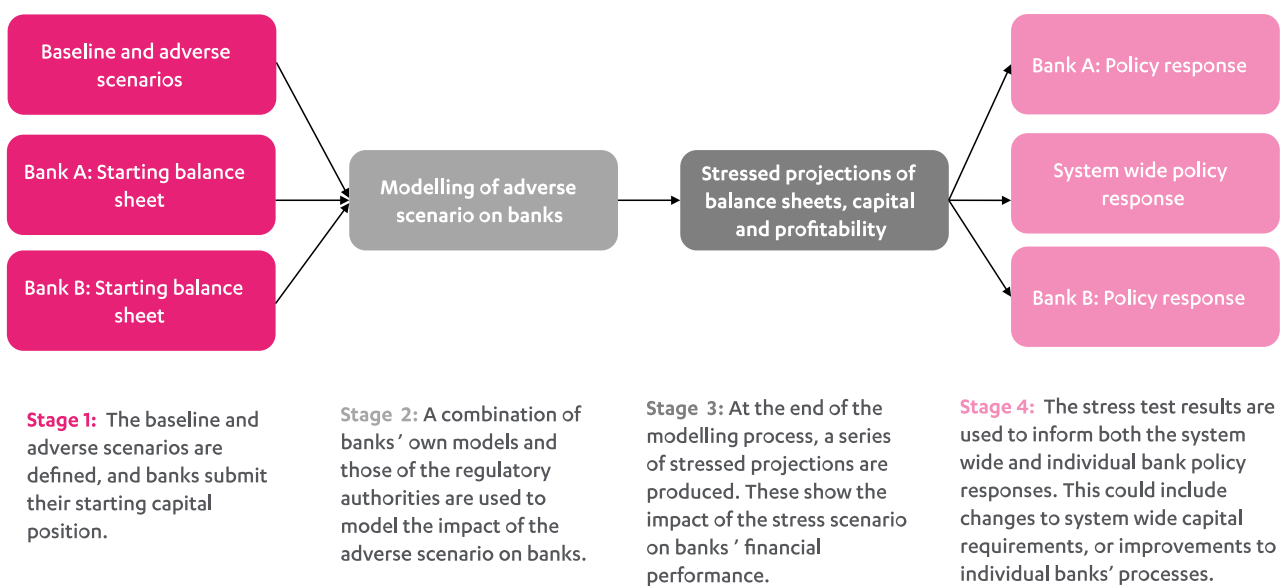
The Bank’s stress tests assess financial institutions’ abilities to cope with stresses such as decreases in global output, falls in house prices, or increases in unemployment,⁸⁶ as well as bespoke scenarios that would be particularly impactful for specific institutions,⁸⁷ without requiring knowledge of what might cause these issues. To do this, the Bank of England:

- requires concurrent tests for specific published scenarios conducted simultaneously across multiple large banks to understand bank specific, as well as sector wide, issues,⁸⁸ see figure 3.1
- requires smaller banks to design and undertake their own stress testing based on guidance^{89, 90}
- requires ‘reverse’ stress tests to find out what constitutes and would lead to failure^{91, 92}
- publishes summary results showing the performance of the banks and an assessment of the banking system’s resilience⁹³
- performs reviews of the banks’ stress testing capabilities⁹⁴ and coordinates independent reviews of sector wide processes.⁹⁵

The Bank can require institutions to act within a certain timeframe if they are found not to be adequately resilient.⁹⁶ Policy interventions are sometimes considered to address systemic vulnerabilities.⁹⁷ Greater regulatory focus on stress testing has helped to drive improvements in banks' own stress testing capabilities and risk management practices.⁹⁸ The framework provides a tool through which authorities can ensure that banks are held to a high standard for risk management and capital planning.

However, stress tests in their current form took time to develop. They existed before the global financial crisis but have been stepped up following it. Over time, the stress tests have become increasingly well organised and the capacity to analyse banks' projections has increased. The Bank has successfully drawn together a wide range of cross Bank expertise to deliver the tests – a major achievement for such a large exercise.⁹⁹

Figure 3.1 Illustration of a concurrent stress test in the banking sector *



* Illustration of concurrent stress tests. Adapted from Bank of England [explainer](#) (2016)

International organisations consider stress testing to be an important part of ensuring infrastructure resilience. The Organisation for Economic Cooperation and Development policy toolkit for governance of critical infrastructure includes multi hazard stress testing,¹⁰⁰ and the EU STREST project suggests that scenarios and methods should be 'harmonised' across sectors to make it possible to form an aggregated understanding of the resilience of the infrastructure system.¹⁰¹ Stress testing is also used in the civil nuclear sector.¹⁰²

Widely used, regular stress testing would enable infrastructure operators to have a better understanding of the resilience of their infrastructure systems and enable them to identify and address vulnerabilities. This could also provide assurance to regulators and government that resilience standards can be met.

Effective stress testing of infrastructure systems would require accurate, up to date data about infrastructure systems, including asset condition and location, which is still not always collected, shared and used effectively.

The Commission's technology study, *Data for the public good*, made recommendations to support infrastructure sectors to collect, share and use data on their assets and systems.¹⁰³ The infrastructure sector should work to improve their collection, sharing and use of data, see box 3.2.

Box 3.2: Collecting and using infrastructure data

High quality available data is essential to improving and maintaining infrastructure resilience and plays an important role in understanding infrastructure systems' abilities to resist, absorb and recover from events, and can also be used during an event in the response and recovery phases.

A range of different types of data can be used to improve resilience. For example, data on the condition of assets can be used to identify assets at risk of failure, data on supply and demand can be used to manage network capacity and revenue fluctuations, geospatial data can help to identify vulnerabilities arising from closely located assets,¹⁰⁴ and satellite imaging has the potential to identify warning signs of future failures.¹⁰⁵ However, data that could be shared often is not, due to concerns about security and commercial confidentiality, lack of secure platforms for sharing data, and the lack of consistent standards for data across the infrastructure sector.^{106, 107, 108}

Trusted information sharing between government and operators can be achieved by providing secure information sharing platforms¹⁰⁹ and there are examples from America;^{110, 111, 112} Canada;¹¹³ and the EU.¹¹⁴ In the UK, Resilience Direct¹¹⁵ supports data sharing between emergency responders, the Civil Contingencies Secretariat of the Cabinet Office with the National Cyber Security Centre manage other resources, and the Data & Analytics Facility for National Infrastructure¹¹⁶ programme is piloting an advanced data sharing platform. In addition, work underway in the UK shows that digital twins could be used to stress test infrastructure¹¹⁷ and to understand interdependencies.¹¹⁸

Some recent infrastructure failures have been exacerbated by lack of data or lack of data sharing: water companies' responses to the 'Beast from the East' were hindered by lack of real time data to diagnose leaks and loss of supply,¹¹⁹ and during the power cuts on August 9th 2019 the electricity system operator found it difficult to manage the failure because they had insufficient real time data about the performance of distributed generators.¹²⁰ Past events have triggered improvements in data capture and sharing. The response to the Summer 2007 floods was inhibited by limited monitoring,¹²¹ and prompted improvements in detection, forecasting and warning systems.¹²²

3.4 Regular stress testing of infrastructure systems

There should be regular, transparent stress testing of the UK's energy, water, digital, road and rail infrastructure systems to help identify and address vulnerabilities in advance of disruptions and failures and ensure that the government's resilience standards can be met. These stress tests should build on existing good practice.

Operators should carry out the stress tests, as they have the best understanding of their systems. Meeting government's resilience standards will ultimately be operators' responsibility, and so they should be responsible for identifying and addressing any resilience weaknesses.

