Ensuring all policies, programmes and investment decisions take account of climate change (with a focus on new infrastructure investment)

Summary

Key Policy messages

There is a goal in the 25 Year Environment Plan on 'making sure that all policies, programmes and investment decisions take into account the possible extent of climate change this century'. This case study assesses whether the Government is on course to achieve this goal, focusing on the area of new infrastructure. It is stressed that the case study is not considering households, and it is not focused on flood defence infrastructure, but rather all other new infrastructure.

The analysis looks at policy, programme and investment decisions for infrastructure, noting this involves public and private sectors, and includes all infrastructure investment not just targeted resilience infrastructure (such as flood defences). These investment levels are very large, for example, the average annual investment set out in the National Infrastructure Delivery Plan is £48 billion/year. The analysis finds that the current actions (in the 25YEP and NAP2) are insufficient to deliver the goal. While there is growing action in the public sector, and to a lesser extent in the private sector, there remains a sizeable adaptation gap. It is also noted that other countries and in particular the Multilateral Development Banks have gone further than the UK to date in integrating climate change into new infrastructure design.

Initial analysis in the case study finds that the additional adaptation needed to achieve the 25YEP goal could involve large additional costs (with an annual cost of £0.2 billion to £4.8 billion) and to deliver this efficiently and effectively, there is a need for enhanced appraisal. The benefits of such adaptation actions have not been calculated to date. A number of further adaptation options (to those currently in NAP2) have been identified which could help deliver the goal. These are primarily around creating the enabling environment for climate risk management (CRM) and adaptation appraisal, in both the public and private sectors (including how to incorporate climate risks and adaptation responses in public-private partnerships, PPPs). To support the 25YEP goal, a recommendation is made to revise and disseminate the Green Book supplementary guidance on climate change adaptation, along with support to enhance uptake of climate risk management in public investment decisions (given that there are no solid examples of where it has been used to date in infrastructure investment decisions). It is also highlighted that there is a need for greater Government action to support and enable the private sector to adapt. Underpinning all of this, there is a need to progress the economic appraisal of adaptation, as well as to develop sector specific guidance and standards to help facilitate uptake of effective and efficient resilience measures for new infrastructure. Finally, looking over the period of the 25 YEP, there will need to be more investment in resilience infrastructure, but also a need to ensure synergies with low carbon infrastructure to achieve the long-term emission reductions targets recommended by the Committee on Climate Change in their Net Zero Report (and now adopted by Government into law).

What is the policy objective and outcome?

The 25 Year Environment Plan (25 YEP) (HMG, 2018) set out the ambition of taking 'all possible action to mitigate climate change, while adapting to reduce its impact', and for the latter, it set a goal of 'making sure that all policies, programmes and investment decisions take into account the possible extent of climate change this century'.

This goal is extremely broad and potentially ambitious, and the 25YEP did not set out how the outcome will be achieved, other than highlighting it would be covered in the 2nd National Adaptation Programme (NAP2). NAP2 (Defra, 2018) adopts a similar goal to the 25YEP (to ensure that all policies, programmes and investment decisions take into account the possible extent of climate change this century), but it also does not set out how the goal will be achieved. The current text of NAP2 only references the 25YEP goal in the business chapter (i.e. for the private sector), and there are no Government actions in detailed action log of NAP2 (the only reference to supporting the action is devolved to the Council for Sustainable Business, which is largely using a voluntary approach). The NAP2 does highlight the work of the Green Finance Taskforce and activities on a potential adaptation standard, but it recommends that the Adaptation Reporting Power (ARP) should use a voluntary reporting approach. At the same time, it is recognised that there are many actions in the NAP2 that will help to deliver the 25YEP goal, such as the Government policy statements, though there is a lack of an overarching framework and specific actions that link back to the goal.

Against this background, this case study has focused on one particular aspect of the 25YEP outcome, and focused down to look at one of the most important policy, programme and investment areas, which is new infrastructure investment (not including flood defence infrastructure which is covered by different policies). For this case study, we therefore adopt an illustrative outcome of making sure that new infrastructure policy, programmes and investment decisions take account of climate change. It is noted that the focus on the infrastructure investment is not explicit in the 25YEP or the NAP2 goal, but it is implicit (as the 25YEP covers 'all').

For this case study, the focus is on new infrastructure programmes and investment decisions, for three reasons. First, new infrastructure has a long life-time and could be exposed to potentially large future climate change impacts. This may result in impacts on assets (risk of damage or failure), operating costs, performance and service / benefits. Second, many infrastructure investment projects involve lock-in, or irreversibility and it is often easier and more cost-effective to build resilience (adaptation) during design (Fankhauser et al., 1999: Warren et al., 2016). Finally, climate risks are now recognised as a financial risk as with the Task Force on Climate-related Financial Disclosure (TCFD, 2017), and the Network for Greening the Financial System (NGFS, 2019), which aims to improve the integration of climate risks into public and private sector decisions. It is stressed that the case study is not considering households, and it is not focused on flood defence infrastructure, but rather new infrastructure as classed by the CCC in their adaptation progress reports (energy, water supply, road, rail, ports, airports, digital, ICT and telecoms).

In recognition of these risk factors, the international public investment banks and several governments have introduced climate risk management systems (CRMs) as part of safeguard processes (e.g. ADB, 2014). These assess project investments and assess the level of climate risk during appraisal, and if needed, include adaptation (resilience) measures. This is now mainstreamed in investment financing and in 2017 the Multilateral Development Banks (MDBs) spent $7.4 billion on climate resilient investments, mostly for infrastructure (MDB, 2017). However, the same level of climate risk management has not yet been fully adopted in infrastructure appraisal, investment and financing in the UK, and existing guidance in UK Government (Green Book Supplementary Guidance, HMT, 2009) has had a low uptake in appraisal (OECD, 2015).

How does climate change affect the outcome, in a 2 vs 4°C pathway?
This case study has focused on investment and financing of new infrastructure. It is also noted that in the adaptation context, there are two types of new infrastructure investment.

- Making sure planned infrastructure investments take account of climate change (often referred to as climate smart decisions). This is also sometimes referred to as climate proofing (though this term is not recommended, because it is often not possible, and/or not economically efficient, to complete climate-proof infrastructure against all risks). This is associated with climate risk

screening and marginal adaptation to make infrastructure projects more climate resilient. Note this can also apply to major refurbishment or renewal infrastructure projects.
- New climate or adaptation infrastructure investment. This focuses on investments where adaptation is the primary objective, such as infrastructure (e.g. e.g. flood defences, water supply infrastructure) to address growing climate risks.

This case study is focused on the first of these, i.e. making sure planned infrastructure policy, programmes and investment decisions take account of climate change, i.e. are climate-smart. However, we also include some discussion on the second. It also considers mitigation as the UK has made commitments to significantly reduce domestic GHG emissions (the Climate Change Act 2008), and has now adopted a net zero target into law (based on CCC, 2019). It is noted that for infrastructure, this will involve public and private programme and investment decisions, through public investment, PPPs, regulated private investment, commercial investment, etc.