However, stress testing cannot be left entirely to infrastructure operators. It is natural to avoid confronting uncomfortable truths about certain high impact risks. And this may mean that some infrastructure operators could have unrealistic assumptions about the future embedded in their culture, which risk being replicated in any stress tests they design. The scope and outcomes of stress tests should be scrutinised to ensure they are not overly optimistic or based on unrealistic, but accepted, assumptions, and to ensure they genuinely test infrastructure resilience to a range of scenarios and expose vulnerabilities as much as possible.

However, this does not mean oversight of stress testing should pass to government. A rigorous approach to stress testing requires independence from short term political considerations. Political acceptability could prevent government from publicly identifying the worst scenarios for stress tests, especially where providing resilience to them may lead to increased costs for consumers. Government is also more vulnerable than the regulators to lobbying by companies who may seek to influence the design of stress tests to avoid costs falling to shareholders. And companies may be unwilling to share sensitive commercial information from stress tests with government.

Regulators should therefore require infrastructure operators to carry out regular stress tests and oversee them, including providing guidance on the outline scenarios, frequency and scope of the stress tests. Regulators should receive additional resources to carry out this role where necessary. Operators should provide outcome reports to regulators, and publish public summary assessments, considering national security concerns. Government will have a role to play in drawing together the outcomes of the stress tests to assess systemic and cross-cutting resilience issues arising across sectors. The roles of the government, infrastructure operators and regulators are set out in more detail below.

Government should set resilience standards to test against

Government will need to ensure the regulators all have resilience duties, as recommended in the Commission's regulation report, *Strategic investment and public confidence*.¹²³ Government should also set out resilience standards, as set out in Chapter 2. The stress tests will assess the ability of infrastructure systems to meet these resilience standards.

The Civil Contingencies Secretariat of the Cabinet Office and lead government departments should support regulators and operators in identifying the most critical elements of the system, which will therefore need the most rigorous stress testing. Following the stress tests, the Secretariat should also use the reports published by the regulators to develop an overview of systemic and cross-cutting resilience issues arising across sectors.

Regulators should require infrastructure operators to do stress testing

Regulators should introduce new obligations on infrastructure operators, to ensure they undertake regular stress tests of their systems. Where necessary, government should introduce legislation to ensure regulators have suitable powers. Regulators should oversee these stress tests, including providing guidance on scenarios, frequency, scope and the content of confidential and public reporting on outcomes. These do not need to be consistent across all operators, and it will be necessary for operators to develop bespoke tests to assess their unique systems, and for regulators to ensure the stress testing is proportionate and maintains fair competition.

The guidance provided to operators might include:

- the **frequency** of the stress tests
- the common **scenarios and hazards** to test for
- principles to **develop bespoke tests** specific to unique vulnerabilities
- common **resilience actions** to assess
- a requirement to identify **what circumstances would cause a loss of service**
- a requirement to **consider their dependencies and interdependencies** including those with other sectors
- what should be included in **outcome reports** provided to regulators
- what should be included in **public summary assessments** considering national security concerns.

The guidance provided on stress tests should be regularly updated to take account of changing circumstances.

Regulators should also require and facilitate expert review of the outcomes of stress tests. Operators may be unconsciously avoiding uncomfortable truths and assuming that, if there have not been problems in the past, there will not be in future. As set out in Chapter 2 for resilience standards, regulators have links to independent experts within and outside industry. Expert peer review of the outcomes of stress tests, including minority views can help ensure that the stress tests are genuinely exposing vulnerabilities, and are not based on overly optimistic, but accepted, assumptions.

Following the stress tests, the regulators should use the outcome reports to publish an overview of the resilience of the sector and confirm what action is needed throughout the sector. The regulators should also enforce the obligation on infrastructure operators to address vulnerabilities identified in the stress tests, while ensuring that operators do not ‘gold plate’ their systems (building in excess resilience) at consumers’ expense.

One further role for the regulators will be to promote sharing of best practice in stress testing across relevant regulators, including learning lessons from the financial sector whilst understanding the unique requirements of the infrastructure sector, and learning from other stress testing already in operation, through the UK Regulators Network.

Operators should carry out the stress tests and address vulnerabilities

Finally, it will be operators’ responsibility to carry out the stress tests, as required and overseen by the regulators, to ensure their systems are capable of meeting government’s resilience standards. As part of each round of stress testing, operators should provide regulators with detailed, confidential accounts of the outcome of stress tests and publish summary assessments.

Stress tests can identify vulnerabilities, but action also needs to be taken. As seen at Toddbrook dam, vulnerabilities can be identified without action being taken to address them, leading to disruptions and failures that could have been prevented.¹²⁴ Operators should be responsible for deciding on the actions that need to be taken to address identified vulnerabilities, including considering innovative solutions, and taking those actions, with the regulators overseeing the process to ensure operators do address the vulnerabilities. Operators need to set out clear timelines and internal accountabilities and budgets, so that action to address vulnerabilities is not delayed.

Recommendation 2: Regulators should require a system of regular stress testing by 2024 for energy, water, digital, road and rail infrastructure operators, to ensure that infrastructure operators’ systems and decision-making can credibly meet government’s resilience standards for infrastructure services

Regulators should introduce obligations by 2023 on infrastructure operators to require them to participate in stress tests and to require remedial action in case of failure of stress tests.

This could be achieved by the following actions over the coming years:

2021	<p>Regulators to set out initial plans for stress tests, including deciding on scenarios, frequency, scope and the content of confidential and public reporting on outcomes.</p> <p>The UK Regulators Network to promote sharing of best practice in stress testing across relevant regulators, including learning lessons from financial sector and other stress testing already in operation.</p>
2023	<p>Regulators to introduce new obligations on infrastructure operators, to ensure they:</p> <ul style="list-style-type: none"> – undertake regular stress tests – develop and implement plans to address vulnerabilities identified by stress tests <p>from 2023 onwards.</p>
2024 (at the latest)	<p>Regulators to ensure the first round of stress tests are complete:</p> <ul style="list-style-type: none"> – operators to provide regulators with detailed, confidential accounts of the outcome of stress tests and publish summary assessments – regulators to use the stress tests to publish an overview of the resilience of the sector and confirm what action is needed – Civil Contingencies Secretariat of the Cabinet Office to use the reports from stress tests to develop an overview of systemic and cross cutting resilience issues arising across sectors. <p>Where operators fail stress tests, regulators should require them to develop and implement plans to address vulnerabilities.</p>

4. Achieving resilience over the long term

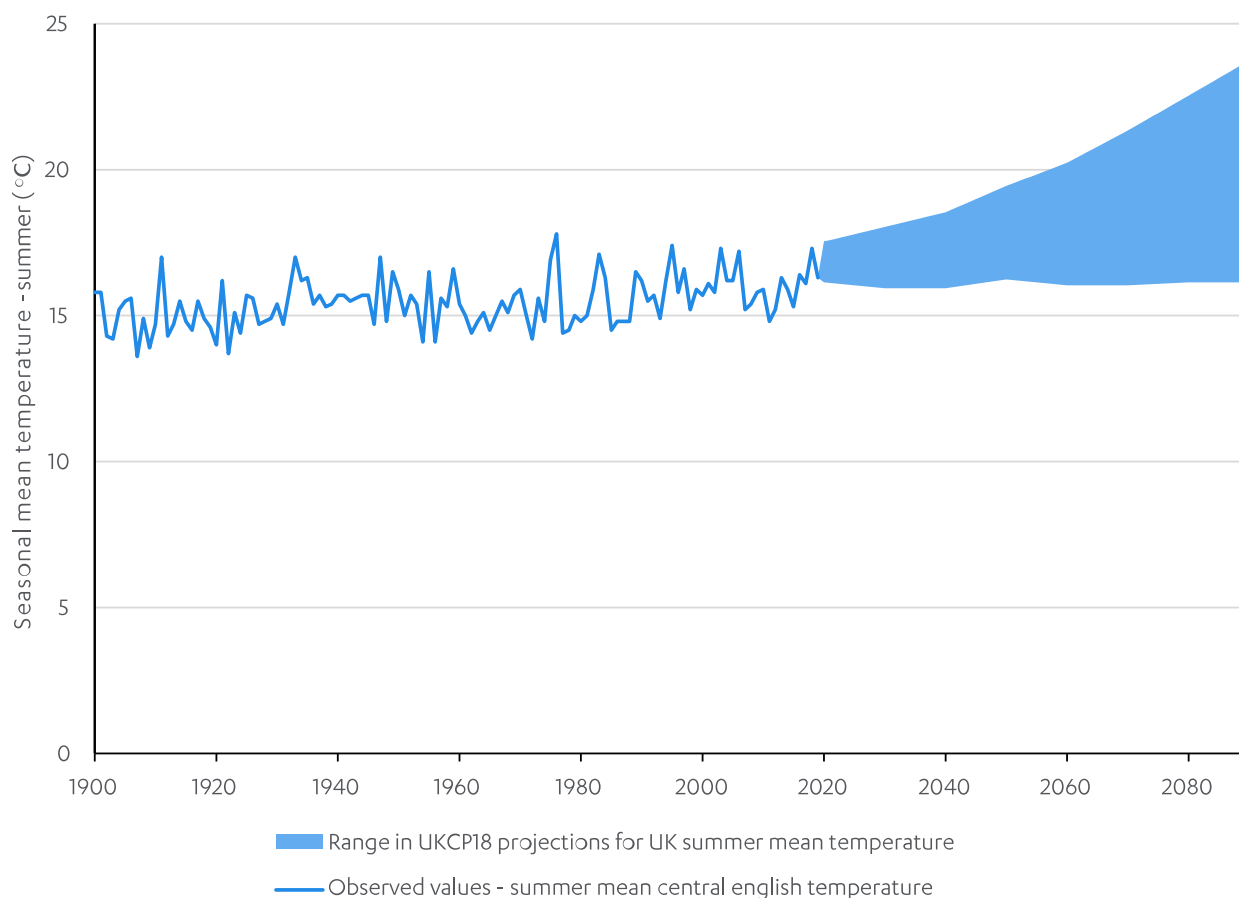
Infrastructure operators should develop strategies to enable them to continue to deliver resilient services over the long term. Infrastructure operators need to be responsible for the resilience of their systems, both now and in the future. This means planning to ensure they can meet government’s resilience standards in the coming years and decades over the, often long, lifetimes of their infrastructure assets. Regulators should provide scrutiny and challenge to these long term strategies, involving government where relevant. Expert advice and scrutiny, led by the regulators, can avoid the risks of these strategies being overly optimistic or based on unrealistic, but accepted, assumptions.

Infrastructure operators should develop long term resilience strategies, with guidance and scrutiny from the regulators, and government where relevant, that set out governance, decision points, and options to proactively manage and adapt infrastructure systems and services. In doing so, they should consider relevant future changes including social, environmental, technological and other factors. These strategies should drive improved resilience in future, allowing operators to address issues promptly, identify and manage interdependencies, and respond to a wider range of potential challenges. At least in some cases, improved resilience will require new investment. In competitive markets, clear standards will ensure a level playing field with firms able to pass costs to consumers, who will capture many of the benefits of resilience as consumers and members of society. In regulated markets, regulators will also need to ensure that, in future price reviews, their determinations are consistent with meeting government’s resilience standards in both the short and long term.

4.1 Infrastructure operators must plan for the future

Over the coming decades the UK will face many challenges and opportunities, including climate change, a growing reliance on electricity and digital, and widespread adoption of new technologies. Infrastructure systems that are resilient today may not be resilient in a year, a decade or a century. Since many infrastructure assets have long lifetimes, infrastructure operators need to plan ahead to ensure they are resilient to future changes.

Future projections cannot be based on a linear extrapolation of the past. For example, figure 4.1 shows the range of climate projections for the UK. Operators will have to take a different approach in future to be resilient to the effects of climate change, even if they have not experienced problems in the past. The impacts of climate change will depend on many variables and decisions, including policy decisions from governments around the world, societal actions and behaviour change.

Figure 4.1 Mean summer temperatures in the UK (1900 – 2090) ¹²⁵

Whilst some drivers of change, like climate change, are widely accepted and considered in long term planning, others may be overlooked. Infrastructure operators should consider a wide range of potential future sources of change and uncertainty when making long term strategies,¹²⁶ including:

- **social factors** – including changes to demand for services, or changes to user behaviours and expectations
- **technology** – including innovative approaches and impacts on society
- **environmental factors** – such as climate change
- **economic factors** – such as economic shocks, and cost pressures on households
- **deterioration of assets** – many infrastructure assets have a long life time and will deteriorate over time
- **external threats** – such as cyber or malicious attacks
- **availability of resources** – due to climate change, the economic climate or government policies
- **other factors** – including government policy and the global context.

Even taking these potential changes into account, the level and impact of these changes cannot always be known, and there will always be changes that are not anticipated in advance. Therefore, infrastructure systems need to be prepared to adapt to a wide range of future outcomes.

4.2 Infrastructure operators are not always prepared for known challenges

Infrastructure operators' long term planning and investment does not always adequately prepare systems for the future. There can be a failure of infrastructure operators to proactively identify actions to take now and over the coming years to better prepare their systems for the needs and challenges of the future, even to address known challenges.

There can be a failure to address known challenges

Facing up to uncomfortable truths is hard. There is not necessarily a lack of long term planning in the UK's economic infrastructure. But many recent disruptions and failures in the UK could also have been prepared for and addressed by implementing long term resilience strategies in advance, as they were not due to unknown challenges.

This issue is not confined to the UK. The increasing risks to low lying cities in coastal areas have been well known for decades, and before Hurricane Katrina it was well known that New Orleans was particularly vulnerable due to subsidence, increasingly extreme storms,¹²⁷ and widescale development in areas below sea level.¹²⁸ However, when the hurricane hit the city in 2005, there were disproportionately large impacts because critical services were not resilient. The city was heavily reliant on engineered levees to protect it from flooding,¹²⁹ but when critical levees failed, people were left without services at a time when they were most vulnerable. This included disruptions to water and sewerage for over a million people,¹³⁰ and transport failures which left over 100,000 people unable to evacuate because they did not have their own cars or had mobility issues.¹³¹ Impacts were catastrophic and extended for months in some cases. Many of these impacts were due to a failure to proactively plan and adapt infrastructure systems to be resilient in the face of climate change and population growth, to consider dependencies between different systems, and to recognise the needs of vulnerable people.

Developing long term strategies can help to:

- **Address issues before problems arise:** London's sewers were built 150 years ago. They now overflow weekly,¹³² polluting the River Thames, mainly due to the large increase in surface water flows as more of the city has been paved and rainfall has increased. This is now being addressed by building the Thames Tideway Tunnel, but, if a forward looking strategy had been developed, the problem could have been addressed before it became too big to ignore.^{133, 134}
- **Identify and manage interdependencies:** The winter flooding of 2015/16 left the city of Lancaster without power for several days when the local substation flooded. Following the power cut, people in the local area found they were unable to use the internet, their mobiles, or cordless phones to contact their families. The digital services they rely on had lost power and did not have back up power sources or alternative communication options available.¹³⁵ This made communication difficult during recovery.¹³⁶ Power outages are known risks to digital and power companies, and they should have been prepared and aware of the interdependencies. Strategic resilience planning and action should have addressed these gaps long before the floods.