The case study has started by investigating the future national infrastructure investment profile. This represents also the potential lock-in risks, i.e. the new infrastructure that will be built in the next few years. In the UK, the National Infrastructure Delivery Plan (NIDP) 2016–2021 sets out the Government's commitment to £483 billion of investment in over 600 infrastructure projects / programmes to 2020-21 and beyond, of which £297 billion is planned by 2020-21 (National Infrastructure and Projects Authority, 2016). Around 50% of the infrastructure Pipeline to 2020-21 will be financed and delivered by the private sector. The average annual investment excluding social infrastructure is around £48 billion.

The study has then assessed the potential climate risks to infrastructure. It focuses on new near-term infrastructure, or major refurbishment or renewal, where there is a short-term investment and thus the opportunity to make this more resilient. There are a number of issues of relevance here (Watkiss and Wilby, 2019):
- Lifetime. In general, longer-lived infrastructure has higher risks, as assets built today could be exposed to higher levels of future climate change (and potentially different risks under a 2 vs. 4°C future). However, these generally refer to the technical or engineering lifetime, not the economic / financial lifetime: the latter are much shorter.
- Level of Precaution. Some types of infrastructure merit a high level of precaution, i.e. there may be a strong case for climate over-design, such as with critical infrastructure. In these cases, there are possible major regrets if the investment subsequently fails, which may justify a greater level of resilience in design.
- Economic and financial risk. For Government, economic analysis of infrastructure investment is carried out from the perspective of the entire economy, using social discount rates, while for the private sector, financial analysis is carried out from the perspective of the investor, considering private rate of returns. This leads to greater barriers to invest in long-term resilience in projects led or financed by the private sector.

The size of climate risks also clearly varies with infrastructure type, as well as geographic location. The main risks to infrastructure in England (Dawson et al., 2016) are considered to be from flooding, noting this also dominates current risks, but windstorms are also a major risk, and heat is likely to become more important in the future. In the short-term, the main difference in projections of climate change (Lowe et al., 2018) are from uncertainties across the climate models (i.e. the 10th to 90th probability level range in UKCP18) rather than from different emission and warming pathways (i.e. 2°C vs 4°C). In the long-term, existing estimates show a strong increase in risk under 4°C pathways, compared to 2°C. There is also a possible risk of stranded assets under higher climate risk futures. Sayers et al (2015) report that infrastructure assets could be subject to significant increases in risk; with the number of sites exposed to the highest chance of flooding (i.e. more frequently that 1:75 years on average) increasing by 30% (under 2°C climate change projection) and 200% (4°C climate change projection) by the 2080s. There is an interesting issue on who bears these risks, especially for PPP projects. If infrastructure investment decisions / finance takes account of climate change, then these impacts are reduced, but if they do not, then the 25YEP outcome could be missed. The case study identifies a gap in current policy.

What are the economic costs of climate change, i.e. the effect on the outcome?
Some of the climate risks to infrastructure are already being addressed, but where these are not, there will be additional costs. Therefore, not achieving the outcome would mean additional costs, affecting not just capital infrastructure, but also the services that infrastructure provides, with the potential for indirect costs. There are not many estimates of the future costs of climate change on infrastructure: most studies are focused on the costs on property, and it is also difficult to estimate the full costs including on infrastructure services. The estimates that do exist suggest large increases in economic costs from current levels, with much higher costs in the long-term in 4°C pathways.

Recent analysis in the financial markets has also highlighted that properly accounting for physical climate risk could - on average – reduce company values by 2-3% due to the costs of insuring assets (if these risks are not managed and reduced), and more than this in some sectors (Economist, 2019).

What are the potential additional adaptation options to address climate impacts?
The starting point for this step is to review the existing adaptation in place, and the additional actions that might be taken to reduce the outcome gap. It is noted that adaptation action for the infrastructure sector includes not only technical (engineering) options but also regulatory, policy and institutional responses, to enhance the adaptive capacity of infrastructure systems.

The CCRA2 Evidence report (Dawson et al., 2016) highlighted evidence that significant adaptation steps to manage climate change risks have been implemented, or are underway, across most infrastructure sectors. However, it also reported these investments will maintain or, in some instances, reduce climate risks over the next decade or two, and that on longer timeframes, projected changes in climate are likely to outpace current adaptation plans. The NAP2 sets out existing activities on infrastructure resilience and there has been further work under the National Flood Resilience Review. Nonetheless, the analysis identifies that there is a potential adaptation gap, i.e. the difference between the current level of adaptation and the level required to address the risks identified. It is noted also that most attention to date has focused on flood risks, with less consideration of other hazards. There is also a growing concern of the increasing interdependencies of infrastructure (Dawson et al., 2016), which means that as well as sectoral guidance there is a need to have an integrated approach.

While there are many good examples, the systematic inclusion of climate risk management (CRM) in public investment programmes and decisions is not well advanced, and there are major gaps in the policy landscape for CRM in the private sector. There is a role for the Government to address these gaps, because of its role in developing and financing public programmes and investment decisions, and because it can create the enabling environment for private adaptation, including in public-private partnerships (Cimato and Mullan, 2010: HMG, 2013).

The main focus for this case study is on climate smart early decisions with long life-times and lock in. However, uncertainty (on future scenarios and from uncertainties within and between climate models, i.e. the 10^{th} to 90^{th} probability level range in UKCP18) makes these early investment decisions challenging. It is relatively easy to design a new investment to be resilient to a single future, but much more difficult to design it to cope with deep uncertainty (noting over-designing projects to cope with the most extreme scenario involves the likely mis-allocation of resources and risk of economically inefficient adaptation). In response, there has been a move to decision making under uncertainty (DMUU). This includes (Watkiss et al., 2014) techniques such as adaptive management, real options analysis, robust decision making, portfolio analysis; decision scaling and decision rules. These address uncertainty with various principles (learning, flexibility, robustness, hedging and minimising regrets). However, these methods can be complex to apply, require detailed data, and are time consuming and resource intensive when applied formally, which can limit applicability.

A number of additional adaptation options have been explored. These include

- Supporting decision-making by providing tools and information;
- Screening climate risks (climate risk management) in public investments;
- Screening climate risks (climate risk management) in private sector investments;
- Enabling infrastructure resilience through policy and regulation;
- Encouraging the disclosure of climate risks/uptake in commercial finance
- Supporting innovative risk spreading (insurance).

What are the benefits and potential costs of adaptation?

The evidence base on the potential costs and benefits of adaptation in this area is low (ECONADAPT, 2017), and estimates are dependent on objective, method, risks and discount rates. Previous studies have derived first order estimates of the costs of adaptation by applying an uplift to infrastructure investment pipelines (e.g. OECD, 2015). Applying this approach to the NIDP economic infrastructure pipeline, using more recent estimates of the uplifts found from project implementation (ADB, 2014b: ECONADAPT, 2017), we estimate that the indicative total adaptation cost of building climate resilience in the current economic project pipeline would be £2.1 billion to £42 billion (primarily over the period to 2021), with an annual cost of £0.2 billion to £4.8 billion. This is a significant amount. Some of this may already be factored into the costs, but it is likely there would still be additional financing needs.