- **Consider a wide range of vulnerabilities:** The water sector makes long term plans for managing drought through Water Resources Management Plans,¹³⁷ but disruptions due to network failures, water quality incidents, and dependencies within and across sectors receive less focus. This was demonstrated by widespread water failures during the 2018 winter storm dubbed the ‘Beast from the East’,¹³⁸ and the review of the 2015 cryptosporidium contamination in Lancashire, which found that contingency plans that existed for water works being out of service due to contamination did not cover the actions required in reality or consider the effects of a prolonged drinking water quality emergency.¹³⁹

Static requirements can constrain adaptation

Part of the reason why infrastructure operators are not prepared for known challenges may be because they are constrained by static or out of date standards, regulation, and governance arrangements. As set out in Chapter 2, when government sets long term resilience standards, it should also carry out an assessment of how existing structures, powers and incentives enable operators to deliver these standards or where changes are needed. This has been carried out effectively in the past: although there is more to do, government worked well with stakeholders across the energy industry and wider economy over the past two decades to remove policy, regulatory, and market barriers for renewable energy generation technologies.¹⁴⁰ This included reforming and facilitating access to the electricity grid, and putting in place an incentive framework to drive investment.

4.3 Long term resilience strategies

Operators must develop long term resilience strategies

Operators in the energy, water, digital, road and rail sectors must make long term resilience strategies, facing up to future challenges and uncertainty, managing interdependencies with other sectors, and taking advantage of opportunities to adapt and transform to improve resilience. Resilience is ultimately the responsibility of the operators, both now and in the long term, and they are best placed to develop long term strategies.

Infrastructure operators’ long term resilience strategies should:

- set out **governance, decision points**, and **options** to proactively manage and adapt operators’ infrastructure systems and services, considering options that can deliver wider benefits to society and the environment or use innovative approaches
- set out relevant **analysis** of **social, environmental, technological, economic** and other changes (see section 4.1) that could impact the ability of systems and services to meet government’s standards for resilience, and **demonstrate options** to address them
- address long term **dependencies on and interdependencies with** other sectors
- identify **opportunities to enhance resilience** proactively
- consider the potential need for **transformation** to meet future needs
- have **transparent** and **regularly updated** assumptions
- be regularly **maintained and updated**
- be **embedded** in organisational governance processes

- be **shared with the regulators**
- be **affordable** and **deliverable**, setting out efficient and pragmatic solutions
- identify potential **trade-offs**, including where **decisions need to be made by others** to resolve issues, while ensuring responsibility remains with the operator
- be **peer reviewed**, facilitated by the regulators (see below)
- identify factors which **constrain or impact** on resilience, such as current system, regulatory or governance arrangements, and distributional impacts of decisions.

Setting clear resilience standards, as recommended in Chapter 2, and requiring infrastructure operators to carry out stress tests, as recommended in Chapter 3, should also support infrastructure operators to understand the level of resilience they should be aiming for, the level they already have, and potential risks and challenges. This should help them to develop realistic, comprehensive and affordable long term resilience strategies.

A range of tools which can support the development of long term resilience strategies, are set out in box 4.1.

Box 4.1: Tools for long term resilience strategies

Keeping options open for future interventions can improve resilience.¹⁴¹ Examples include building flexibility into systems, such as bidirectional charging infrastructure for EVs and reserving land in case future growth is needed; not shutting down legacy systems which already exist,¹⁴² such as the gas grid, which could be used for hydrogen in future,¹⁴³ or trialling new options before scaling them up, for example for hydrogen and electrified heating, to develop the evidence base to progress towards zero carbon heat.¹⁴⁴ Keeping options open can be costly, but it can also provide flexibility and enhance overall resilience, including until legacy services are no longer needed. However, infrastructure operators should also consider whether it is more cost effective to build resilience into new systems.

Managed adaptive approaches aim to proactively and incrementally adapt, while keeping options open by building flexibility into systems.¹⁴⁵ Managed adaptive approaches identify a range of options or potential pathways, and system ‘tipping points.’ The tipping points are monitored, and, when reached, trigger implementation of the best option for the circumstances. These options or pathways can be tailored over time to suit unfolding conditions. This approach allows infrastructure operators to make least regret decisions, respond to future risks and demands as they emerge, and spread resilience costs over time.¹⁴⁶ Managed adaptive approaches may not be possible for some systems, particularly where the turnover in assets is short and decisions need to be made quickly. Keeping options open incurs costs, and it’s likely that several options won’t be progressed, so there is a need to balance investment in adaptive capacity with affordability and time pressures.

Systems mapping can be used in infrastructure to explore how different decisions can impact the level of service delivered to consumers, and consider the impact of decisions within and across sectors. Increasing reliance on electricity and digital communications, as well as increasing interaction between technological developments and decarbonisation in energy and transport will not be manageable if they are only thought about within individual sectors. As part of this study, the Commission worked with Arup to produce system maps which demonstrate the relationships between decision making in infrastructure systems and their resilience.¹⁴⁷

Regulators must require and scrutinise long term strategies

While infrastructure operators are best placed to develop long term resilience strategies for their infrastructure systems and services, long term resilience planning cannot be left entirely to the operators. As set out in previous chapters, infrastructure operators do not always have the right incentives for resilience and may have internalised assumptions that are unrealistic or optimistic. Regulators, who should have a resilience duty as set out in the Commission's regulation study,¹⁴⁸ therefore have a role to: require infrastructure operators to produce long term resilience strategies; produce guidance on developing those strategies to ensure a proportionate approach; and scrutinise those strategies. Where government, not the regulator, has resilience responsibilities, or multiple regulators are involved, all relevant parties should be involved in scrutinising the long term strategies.

In some sectors, regulators are already involved in the development of forward looking strategies by infrastructure operators, such as the future energy scenarios developed by National Grid Electricity System Operator.¹⁴⁹ Alongside the guidance and tools set out above, regulators should provide additional guidance in developing long term strategies, sharing best practice from within the sector, ensuring a proportionate approach, and providing guidance on the appropriate time horizon. The regulators should use the strategies to develop a sector wide view of resilience strategies.

Regulators should also require and facilitate expert review of the long term strategies, using their links to independent experts within and outside industry, including involving government where relevant. Operators may be unconsciously avoiding uncomfortable truths and assuming that, if there have not been problems in the past, there will not be in future. Expert review of the long term strategies, including minority views can help ensure that the strategies address a range of future challenges, while ensuring they are affordable and deliverable.

The regulators can support the development of long term strategies through promoting the sharing of best practice through the UK Regulators Network. Once the regulators have provided scrutiny of the long term strategies, they should continue to ensure that infrastructure operators are delivering on the strategies they have produced.

At least in some cases, meeting the resilience standards, and addressing vulnerabilities identified through stress testing, will require investment in assets, processes or systems. The long term resilience strategies, alongside the stress tests, will identify where this is the case. In competitive markets, the requirement to meet standards should provide a level playing field for all providers. Investment will be priced in for consumers, in the same way as health and safety standards are now.

If the standards have been set correctly, the benefits to consumers and wider society will outweigh the costs. In setting standards, government will need to pay particular attention to the ability of consumers in vulnerable circumstances to pay the costs, but also be aware that the benefits may be greatest for people who are vulnerable. In regulated markets, regulators will need to take the costs of resilience into account in their future price determinations, acting on consumers' behalf. In doing so, the regulators will need to ensure investment can be made to enable government's resilience standards to be met, while also scrutinising companies' resilience bids to ensure they are proportionate, and consumers will not be paying for excess resilience ('gold plating').

Long term resilience strategies and recovery

As set out in previous chapters, too often vulnerabilities are only addressed, and infrastructure systems and services made more resilient, after a disruption or failure. While it is important that resilience is considered before a disruption or failure – much of this report aims to improve proactive resilience – developing long term resilience strategies can also improve the response to disruptions and failures.

Often when there is a large disruption or failure, the focus of the response can be on returning the system or service to normal operation as quickly as possible. But having a long term strategy in place can help government, regulators and operators to take decisions which enable the response to recovery to represent an improvement on the previous functioning of the system or service.¹⁵⁰ For example, Manchester developed a strategic regeneration plan to support the city's 1992 bid to host the Olympic games.¹⁵¹ This meant that when an IRA bomb destroyed much of Manchester city centre in 1996, the recovery process was used as an opportunity to accelerate regeneration and deliver improved public spaces and transport services.¹⁵²

However, opportunities to enhance resilience have not always been taken following failures. Lessons should be learnt and shared following disruptions and near misses. Despite the widespread impacts from the 2007 floods there has been little progress on surface water flooding since the Pitt Review.¹⁵³ Continually revisiting and updating requirements can also support delivering improved infrastructure services in recovery processes. Revised, improved, standards will mean that when rebuilding after a disruption or failure, the new systems and services will automatically be of a higher standard than those in the past.

4.4 Long term resilience and government

Government, too, may need to act to ensure its long term resilience standards can be met. Much of what is needed to meet the government's standards for resilience can be delivered by infrastructure operators with the support of regulators. However, there may be some areas that require government intervention.

In particular, when making decisions with large, long term consequences government should explicitly assess the impact of different options on resilience, and whether there may be costs or a need for further changes to ensure resilience standards remain suitable and can be met. For example, the UK will need to decarbonise heat to meet its obligations to achieve net zero greenhouse gas emissions by 2050.¹⁵⁴

In decarbonising heat, there is a choice to be made between mainly decarbonising heat through hydrogen heating, or electrification of heat, through the use of heat pumps. There are many factors relevant to this choice, including cost, disruption, consumer acceptability and supply chain capacity. But resilience also needs to be taken into account in these decisions: for example, widespread use of electrified heat would make people more dependent on their electricity supply, and a decision on decarbonising heat may require changes to other standards, such as for the resilience of electricity supply, and the arrangements for vulnerable customers.

When government sets resilience standards, as recommended in Chapter 2, it should also carry out an assessment of how existing structures, powers and incentives enable operators to deliver these standards or where changes are needed. If, during this assessment, government identifies that the right architecture is not in place to deliver on its resilience standards, then government will need to act to ensure its resilience standards can be delivered.

Recommendation 3: Energy, water, digital, road and rail infrastructure operators should develop and maintain strategies to ensure infrastructure services can continue to meet resilience standards in the long term. To ensure this, regulators should:

- **introduce obligations by 2023 on infrastructure operators to require them to develop and maintain long term resilience strategies (where there is no current requirement)**
- **set out, in future price reviews, how their determinations are consistent with meeting standards of resilience in both the short and long term.**

This could be achieved by the following actions over the coming years:

2023	Regulators to introduce new obligations on infrastructure operators, to ensure they develop and maintain long term resilience strategies from 2023 onwards.
2023 onwards	Regulators to produce guidance on long term strategies . Operators to provide full, confidential strategies to regulators Operators to publish summary versions of the strategies publicly. Regulators to: <ul style="list-style-type: none"> – scrutinise operators’ strategies drawing on a range of expertise – develop sector wide views of strategies – assess whether operators are acting on their strategies. UK Regulators Network to promote cross sector sharing of best practice .
Future price reviews	Regulators to ensure their determinations in future price reviews are consistent with meeting resilience standards in the short and long term.

Glossary

Absorb	The actions that, accepting there will be or has been an impact on infrastructure services, aim to lessen that impact, such as building a water transfer network to prepare for future droughts.
Adapt	The actions that change the system to enable it to continue to deliver services, for example using storage in the electricity system to support renewable generation.
Adaptive approach	A strategy, process, or intervention designed to be changed over time as new information becomes available or as the situation changes.
Anticipate	The actions to prepare in advance to respond to shocks and stresses, such as collecting data on the condition of assets.
As low as reasonably practicable	In this report, this implies setting levels of service for extreme events that enable their risks to be minimised as far as is reasonably practicable.
Assurance	The provision of accurate information about the level of compliance with policies and obligations.
Black start	The procedure used to restore power in event of total or partial shutdown of national electricity transmission system.
Cascade failure	The failure of parts of an interconnected system triggered by failures in other parts of the system.
Commercial confidentiality	Refers to issues around protecting the privacy of information that is commercially sensitive.
Decarbonisation	Decarbonisation refers to the removal or reduction of carbon dioxide (a greenhouse gas) emissions with the purpose of reducing the impact of climate change.
Dependencies	In the context of an infrastructure system, dependencies are the functions, services, decisions or other items that part of a system relies on.
Digital twin	A representation of a system which captures the system's real world behaviour and, in some cases, that of the surrounding environment. This may be a real-time updated collection of data, models, algorithms or analysis and may feed decision or instructions back into the real-world system.
Disruption	A disturbance which interrupts the usual functioning of an infrastructure system or service, and its impacts.
Distributional impact	Distributional impacts describe the assessment of the impact of interventions on different groups in society eg different regions, or socioeconomic groups.
Emergent	Properties of a system that arise from the interactions of the system components and are not exhibited by the components in isolation.
Event	An incidence of disruption or failure and its impacts.
Failure	The loss of usual functioning of an infrastructure system or service. May lead to disruption in availability or reliability in that system and/or others.

Infrastructure operators	In this report, the term ‘infrastructure operators’ has been used to mean all those owning and operating infrastructure services, systems or assets. For clarification, in the transport sector this is also intended to include train operating companies, and in the energy sector it is intended to cover all energy operators and providers, not just the electricity system operator.
Insurer of last resort	The role of government to take on risks that others cannot, often to protect the population and provide stability when unforeseen events occur. This can help improve markets and provide protection against risks the private sector is unable to cover without some degree of government intervention.
Interdependent	Where one part of a system is dependent on another and vice versa. They are mutually dependent.
Levels of service	Standards or thresholds that are used to express the quality and/or availability of an infrastructure service that an infrastructure provider should aim for.
Localised capacity	Measures that are implemented locally to the impacted asset or sub-system which provide back-up, redundancy, buffering, or additional capacity.
Natural capital	The stock of natural assets that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions.
Net zero	The UK government’s legislated target for net zero greenhouse gas emissions for the whole economy by 2050.
Network capacity	The measures implemented across the network or system which provide back-up, redundancy, buffering, or additional capacity. This may be through interconnectivity, decentralisation, and the ability to re-route flows in the system.
Primary duty	Duties which are set for each of the regulators through legislation and are the statutory basis for their activities. Also known as principal objectives.
Recover	The actions that help quickly restore expected levels of service following an event, such as procedures to restart services following an incident such as a nationwide loss of power.
Resist	The actions taken in advance to help withstand or endure shocks and stresses to prevent an impact on infrastructure services, such as building flood defences.
Revealed preference	A technique that uses observed consumer behaviour to deduce consumer preferences.
Risk	The possibility of negative consequences arising from a threat. Risk is the product of exposure, hazard, and vulnerability.
Risk Management	Identifying, evaluating, and prioritising risks, followed by coordinated and economical application of resources to minimise, monitor, and control the likelihood or impact of unfortunate events.
Self-insurance	A risk management technique in which a company or individual sets aside a pool of money or other resources to be used to remedy an unexpected loss.
Shock	A sudden, unexpected event that puts pressure on infrastructure systems.
Stated preference methodologies	Stated preference methodologies use surveys to estimate customer willingness to pay for or accept a particular level of service.