In practice, costs will range significantly with sector and context. There are some studies in the UK on infrastructure resilience costs, but these tend to be focused on the costs of major resilience works, i.e. flood defence measures (e.g. NIC, 2018: EA, 2019), rather than the costs of climate-smarting new infrastructure (although flood protection would provide more comprehensive protection for all assets, including infrastructure). It is also highlighted that there is ongoing work on the economics of infrastructure adaptation within the International Financial Institutions (ADB, 2015: MDBs, 2017: Hallegatte et al., 2019), which highlights that there are different approaches for building resilience, with different costs. The decision on which of these to do is determined by particular climate risk and economics, as well as lifetime, degree of lock in (cost of retrofitting later) and level of precaution. Emerging work is looking to standardise approaches within sectors (Watkiss and Wilby, 2019), to aid this decision-making process. Early experience has also identified financial and implementation challenges with many of the approaches recommended in the literature, i.e. those that use iterative (adaptive) management. This is because there are barriers to these options, due to the need for long-term monitoring and institutional capacity, as well as sequenced financing. A further set of recommendation are therefore included to advance the economics of adaptation, and to investigate how to incentivise adaptive management in financing.

Finally, there is also an issue of ensuring adaptation and mitigation synergies with planned investment in new infrastructure to reduce UK greenhouse gas emissions, consistent with the existing and proposed UK's long term GHG emission commitments (CCC, 2019).

Step 1: What is the policy objective and outcome?

The 25 Year Environment Plan (HMG, 2018) sets out the goal of mitigating and adapting to climate change, stating it would take all possible action to 'mitigate climate change, while adapting to reduce its impact'. It included a specific adaptation goal of 'making sure that all policies, programmes and investment decisions take into account the possible extent of climate change this century'.

This goal is the focus of this case study. However, this goal (or outcome) is extremely broad and is potentially very ambitious. Indeed, the 25 YEP does not specify how it will be achieved, reporting only (see Chapter 6 of the 25YEP) that the second National Adaptation Programme will set out how 'we will adapt to a range of projected climate impacts'. The 25YEP Plan also has a target for 'boosting the long-term resilience of our homes, businesses and infrastructure'. The objective is an adaptation one, i.e. it is specifically focussed on reducing the risk resulting from weather-related events. However, this is again very broad in scope by including 'people, the environment and the economy', as well as multiple hazards.

The Second National Adaptation Programme (Defra, 2018) does mention the goal in the Ministerial Foreword. It also includes a wide range of adaptation actions that would, in general terms, help to address the 25YEP goal. It reports the goal of the 25YEP as to 'ensure that all policies, programmes and investment decisions take into account the possible extent of climate change this century'. However, this goal is only included explicitly in Chapter 5: Business and industry, under section 5.4 (Access to capital and risks and opportunities associated with changing demand for goods and services), in the section headed non-financial reporting. The specific action in the 2NAP for this goal is:

Implementing the 25 Year Environment Plan, Defra will work with the Council for Sustainable Business (CSB), which will act as a sounding board, challenger, critic, innovator and advisor to the Secretary of State, Ministers and Defra policy teams[1].

It is noted, however, that no action for this appears in the Detailed Action log of NAP2 (Annex 2).

The 25 Year Environment Plan also sets out some of the areas on which the CSB could act and provide advice, although these are primarily focused on environmental goods and natural capital reporting and natural capital services/goods.

The NAP2 also highlights that:

- The Non-Financial Reporting Directive was transposed into UK regulations in December 2016. These regulations require large public interest entities to report on environmental matters and a description of the principal risks in this area.
- Government has engaged with the British Standards Institution (BSI) and key stakeholders to consider the possibility of developing a standard in climate adaptation and business resilience.

In the Chapter on Adaptation Reporting (7), NAP2 reports that the Adaptation Reporting Power (ARP) has changed over time. Following the Climate Change Act, ARP1 focused on major infrastructure providers from the energy, transport and water sectors and 91 organisations were directed to report. A number of other organisations were invited to submit voluntary reports. In total, 105 organisations

[1] And that the Council will work with business leaders to:
•identify environmental innovation and entrepreneurialism that will advance 25 Year Environment Plan ambition and goals;
•strengthen the financial case for sustainable business;
•advise on the development of the right regulatory frameworks, fiscal policies and support structures to achieve these ambitions

took part. The second cycle, ARP2 moved to a voluntary, light touch and flexible approach to reporting, with no guidance. 86 organisations took part.

Based on consultation, NAP2 sets out that a '*voluntary reporting process is the most constructive and collaborative approach for engaging reporting organisations and would allow the greatest flexibility and innovation in approaches to address climate risk and enable efforts to increase resilience. Government will not issue directions under the third round of the ARP, but we will invite reporting on a voluntary basis, in line with the 2008 Climate Change Act'.*

NAP2 sets out the organisations will be invited to report under the ARP. It is noted that the CCC recommended the ARP should be mandatory.

The published text in the NAP2 therefore only refers the 25YEP goal in the context of the private sector (as it only appears in the Chapter on Business) and there is no explicit action assigned to Government in the NAP2 detailed action log for this goal.

However, there are many other actions in the NAP2 that will help deliver the goal – many of which are set out in the chapter on infrastructure. The NAP recognises that there is a need to ensure that infrastructure is located, planned, designed and maintained to be resilient to climate change, including increasingly extreme weather events. As examples of the NAP2 actions in this area, there is:

- Government's £2.6 billion six year capital investment programme to reduce flood and coastal erosion risk, which will provide over £30 billion in economic benefits.
- For roads, the work of Highways England on climate change, which include several activities to address flooding (including a Flooding Action Plan) and future plans to consider as part of their strategy and future planning to the road network. There is also a discussion for local roads, which sets out the relevant issues (that climate change should form part of every authority's capital and maintenance programmes as well as their decision-making processes) although there is no specific action on how to help deliver this.
- There are a number of Government policy statements and strategic policy statements that are relevant to the goal, including Energy National Policy Statements (which require applications to consider climate change), the policy statement on Flood and Coastal Erosion Risk Management (FCERM), strategic policy statement to Ofwat (which includes long-term resilience thinking), and a National Policy Statement (NPS) for Water Resources.

Nonetheless, there is no overarching framework for the delivery of the 25 YEP, and there are no NAP2 actions on it in the NAP2 detailed actions log.

Infrastructure policy, programmes and investment decisions

To make this case study manageable, there is a need to focus. The case study has focused on one particular aspect of the 25YEP outcome, which is infrastructure. For this case study, we therefore adopt an illustrative outcome, which is to make sure that all infrastructure policy, programme and investment decisions take account of climate change. It is noted that the focus on the infrastructure investment is not explicit in the 25YEP or the NAP2, but it is included as the actions in both documents refers to 'all'.

This focus has been chosen because climate change risks are particularly relevant for new large infrastructure projects for two key reasons.

- Infrastructure has a long life-time, and thus will be exposed to future climate change. This may result in climate change affecting the operating costs, performance or anticipated service or benefits of the infrastructure, and in turn the rate of return. It could also result in changing patterns of extreme events from climate change affecting the infrastructure or exceeding the design criteria, causing damage or failure.

- Furthermore, many investment projects involve lock-in, or irreversibility, in that they alter patterns of exposure or vulnerability to future climate change. As an example, the siting of new infrastructure has to be carefully considered, because current patterns of climate risks could change in the future. What might be an area at low risk of flooding today could become high risk under climate change. The key issue here is that once infrastructure has been built, and land-use change has happened, it is very difficult to change it later. Relocation is extremely expensive or not possible, and locking in infrastructure to the need for future protection or retrofitting is likely to be high cost. A key issue is that it is often easier and more cost-effective to build resilience (adaptation) into projects at the design stage, rather than retrofitting later, because retrofitting is often more expensive, or sometimes not possible.

This is reflected in the greater weight being given to financial reporting of climate risks, notably through the Task Force on Climate-related Financial Disclosure (TCFD)[2] established by the G20's Financial Stability Board. TCFD identifies two types of climate risks.

- Transition risks, i.e. the policy, legal, technology, and market changes to transition to a lower-carbon economy and financial and reputational risk to organizations (reported as policy and legal risks, technology risks, market risk and reputational risk).
- Physical risks, resulting from climate change from events (acute) or longer-term shifts (chronic) in climate patterns, and the financial implications for organizations, such as direct damage to assets and indirect impacts from supply chain disruption, as well as from changes in water availability, sourcing, and quality; food security; and extreme temperature changes affecting organizations' premises, operations, supply chain, transport needs, and employee safety.

The initial focus in this area was on transition risk, i.e. stranded assets or investment risks because of mitigation policy and carbon taxation, i.e. affecting investment in fossil fuel reserves or fossil generation plants (McGlade and Ekins, 2015: Mecure et al, 2018). However, there is an increasing recognition of the need to assess and disclose physical climate impact risks and TCFD is developing protocols for reporting risks. It is hoped that the disclosure of this information will improve the integration of climate risks into private sector decisions, i.e. if climate risks are recognised as financial risks then financial markets will take account of exposure in the allocation of capital.

This has been followed up with the Network for Greening the Financial System (NGFS, 2019), which involves a number of central banks (including the Bank of England). This network also identified climate change as a source of financial risk[3], and highlighted the need to *enhance the role of the financial system to manage risks and to mobilize capital for green and low-carbon investments in the broader context of environmentally sustainable development*.

It is also highlighted that a number of the rating agencies and stock exchanges are starting to consider climate risk in credit worthiness assessments, both at the country level and also for individual companies (Moody's, 2017: Standard & Poor's, 2015). Indeed, something that is already starting to happen is the addition of basis points for developing countries due to climate risks (ICBS and SOAS 2018), and for private companies. For the latter, properly accounting for physical climate risk could - on average – reduce company values by 2-3% due to the risk costs of insuring assets (if these risks are not managed and reduced), and more than this in some sectors[4].

[2] See https://www.fsb-tcfd.org
[3] https://www.bankofengland.co.uk/-/media/boe/files/research/greening-the-financial-system-statement.pdf
[4] https://www.economist.com/business/2019/02/23/business-and-the-effects-of-global-warming

In recognition of these issues, the large multi-lateral development banks (MDBs) and investment banks/international financial institutions (e.g. the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD), Asian Development Bank, (ADB), World Bank, etc.) as well as EU funds (E.g. structural funds) have implemented climate risk management systems (CRMs) as part of their safeguard process (EUFIWACC, 2016). These assess project investments and assess their level of climate risk during the project appraisal cycle, and if needed, include adaptation (resilience) measures in their design to manage these. These climate risk screening processes are undertaken as part of the routine project investment appraisal cycle and it has become part of mainstreaming investment financing: in 2017 the MDBs spent $7.4 billion on such climate resilient investments, mostly for infrastructure (MDB, 2018). These investments are primarily for public infrastructure, or public private partnerships, although in some cases, it involves direct private sector lending.

Infrastructure investment in the UK

At the global level, several recent studies have estimated the level of new infrastructure investment that is needed over the next decade or so. The New Climate Economy (2016) estimated total investment needs of $57 trillion by 2030 while the OECD (2017) estimated $95 trillion from 2016 by 2030 is needed (the latter equivalent to $6.3 trillion/year over the next decade), primarily in energy, water, transport and telecoms.

It is stressed that this infrastructure will be delivered through both the public and private sectors. It can include public investments (noting these often use the private sector to build), public-private partnerships, private sector investments in regulated sectors (i.e. former public sector areas, notably energy and water), and commercial private sector investments.

At the UK level, the National Infrastructure Delivery Plan (NIDP) 2016–2021 (Infrastructure and Projects Authority, 2016) sets out the Government's plans for economic infrastructure over the next 5 years. It reflects the Government's commitment to invest over £100 billion by 2020-21, alongside significant ongoing private sector investment in infrastructure.

The NIDP updates and replaces the previous NIP, outlining details of £483 billion of investment in over 600 infrastructure projects and programmes in all sectors and spread across the UK, to 2020-21 and beyond (of which over £297 billion is planned to 2020-21). Of this, economic infrastructure is £239.7 bn and Social £57.6 bn: for this case study we are more interested in the former. The Pipeline contains both individual projects over £50 million and programmes over £50 million containing multiple individual projects. This includes over 4,000 individual projects when including those grouped within active programmes. It sets out what will be built and where, focusing on the Pipeline that will be delivered over the next 5 years to 2020-21. Around 50% of the infrastructure Pipeline to 2020-21 will be financed and delivered by the private sector (NIDP, 2016).

The average annual investment excluding social infrastructure is around £48 billion (and £426 billion in total).

It is noted that this does include some adaptation targeted infrastructure investment (flood and coastal erosion protection infrastructure investment). It is also likely that a proportion of the water investment is associated with climate related activities. This is discussed in a separate case study.

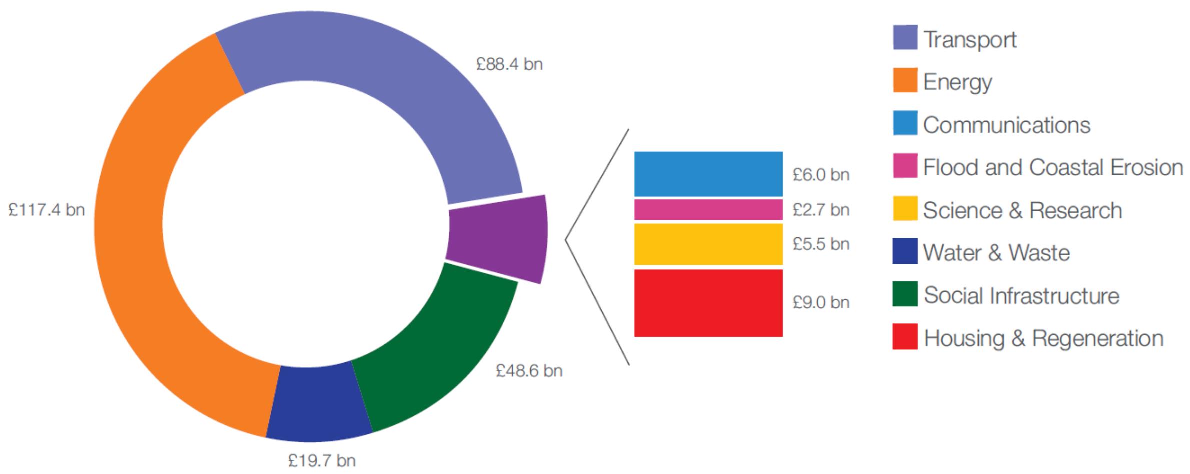


Figure 1 UK Infrastructure investment, by sector, spend from 2016-17 to 2020-21 (NIDP: IPC 2016)

Table 1 Infrastructure pipeline, 2016-17 onwards. Source NIDP, IPA, 2016.