Strategic Policy Statements	A published statement setting out the government's strategic priorities and objectives for a regulator. They are designed to provide a clear strategic context in which independent economic regulators, customers and investors can take informed decisions.
Stress	In the context of an infrastructure system, a stress is a longer term pressure that pushes a system towards or beyond its working limits.
Stress testing	Testing a representation or simulation of a system to reveal its performance under certain conditions or to reveal the conditions that could lead to failure.
Transform	The actions that regenerate and improve infrastructure systems, for example transforming infrastructure to meet the net zero target.
Uncertainty	Limited and unknowable knowledge about future, past, or current events and conditions. Uncertainty includes natural variability (aleatory uncertainty), knowledge gaps (epistemic uncertainty), ambiguous meanings (semantic uncertainty), unknown unknowns (ontological uncertainty), and subjectivity.
Vulnerability	In the context of infrastructure systems, a vulnerability is a characteristic of the system or weakness in the system that has the potential to lead to partial or full failure of the system.

Acknowledgements

The Commission is grateful to everyone who engaged with the development of this report. The list below sets out organisations that have engaged with the Commission in delivering this report. Former Commissioner Dame Kate Barker was a member of the Commission during earlier stages of the development of this report and contributed to the study while she was a member of the Commission.

The Commission would like to thank everyone who responded to the consultation in the scoping report published in September 2019. The Commission acknowledges the contribution of its expert advisory groups, and the consultants that have been engaged by the Commission to develop this piece of work.

The Commission is also grateful to officials from across government, members of the public who took part in social research workshops and polling, and others who have engaged with the development of this report in an individual capacity, including members of the Commission's Young Professionals Panel and Design Group.

The Commission would like to acknowledge the members of the Secretariat who worked on the study team: Samuel Aggrey, Emily Anderson, Tom Bradbury, Pete Burnill, Matt Crossman, Fazila Deen, Manuela Di Mauro, Phil Graham, Francis Heil, Tom Hughes, Catherine Jones, Ryan Lee-Shield, Chloe Maycock, Giles Stevens, Owen Tarrant, Eleanor Voss and Vasilis Papakonstantinou.

Organisations engaged:

100 Resilient Cities	The Civil Contingencies Secretariat of the Cabinet Office	Department for Business, Energy & Industrial Strategy
AECOM		
Airport Operators Association	The Consumer Council for Water	Department for Digital, Culture, Media & Sport
The Alan Turing Institute	Centre for the Protection of National Infrastructure	Defence Science and Technology Laboratory
Anglian Water	Chartered Institute of Water and Environmental Management	Department for Environment, Food & Rural Affairs
Arcadis LLP	Chartered Institution of Water and Environmental Management Climate Change Panel	Department for International Trade
Arup		Department for Transport
Atkins	CIRIA	Digital Framework Task Group
Bank of England	Citizens Advice Bureau	Drax Group plc
British Hydro Association Tidal Range Alliance	COMIT Projects Limited	Durham University Institute of Hazard, Risk and Resilience
British Water	Committee on Climate Change	The Electronic Communications Resilience and Response Group
BT Group plc	Consumer Council for Water	EDF Energy
Buckinghamshire County Council	Cranfield University	Energy & Utility Skills
Cadent	Data & Analytics Facility for National Infrastructure	Energy Networks Association

Energy Technologies Institute	Network Rail	Suffolk Public Sector Leaders Group
Energy UK	NeuConnect	Thames Water
Environment Agency	Nichols Group	Turner & Townsend
First Group Plc	Nominet	UK Collaboratorium for Research on Infrastructure and Cities
Future Water Association	Northern Ireland Executive	UK Climate Impacts Programme
Gatwick Airport	Telefonica UK Ltd	The UK Infrastructure Transitions Research Consortium
Greater London Authority	Organisation for Economic Cooperation and Development	UK Power Networks
Global Centre for Adaptation	Ofcom	UK Regulators Network
Greater Manchester Combined Authority	Office of Rail and Road	United Utilities
Highways England	Ofgem	University College London
HM Treasury	Ofwat	University of Bristol
HR Wallingford	Ombudsman Services	University of Cambridge
Imperial College London	Openreach	University of Oxford
Infrastructure Operators Adaptation Forum	Ordnance Survey	University of Sheffield
Institute and Faculty of Actuaries	Rail Delivery Group	University of Surrey
Institute of Asset Management	Rail Safety & Standards Board	Venables Consultancy
Institution of Civil Engineers	Redroof Consulting	Virgin Media
Institution of Engineering Technology	Resilience First	Vodafone
Infrastructure and Projects Authority	Resilience Shift	Water Resources East
Jacobs	Royal Academy of Engineering	Water Resources South East
John Dora Consulting	Royal Engineers	Welsh Government
KCOM Group	Science and Technology Facilities Council	WSP
Landscape Institute	Scottish and Southern Electric	Yorkshire Water
Lloyd's Register Foundation	Scottish Government	
Met Office	Severn Trent Water	
Mott MacDonald	SGN	
National Cyber Security Centre	Smart DCC	
National Grid	South West Water	
National Grid System Operator	Southern Water	
National Infrastructure Commission for Wales	SP Energy Networks	
The Natural Environment Research Council	Stantec	
	Steer Davies Gleave	
	Strathclyde University	