Sectors	Projects (number)	Programmes (number)	Pipeline Value (£ billion)
Communications	2	4	6.0
Energy	109	58	255.7
Flood	6	23	4.1
Science and Research	25	7	5.5
Transport	166	163	134.5
Waste	10	0	0.5
Water	1	28	19.3
Total	*319*	*283*	*425.6*

The NIDP covers infrastructure across the UK where it is not a devolved responsibility. The NIDP does report on how much of the allocations to Northern Ireland, Scotland and Wales combined. However, the split between the responsibility of the UK Government and each of the devolved administrations for infrastructure policy and funding varies according to the distinct devolution settlement in place, thus there are no DA or England-only values presented. Around 45% of the value of the Infrastructure Pipeline to 2020-21 is allocated to English regions, but this excludes additional national level projects that cross regions (or countries).

The NIDP also sets out that to achieve these plans requires:

- establishing the right framework: to ensure the right projects are delivered well;
- identifying the right priorities: determining the project and programme delivery milestones that the Government should focus on;
- getting the right finance in place: recognizing that both public and private investment is required to deliver UK infrastructure.

As mentioned above, the Government has set up a National Infrastructure Commission, to produce a clear picture of the future infrastructure the country needs and provide expert, independent, analysis and advice on pressing infrastructure issues. The NIC gives advice on the UK's infrastructure needs and put forward priorities for the next 30 years. The NIC's National Infrastructure Assessment (2018) sets out recommendations for a pathway for the UK's economic infrastructure. Two of the seven recommendations relate to adaptation:

- ensuring resilience to extreme drought;
- a national standard of flood resilience for all communities by 2050.

However, these are focused on infrastructure for adaptation (rather than adaptation [resilience] for infrastructure). The Commission set out a recommendation that 'a national standard should be set for resilience to flooding with an annual likelihood of 0.5 per cent by 2050, where feasible. Over longer time periods, higher standards might be achievable. Densely populated areas, where the consequences of flooding are potentially much more serious, should be resilient to flooding with a likelihood of only 0.1 per cent a year by 2050. It set out that this long-term strategy for flood protection would allow a nationwide standard of resilience to flooding, with catchment-based plans, noting that these plans should evaluate the full range of options including traditional flood defences, 'green infrastructure', individual property measures and spatial planning. Supporting this was a more in-depth analysis on the impact of climate change on infrastructure (NIC, 2018b). The NIC in 2019 is undertaking a study on resilience, to look more closely at what is needed by way of resilient infrastructure for climate change.

Roles and responsibilities in delivering the Outcome

The legislative framework governing infrastructure adaptation comprises a number of high-level laws and acts, as well as sectorial policies and responsibilities. These are set out in the Appendix.

In the UK, the Treasury Green Book (HMT, 2018) presents the recommended framework and guidance for the development and appraisal of all policies, programmes and projects in UK Government. The Green Book sets out the key stages in the development of a proposal, from the articulation of the rationale for intervention and the setting of objectives, through to options appraisal and, eventually, implementation and evaluation. The Green Book emphasises the economic principles that should be applied during this appraisal process, from the economic justification for public intervention, through to the economic appraisal of alternative ways of delivering objectives. This includes the identification of options that could meet the stated objectives, which are subject to an appraisal which assess their costs and benefits (from a societal perspective). The Supplementary Guidance on Valuing Infrastructure spend (HM Treasury, 2015b) sets out wider economic considerations for appraising infrastructure. There is existing Green Book Supplementary Guidance on for climate change - Accounting for the Effects of Climate Change (HMT, 2009), but a review of the use of this climate supplementary guidance in Government found that the use was extremely low, with ***no*** concrete examples of its application in economic appraisal (see OECD, 2015). However, there is additional guidance in certain sectors that may help to address this. For example, there is Environment Agency guidance for economic appraisal of FCERM schemes (EA, 2016), with guidance for Adapting to Climate Change: Advice to Flood & Coastal Risk Management Authorities. There is also some guidance in some of the national policy statements (see earlier discussion). Nonetheless, the systematic inclusion of climate risk management in public investment programmes and decisions is not well advanced. This includes, for example, the cascade of climate risk assessment down to regional and local programmes and investments.

At sectoral level, different acts shape the regulatory framework, roles and responsibilities of different parties on adaptation (See NAP2).

Mitigation and adaptation linkages

A final infrastructure issue is highlighted: the UK has made commitments to significantly reduce domestic GHG emissions, and has just adopted a net zero target by 2050 into law. There is an important need to consider the potential synergies and conflicts for low carbon and climate resilient long-term infrastructure pathways. This will have major implications for infrastructure, notably in the energy and transport sectors. The European Commission has also published a Long-Term Strategy (EC, 2018). The LTS sets out a vision that can lead to achieving net-zero greenhouse gas emissions by 2050. It sets out alternative future pathways for emissions reductions, and seven building blocks (energy efficiency in building, renewables, clean mobility, circular economy, smart networks, bio-economy and carbon sinks, and carbon capture and sequestration).

Step 2: How does climate change affect the outcome, in a 2 vs 4°C pathway?

The case study has focused on investment and financing, where possible focusing on new infrastructure. It is also noted that in the adaptation context, there are two types of infrastructure investment.

- Making sure planned infrastructure investments take account of climate change, i.e. that they are climate smart. This ensures that new investments, i.e. new infrastructure built as part of ongoing activities and economic development, take account of climate change risks. This is sometimes referred to as climate proofing (though this term is not recommended, because it is often not possible, and certainly not normally economically efficient, to complete climate-proof infrastructure against all risks over all time periods). This is associated with climate risk screening and marginal adaptation to make existing projects more climate resilient. Note this can also apply to major refurbishment or renewal infrastructure projects.
- Climate or adaptation infrastructure investment. This focuses on investments where adaptation is the primary objective (or one of the primary objectives). This invests in infrastructure (e.g. flood defences) to specifically address growing climate risks. This is likely to be an increasing portion of the English infrastructure investment portfolio in future years as climate change increases.

This case study is focused on the first of these. However, later in the case study, there is also a brief discussion on the second, and the need to scale up adaptation investments.

The impacts of climate change on infrastructure

The size of climate risks clearly varies with infrastructure type, as well as geographic location. The primary way that climate affects infrastructure is primarily affected by weather extremes. The impacts of such events are also rising and global losses from weather related disasters and geophysical hazards in recent years are among the highest on record (Munich Re, 2018; Swiss Re, 2017). These disasters have major impacts on infrastructure.

As reported in CCRA1 (2012) and CCRA2 (2017), increased frequency of flooding from all sources is the most significant climate change risk to English infrastructure, including energy, transport, water, waste and digital communications (see Table 4 below). However, this reflects the fact that existing infrastructure assets are already situated in locations that are exposed to river or coastal, groundwater and surface water flooding. These include (CCRA2 – based on Sayers et al. 2015) power stations (41%, 6% and 18% of all power stations in England are at risk of river and coastal flooding, surface water, and groundwater flooding respectively), proportions of railway track (17, 9 and 17%) and railway stations (14, 3 and 16%), A-roads and motorways (9, 6 and 9%) and clean and wastewater treatment sites (33, 12 and 24%).

Sayers et al. (2015) reports infrastructure assets could be subject to significant increases in risk; with the number of sites exposed to the highest chance of flooding (i.e. more frequently that 1:75 years on average) increasing by 30% (under 2°C climate change projection) and 200% (4°C climate change projection) by the 2080s. Protection to an even higher standard, which might be achieved with more engineering intervention or via other adaptation strategies, would be required to cope with climate changes anticipated for the 2080s, particularly under a 4°C rise in mean global temperatures. Note that the analysis of the baseline adaptation scenario assumed local protection of the majority of Category A infrastructure sites. As a result, the number of infrastructure assets exposed to frequent flooding (more often than 1:75 years on average) is mitigated in the 2020s, but would increase significantly under a 4^{o}C scenario.

Table 2 Overview of key climate risks for each infrastructure sector

Hazard / Sector	Floods	Water scarcity	High temperatures	(Wind) Storms	Geohazards (inc. subsidence and landslides)
Water and waste water	✓✓	✓✓	✓		✓
Transport	✓✓		✓	✓✓	✓✓
Energy generation	✓✓	✓	✓	✓	
Energy distribution	✓✓		✓	✓✓	✓
Flood and coastal defences	✓✓			✓	✓
Solid waste	✓		✓		
ICT	✓✓		✓	✓✓	✓

Source: Expert judgement arising from the literature reviewed in this chapter.
Notes: A single tick denotes a relationship; a double tick denotes a strong relationship. These do not consider dependencies between infrastructures.

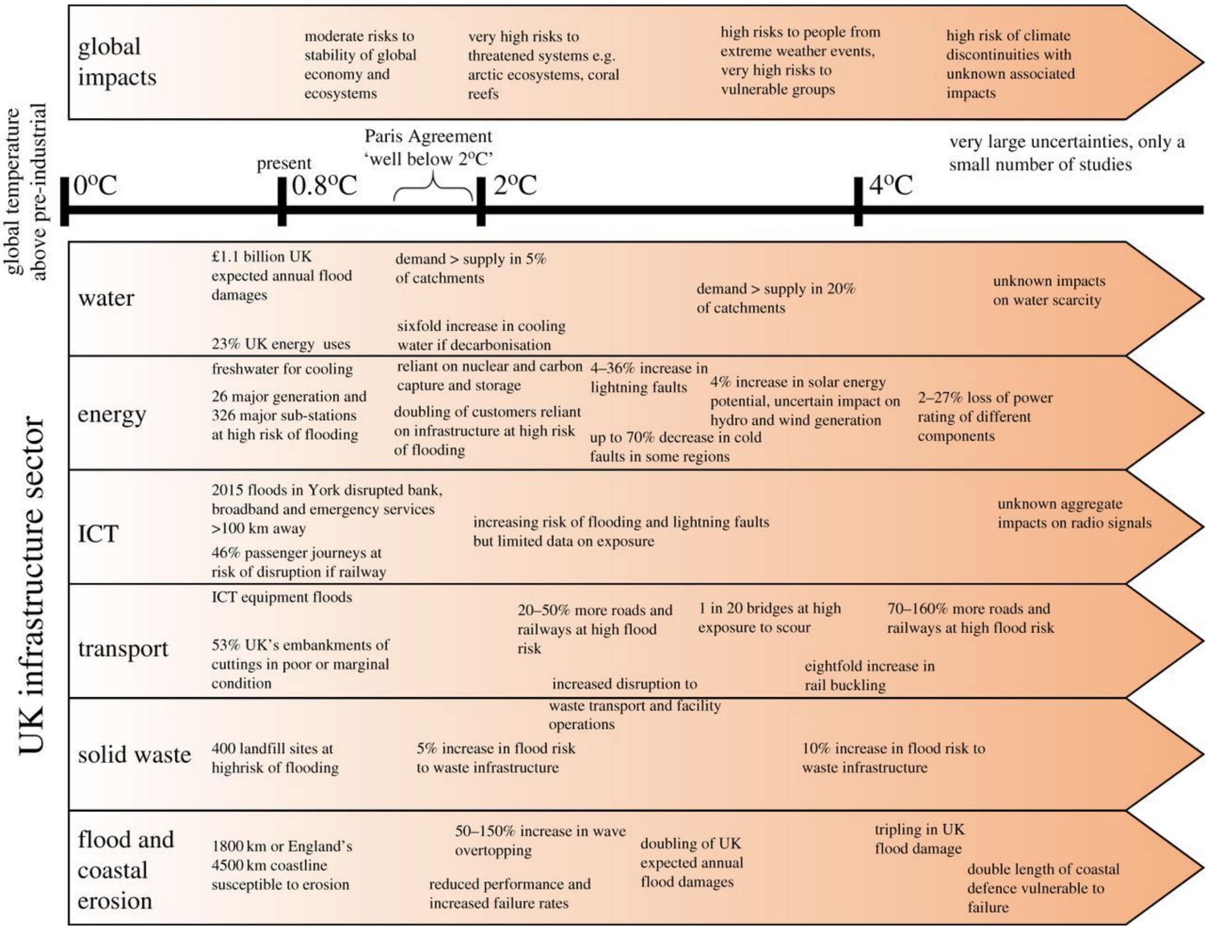
Source: CCRA 2 (2017)

Table 3 England: Headline risks under the Baseline Adaptation Scenario (i.e. assuming a continuation of current levels of adaptation)

		2020s			2050s			2080s		
Risk Metric	Present day	2 Deg	4 Deg	H++	2 Deg	4 Deg	H++	2 Deg	4 Deg	H++
Infrastructure (at risk of flooding more frequent than 1:75)										
Water										
No. clean and wastewater sites	220	-60%	-53%	-35%	-32%	-9%	19%	2%	39%	60%
Transport										
No. of rail stations	430	0%	3%	15%	2%	14%	30%	8%	26%	37%
Length of railway (km)	3,900	1%	14%	70%	12%	81%	170%	70%	230%	310%
Length of road (km)	1,400	1%	15%	57%	11%	62%	120%	51%	150%	210%
Energy										
No. Generation and transmission stations	230	-49%	-38%	-13%	-11%	26%	65%	39%	98%	120%
Social										
No. Care homes	370	1%	16%	73%	13%	72%	140%	51%	160%	210%
No. Schools	760	1%	11%	52%	9%	53%	110%	40%	120%	170%
No. Emergency services	140	1%	14%	63%	11%	60%	120%	37%	120%	160%
No. Hospitals	89	1%	6%	27%	4%	27%	52%	23%	65%	90%
No. GP surgeies	510	1%	14%	66%	12%	64%	130%	46%	140%	190%
Waste										
No. landfill sites	380	0%	2%	5%	1%	6%	9%	5%	10%	14%

Dawson et al. (2018) present a visual summary of the main climate change risks to UK infrastructure identified in the CCRA2 Evidence Report Infrastructure Chapter. Flooding is shown to be a significant risk across all sectors, almost doubling between a 2^{o} and 4^{o} degree scenario.