Endnotes

- 1 Office of Rail and Road (2020), **Report following railway power disruption on 9th August 2019**
- 2 University of Bristol (2020), **Understanding emergent behaviour within the economic infrastructure system-of-systems**
- 3 Council For Science and Technology (2009), **A National Infrastructure for the 21st Century**
- 4 Government Office for Science (2012), **Infrastructure and Resilience**
- 5 University of Bristol (2020), **Understanding emergent behaviour within the economic infrastructure system-of-systems**; S. Neda Naghshbandi, L. Varga, T. Dolan, Civil, Environmental and Geomatic Engineering Dept, University College London (2020), **Review of emergent behaviours of systems comparable to infrastructure systems and analysis approaches that could be applied to infrastructure systems**
- 6 Dr Raghav Pant, Mr. Tom Russell, Dr Conrad Zorn, Dr Edward Oughton, Prof. Jim W. Hall, Environmental Change Institute, University of Oxford (2020), **Systems analysis of interdependent network vulnerabilities**
- 7 Association of Drainage Authorities (2019), **Wainfleet flooding**
- 8 Gov.uk (2019), **Government activates Bellwin scheme to support local communities hit by flooding**
- 9 Environment Agency (2019), Blog: **Flood response at Wainfleet in Lincolnshire**
- 10 The Environment Agency estimates that routine vegetation maintenance (clearance) of a river embankment can cost between £20 – £17,225 per kilometre per year. The large range in the cost estimate reflects the number of factors that influence effective maintenance operations. It is estimated that there were 11km of defences in the asset system protecting the village of Wainfleet and surrounding land flooded. Environment Agency (2015), **Cost estimation for fluvial defences – summary of evidence**
- 11 Norfolk County Council (2020), **Investigation into the flooding in Wainfleet in June 2019**
- 12 OECD (2020), **Good Governance for Critical Infrastructure Resilience**
- 13 Cabinet Office (2010), **National Risk Register of Civil Emergencies**
- 14 James Crotty (2009), Structural causes of the global financial crisis: a critical assessment of the ‘new financial architecture’, Cambridge Journal of Economics; Reinhart, Rogoff (2009), This time is different: eight centuries of financial folly
- 15 Chatham House (2012), **Preparing for High-impact, Low-probability Events**
- 16 Professor David Balmforth (2020), **Toddbrook Reservoir Independent Review report**
- 17 New Civil Engineer (2019), **How engineers scrambled to save Toddbrook reservoir dam**
- 18 OECD (2019), **Good Governance for Critical Infrastructure Resilience**
- 19 The Resilience Shift (2019), **The Role of Public Policy in Critical Infrastructure Resilience**
- 20 Ofwat (2017), **Resilience in the Round**
- 21 Cabinet Office (2011), **Keeping the Country Running: Natural Hazards and Infrastructure**
- 22 The Royal Academy of Engineering (2011), **Infrastructure, Engineering and Climate Change Adaptation – ensuring services in an uncertain future**
- 23 House of Lords (2004), Opinions of the lords of appeal for judgment in the cause A (FC) and others (FC) (Appellants) v. Secretary of State for the Home Department (Respondent); X (FC) and another (FC) (Appellants) v. Secretary of State for the Home Department (Respondent) [2004] UKHL 56
- 24 Professor David Balmforth (2020), **Toddbrook Reservoir Independent Review Report**
- 25 Gov.uk (2020), **Government decision on Northern Rail**
- 26 Flood Re (2020), **Why do we need Flood Re?**
- 27 Pool Re (2020), **Reinsurance**
- 28 HM Treasury (2020), **Government as insurer of last resort: managing contingent liabilities in the public sector**
- 29 Andrea Harris (2004), **Corporate Decision Making: Protecting Against Power Outage Loss**, Wharton Research Scholars
- 30 ICF Consulting Limited for the Consumer Council for Water (2017), **Improving willingness-to-pay research in the water sector**
- 31 Kates (1962), Hazard and choice perception in flood plain management
- 32 Scott Kelly (2015), **Estimating economic loss from cascading infrastructure failure: a perspective on modelling interdependency, Infrastructure Complexity**
- 33 Ofwat (2011), **Affordable for all**
- 34 Honorata Mazepus and Florian van Leeuwen (2019), **Fairness matters when responding to disasters: An experimental study of government legitimacy, Governance**
- 35 Atkinson and Stiglitz (1980), Lectures on Public Economics
- 36 National Infrastructure Commission (2018), **National Infrastructure Assessment**
- 37 National Infrastructure Commission (2019), **Strategic investment and public confidence**
- 38 National Infrastructure Commission (2019), **Strategic investment and public confidence**
- 39 Ofgem (2015), **Know your rights: power cuts**
- 40 Ofwat (2020), **Standards of service**
- 41 Ofgem (2020), **Security and Quality of Supply Standards (SQSS)**
- 42 legislation.gov.uk (2016), **The Water Supply (Water Quality) Regulations 2016**
- 43 Drinking Water Inspectorate (2017), **Report of the Drinking Water Inspectorate’s Investigation into the Cryptosporidium Contamination of Franklaw Treatment Works in August 2015**
- 44 Drinking Water Inspectorate (2017), Press release: **United Utilities fined for drinking water offence**
- 45 Network Rail (2020), Website page: **Snow and Ice**
- 46 Network Rail (2017) **Weather Resilience and Climate Change Adaptation Strategy 2017-2019**
- 47 Highways England (2019), **Highways England Delivery Plan 2019-2020**

- 48 Ofcom (2015), **Consolidated Version of General Conditions as at 28 May 2015** (including annotations)
- 49 Ofcom (2017), Press release: **Three fined £1.9m for emergency call service failure**
- 50 Ofcom (2017), **Ofcom guidance on security requirements in sections 105A to D of the Communications Act 2003**
- 51 Cologna, Bark, Jouni and Paavola (2017), **Flood risk perceptions and the UK media: Moving beyond “once in a lifetime” to “Be Prepared” reporting**
- 52 June Wiseman and Stacey Hughes (2018), **Availability and affordability of insurance**
- 53 Ofwat (2016), **Ofwat’s customer engagement policy statement and expectations for PR19**
- 54 Steer Group (2020), **Investigating the methods used to set committed levels of service**
- 55 Steer Group (2020), **Investigating the methods used to set committed levels of service**; Arup (2019), **UK Levels of Infrastructure Service Review**
- 56 National Infrastructure Commission (2020), **Principles for setting levels of service**
- 57 National Infrastructure Commission (2018), **National Infrastructure Assessment**
- 58 National Infrastructure Commission (2018), **Preparing for a drier future**
- 59 Cabinet Office (2017), **National Risk Register of Civil Emergencies**
- 60 Cabinet Office (2018), **Public Summary of Sector Security and Resilience Plans**
- 61 Institute for Government (2012), **Evidence and Evaluation in Policy Making: A problem of supply or demand?**
- 62 National Infrastructure Commission (2019), **Strategic investment and public confidence**
- 63 Eight metropolitan areas have metro mayors; London also has a directly elected mayor but the role, and the structures supporting it, differs slightly from that of a metro mayor. Centre for Cities (2019), **Everything you need to know about metro mayors**
- 64 Defined as below 48.8Hz (the threshold to trigger the low demand disconnection scheme). 50.2Hz – 49.8Hz is generally considered to be the operational limits and anything between 49.5 – 50.5 Hz is within the statutory range. National Grid ESO (2019), **Technical Report on the events of 9 August 2019**, page 5
- 65 National Infrastructure Commission analysis of data provided by Ofgem
- 66 National Infrastructure Commission analysis of data provided by Ofwat
- 67 Ofcom (2019), **Connected Nations 2019**
- 68 The Northern Powerhouse Partnership (2018), **Devolving our railways; Learning the lessons from a summer of Northern rail chaos**
- 69 Professor David Balmforth (2020), **Toddbrook Reservoir Independent Review Report**
- 70 Drinking Water Inspectorate (2017), **Report of the Drinking Water Inspectorate’s Investigation into the Cryptosporidium Contamination of Franklaw Treatment Works in August 2015**
- 71 Ofwat (2011), **Water and sewerage services during the summer 2007 floods**
- 72 HM Government (2016), **National Flood Resilience Review**
- 73 Office of Rail and Road (2020), **Report following railway power disruption on 9th August 2019**
- 74 Ofwat (2018), **Out in the Cold – Water companies response to the ‘Beast from the East’**
- 75 Met Office (2018), **Snow and Low Temperatures February to March 2018**
- 76 Ofwat (2018), **Letter to Chief Executive of United Utilities plc**
- 77 Ofwat (2018), **Letter to Chief Executive of Bristol Water plc**
- 78 Ofwat (2018), **Letter to Dwr Cymru about the review of the freeze/thaw incident**
- 79 Office of Rail and Road (2018), **Independent inquiry into the timetable disruption in May 2018**
- 80 HM Government (2016), **National Flood Resilience Review**
- 81 Office of Rail and Road (2020), **Report following railway power disruption on 9th August 2019**
- 82 Department for Transport (2014), **Transport Resilience Review, A review of the resilience of the transport network to extreme weather events**
- 83 National Cyber Security Centre (2019), **NCSC CAF guidance**
- 84 Ofwat (2015), **Towards resilience: how we will embed resilience in our work**
- 85 Ofcom (2017), **Ofcom guidance on security requirements in sections 105A to D of the Communications Act 2003**
- 86 Bank of England (2019), **Stress testing the UK banking system: key elements of the 2019 annual cyclical scenario**
- 87 Bank of England (2020), **The Internal Capital Adequacy Assessment Process (ICAAP) and the Supervisory Review and Evaluation Process (SREP)**
- 88 Bank of England (2016), Quarterly bulletin 2016 Q3 – **Stress testing of banks: an introduction**
- 89 Bank of England (2020), **The Internal Capital Adequacy Assessment Process (ICAAP) and the Supervisory Review and Evaluation Process (SREP)**
- 90 Bank of England (2020), Website: **Stress testing**
- 91 Bank of England (2020), **The Internal Capital Adequacy Assessment Process (ICAAP) and the Supervisory Review and Evaluation Process (SREP)**
- 92 Bank of England (2016), **Solvency II: ORSA**
- 93 Bank of England (2019), **Financial Stability Report - The results of the 2019 stress test of UK banks**, pages 1-20
- 94 Bank of England (2019), **Stress testing the UK banking system: key elements of the 2019 annual cyclical scenario**
- 95 Bank of England (2019), **Evaluation of the Bank of England’s approach to concurrent stress testing**
- 96 Bank of England (2020), Website: **Stress testing**
- 97 Bank of England (2016), Quarterly bulletin 2016 Q3 – **Stress testing of banks: an introduction**, page 137
- 98 Bank of England (2019), **Evaluation of the Bank of England’s approach to concurrent stress testing**
- 99 Bank of England (2019), **Evaluation of the Bank of England’s approach to concurrent stress testing**
- 100 OECD (2019), **Good Governance for Critical Infrastructure Resilience**, page 50 and 108