Figure 2 Relationship between global temperature change relative to pre-industrial era, and key climate change risks to UK infrastructure. A high risk of flooding has a likelihood of flooding more frequently than 1 in 75 years (AEP ≥ 0.013).



Source: Dawson et al. (2018)

As highlighted above, as well as direct risks, there are also interconnection and interdependency risks between sectors: failure of one infrastructure network can cause disruption and failure in other dependent networks, amplifying risks. There have been some specific assessments of this, for example, Pant et al. (2018) assessed the exposure of infrastructure (electricity transmission, wastewater, water supply and telecoms.) to flooding and disruption in the Thames catchment, estimating direct and indirect risks. They highlight how indirect disruption can extend beyond the boundary of the flooded area across multiple boundaries. WSP are currently undertaking a project to quantify cascade effects across infrastructure, built environment and the natural environment to inform CCRA3.

Due to the complexity and interdependency of the infrastructure network, threshold risks cannot be known nor estimated in advance. However, one important consideration should be made. All service providers are usually committed and/or requested by the regulators to guarantee a certain level of service. Hence, for each service provider, a question arises as to whether maintaining such level, in the face of climate risks, would continue to be cost-efficient in the future. That constitutes an 'adaptation threshold' for service providers, beyond which adaptation would not be financially feasible and /or would translate in higher costs of services to customers.

The effect of these potential risks on the outcome is somewhat circular, in that if infrastructure investment decisions and financing take account of climate change, then these impacts are reduced, whereas if they do not, then the outcome will obviously be missed. The key issues are therefore around:

- Whether there is a gap in policy?
- Whether there is any evidence of planning for 2°C, but a lack of planning for 4°C?
- Where a future 4°C world makes it much more difficult to achieve the outcome?

For the first of these questions, the analysis by CCC (2017) indicates there is a gap. It is more difficult to address the second question, and the 2 and 4°C pathways do not diverge significantly until after 2050. There is, however, and issue of whether organisations are planning for uncertainty, i.e. for the range across the projections in 2050s, i.e. the UKCP18 10^{th} to 90^{th}). As an example, current water sector investment plans (25 year plans) have mainly planned for the medium emissions scenario (although some do use high emissions as a sensitivity).

At higher levels of climate change, there are also potentially higher risks of stranded assets. The concept of stranded assets has been well advanced in the mitigation literature (Caldecott, 2018). However, it can also apply to projects affected by physical climate change impacts. An example is with irrigation in water scarce areas or new hydropower projects. In these cases, a drier future climate may be detrimental, as it could affect the return on major capital investment, if there is insufficient water to be available to deliver the return on investment.

What influences risks

The figures above show the short-term infrastructure investment pipeline set out in the National Infrastructure Delivery Plan, however, not all of this is equally at risk. As well as the size and type of risks (discussed later), the infrastructure risk is a factor of (Watkiss and Wilby, 2019):

- The lifetime;
- The level of precaution;
- The economic and financial level of risks.

Lifetime

Projects with a longer operational lifetime are likely to be exposed to more severe future climate change (especially under a 4°C scenario), as the climate signal is stronger in later years. This means they may need to consider more climate resilience (though they still need to assess if this makes economic sense). Conversely projects with a short life-time should focus more on current climate variability. To illustrate, wind turbines have a short operational and lifetime (under 20 years) and so future climate change impacts are less important, whereas new bridges have a very long life-time, well in excess of 50 years, and could be exposed to much greater impacts especially under a 4ºC future. This forms a major link back to the difference between a 2 and 4°C future, because long lived infrastructure has potentially higher risk exposure. There are anticipated lifetimes for different infrastructure investments.

In practice, however, things are a little more complicated. There is a large range of lifetimes within a specific project. A nice example of this is from earlier work by the Highways Agency, which identified the lifetime of different investments, shown in figure 2. Culverts, bridges, tunnels and retaining walls have the longest- lifetime. These lifetimes were subsequently used to identify the priorities for early adaptation, identifying those with the longest long-life-time as priorities. The analysis also identified where early action was needed because of long lead times, or because of the need for planning/smoothing of a lengthy national programme of works.

Table 4 Examples of lifespans. (Based on Hallegatte, 2009: Ranger et al, 2013: OECD, 2017).

Infrastructure	Timescale (years)
Power plants (thermal)	20 to 60
Buildings	30 to 150
Transport infrastructure	30 to 200
Water infrastructure	30 to 200
Land-use plans	Typically >100

Moreover, these examples generally refer to the technical or engineering lifetime, not than the economic or financial lifetime. The latter are much shorter. The financial lifetime is usually associated with the investment or loan lifetime. The economic life is defined as the number of years before the annual economic cost of operations begins to exceed annual economic benefits. This is of key importance: while there may be a strong technical case for adapting infrastructure based on the design lifetime, and this is often inferred in the literature, there is usually much less justification to do so based on the economic or financial lifetime, because the additional adaptation investment is not justified under an economic cost benefit analysis or on the basis of the financial internal rate of return.

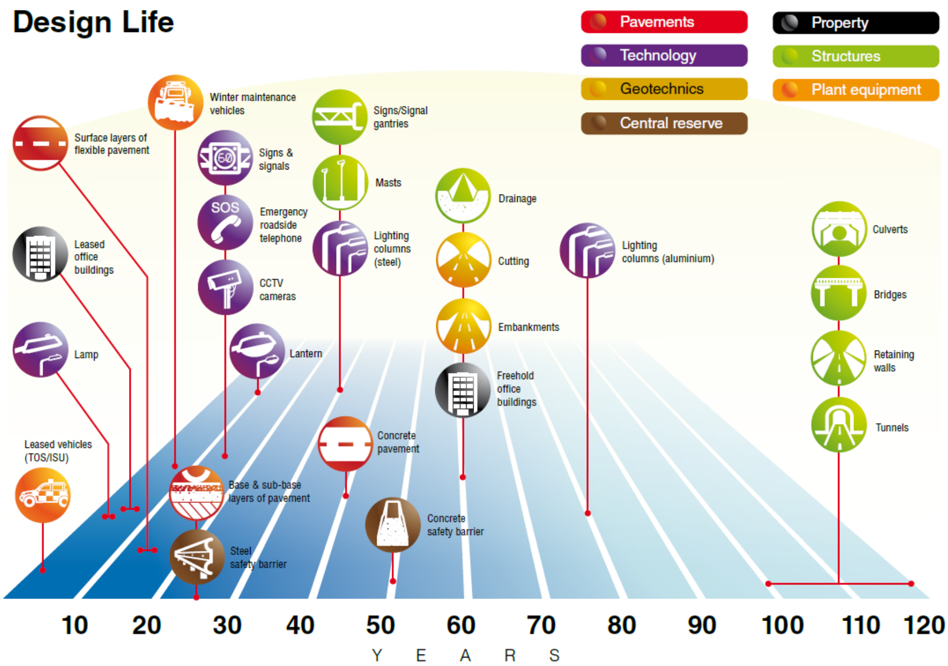


Figure 3 Design life of different road transport components. Source Highways Agency (2011).