- 101 Cotton F, Iervolino I, Pitilakis K, Stojadinović B, Zwicky P, Tsionis G (ed), Pinto A (ed), Giardini D (ed), Mignan A (ed), (2016), **Harmonized approach to stress tests for critical infrastructures against natural hazards**, Joint Research Centre, page 4
- 102 Office for Nuclear Regulation (2020), Website: **Stress Tests**
- 103 National Infrastructure Commission (2017), **Data for the Public Good**
- 104 Ordnance Survey (2020), **Managing underground assets: Project Iceberg**
- 105 Professor David Balmforth (2020), **Toddbrook Reservoir Independent Review Report**
- 106 UK Regulators Network (2019), **Infrastructure Data Sharing**
- 107 Mott MacDonald (2019), **Commons challenges, shared response**
- 108 Institution of Civil Engineers (2018), **Ripe for transformation, ready for change?**
- 109 OECD (2019), **Good Governance for Critical Infrastructure Resilience**
- 110 Department of Homeland Security (2020), **Critical Infrastructure**
- 111 Cybersecurity & Infrastructure Security Agency (2020), **Infrastructure Protection Gateway**
- 112 Office of the Director of National Intelligence (2020), Website: **About the ISE**
- 113 **Canadian Critical Infrastructure Information Gateway**
- 114 OECD (2019), **Good Governance for Critical Infrastructure Resilience**
- 115 EPC, **Resilience Direct**
- 116 DAFNI **website**
- 117 New Civil Engineer (2019), **New digital twin for Newcastle to stress test infrastructure**
- 118 Centre for Digital Built Britain, **Analysing Systems Interdependencies using a Digital Twin**
- 119 Ofwat (2018), **Out in the Cold – Water companies response to the ‘Beast from the East’**
- 120 Ofgem (2020), **9 August 2019 power outage report**
- 121 Cabinet Office (2008), **The Pitt Review**
- 122 Environment Agency (2017), Blog: **Flood risk management 10 years on - a journey of high and low tech improvements**
- 123 National Infrastructure Commission (2019), **Strategic investment and public confidence**
- 124 Professor David Balmforth (2020), **Toddbrook Reservoir Independent Review Report**
- 125 The line represents observed values from the **Hadley Centre Central English dataset**. The shaded area represents the difference between the maximum projection, and minimum projection of summer average temperatures from UKCP18. We have taken the minimum to be the RCP2.6 scenario, at the 5th percentile, and the maximum to be the RCP8.5 scenario at the 95th percentile. The absolute values are calculated using the anomaly values in the **UKCP18 summary data**, relative to the 1981-2000 baseline, calculated as 15.7°C.
- 126 Marchau, Walker, Bloemen, Popper (2019), **Decision Making under Deep Uncertainty**
- 127 Federal Emergency Management Agency (2004), Press release: **Hurricane Pam Exercise Concludes**
- 128 RMS (2006), **Flood risk in New Orleans – Implications for future management and insurability**
- 129 Rogers, Kemp, Bosworth, Seed (2015), **Interaction between the US Army Corps of Engineers and the Orleans Levee Board preceding the drainage canal wall failures and catastrophic flooding of New Orleans in 2005**
- 130 Congressional Research Service (2006), **Hurricane-Damaged Drinking Water and Wastewater Facilities: Impacts, Needs and Response**
- 131 National Academy of Engineering (2006), **The Aftermath of Katrina**
- 132 Thames Tideway Tunnel (2016), Application for development consent – **Needs report**
- 133 National Audit Office (2017), **Review of the Thames Tideway Tunnel**
- 134 Stride (2019), **The Thames Tideway Tunnel: Preventing another great stink**
- 135 Royal Academy of Engineering (2016), **Living without electricity**
- 136 Electricity North West, **Building in resilience to cope with future challenges**
- 137 Department for Environment, Food and Rural Affairs (2017), **Water resources planning: how water companies ensure a secure supply of water for homes and businesses**
- 138 Ofwat (2018), **Out in the cold: Water companies’ response to the ‘Beast from the East’**
- 139 Drinking Water Inspectorate (2017), **Report of the Drinking Water Inspectorate’s Investigation into the Cryptosporidium Contamination of Franklaw Treatment Works in August 2015**
- 140 Department of Energy and Climate Change (2011), **UK Renewable Energy Roadmap**
- 141 Chester and Allenby (2019), **Toward adaptive infrastructure: flexibility and agility in a non-stationarity age, Sustainable and Resilient Infrastructure**
- 142 Real Wireless report for the UK Spectrum Policy Forum (2019), **The Potential Impact of Switching Off 2G in the UK**
- 143 Melaina, Antonia, and Penev (2013), **Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues**
- 144 National Infrastructure Commission (2018), **National Infrastructure Assessment**
- 145 Marchau, Walker, Bloemen, Popper (2019), **Decision Making under Deep Uncertainty**; Gersonius, Ashley, Pathirana et al. (2013), **Climate change uncertainty: building flexibility into water and flood risk infrastructure**; Kwadijk, Haasnoot et al (2010), **Using adaptation tipping points to prepare for climate change and sea level rise: A case study in the Netherlands**
- 146 Environment Agency (2012), **TE2100 Plan**
- 147 Arup (2020), **System Mapping for UK Infrastructure Systems Decision-making**
- 148 National Infrastructure Commission (2019), **Strategic investment and public confidence**
- 149 National Grid ESO (2020), **2020 Stakeholder Feedback Document**
- 150 UN Office for Disaster Risk Reduction (2017), **Build Back Better**
- 151 Brown, Massey (2001), **The sports development impact of the Manchester 2002 Commonwealth Games: initial baseline research**
- 152 Dr. S Tsenkova, University of Calgary (2001), **Urban Regeneration, Chapter 4**

153 National Infrastructure Commission (2018), **National Infrastructure Assessment**

154 National Infrastructure Commission (2020), **Net zero: Commission recommendations and the net zero target**

National Infrastructure Commission
Finlaison House
15-17 Furnival Street
London
EC4A 1AB
@NatInfraCom

 [nic.org.uk](https://www.nic.org.uk)
 [NatInfraCom](https://twitter.com/NatInfraCom)

May 2020