Level of precaution

A further issue that has emerged (Watkiss and Wilby, 2019) is that some types of infrastructure merit a high level of precaution, i.e. there may be a strong argument for over designing and over protecting against future risks across the lifetime of the infrastructure investment. This is the case for critical infrastructure. Some infrastructure investments are already built with much higher design criteria, to reduce the chance of failure. An example is for new hydropower dams, which are design to withstand the estimated probable maximum flood[5]. A high level of precaution is often also warranted for critical infrastructure, given the large direct and indirect risks that could result from failure. In these cases, there are potential large regrets if impacts occur. This logic can also be applied to critical components

[5] The Probable Maximum Flood (PMF) is the theoretically largest flood resulting from a combination of the most severe meteorological and hydrologic conditions that could conceivably occur in a given area (LaRocque, 2013).

in an infrastructure project, i.e. to overprotect key components (See NYCMMC, 2018).

Another relevant issue here is increasing recognition of the risk of converging and cascading interactions from disaster risks on infrastructure (Dawson et al, 2016). Infrastructure services such as heating, lighting, mobility and sanitation are essential for modern society and they are increasingly reliant on each other (e.g. for power, control, and access, and through ICT links). Impacts on infrastructure can therefore lead to important indirect (cascading) economic costs, including interdependent infrastructure linkages, such as the impacts on electricity supply or transmission infrastructure on ICT or transport networks. This can therefore have important knock-on effects, affecting the productivity and services including critical services such as electricity, water supply, health and emergency services. The main interdependencies and interconnectivities are centred on energy, water, transport and ICT, and are associated with major extreme events, i.e. floods, storms or extreme heat, now and increasingly over time with climate change. These cascading risks require a systems approach, i.e. to consider infrastructure resilience as part of a wider system. This requires a more integrated approach to assess the interlinkages from disaster and climate risks, beyond the individual infrastructure investment alone, and this is a major priority for future English investment.

It is noted that a major concern among infrastructure operators (as shared in the Infrastructure Operators Adaptation Forum) are increasing interdependencies of infrastructure. This also highlights that just considering individual risk assessment may not be sufficient, i.e. that individual CRM and sectoral guidance is important, but there is a need to consider the integrated infrastructure system.

Economic and Financial Risk

Much of the available literature on adaptation for infrastructure has focused on the scientific and technical case for action, based on the analysis of future climate risk. However, a critical issue is to consider the economic and financial perspective. For Government projects, some form of economic and financial appraisal of projects is usually undertaken. These appraisals involve the identification of project benefits and costs and the calculation of the Net present value (NPV)[6] and/or the Internal rate of return (IRR)[7]. However, there are major differences between economic and financial appraisal:

- Financial evaluation is carried out from the perspective of the project, and it considers the incremental cash flows (revenues and costs) generated, to assess the ability of the project to generate adequate incremental cash flows to recover its financial costs (generate profit or repay a loan). The costing uses market prices and includes relevant taxes and charges.
- Economic analysis is carried out from the perspective of the entire economy, and it assesses the impact of a project on the welfare of society. The analysis includes the economic valuation of non-market areas, such as environmental costs and benefits, and it adjust values (excluding taxes/charges, using shadow prices, etc.).

This difference is really rather important. For an individual project investment, climate change can affect the future return on investment and the financial IRR, either by changing project costs or revenues, or by changing the risk of damage to investments. This is particularly important for investments that are investing in climate sensitive sectors (water management), sited in climate risky locations, and/or that rely on climate sensitive inputs for their operation and profitability (e.g. water for irrigation). Climate change may also affect the overall economic costs and benefits of a project, but the effects will be different (e.g. affecting socio-economic benefits), therefore climate change may impact the economic return of a project, but not the financial return. Following from this, the benefits

[6] Total discounted benefits minus total discounted costs. Sometimes presented as a benefit to cost ratios (NPV benefits divided by NPV costs). In economic analysis, this estimates the economic NPV (ENPV) and economic IRR (EIRR) while for financial analysis, the financial NPV (FNPV) and financial IRR (FIRR).

[7] the rate at which the NPV is zero, which can be compared with the discount rate to assess if a project generates a sufficient return on investment to be viable.

of adaptation are different, as assessed by a financial analysis by the private sector than they will be to the government, when assessed with economic analysis. This makes it much more difficult to justify up front adaptation of projects when these are led by the private sector, or when there is a need for the private sector to generate a sufficient return on investment.

Table 5 Economic and Financial Risks from Climate Change on Investment Projects.

<table>
<tr><th>Category</th><th>Current weather and extremes</th><th>Future climate change</th></tr>
<tr><td>Asset /Capital Cost</td><td rowspan="5">Current weather extremes (e.g. shocks such as floods)
Current climate variability
Possible threshold levels</td><td rowspan="5">Slow onset change – average trends
Changes in the intensity or frequency of extreme events
Changes in variability.
Exceedance of thresholds</td></tr>
<tr><td>O&M / O&M costs</td></tr>
<tr><td>Revenues / benefit stream</td></tr>
<tr><td>Access to finance/ insurance</td></tr>
<tr><td>Socio-economic effects (economic)</td></tr>
</table>

It is also difficult to address these economic risks (OECD, 2015). Firstly, it is it challenging to know what future risks are, and thus how much adaptation it may be economically sensible to build into a project with a long lifetime (i.e. more than 30 years) when designing it today, because the future risks of climate change are uncertain, i.e. the level of adaptation for a 2 versus a 4°C future. Second, it is often difficult to make a strong economic case (and especially a financial case) for adaptation to address these risks. This is because climate change is gradual and larger impacts only emerge after the 2040s. The full benefits of adapting to these future impacts therefore also arise in the longer-term, thus they are low in present value terms (in an economic analysis, e.g. using the social discount rate recommended by UK Government (HMT, 2018) of 3.5% declining) when compared to the up-front adaptation costs incurred during project construction. The economic case for climate investment is further weakened by uncertainty, e.g. there is a risk of investing in adaptation that turns out not to be needed. While there are ways to address risk in economic appraisal (as set out in the Green Book and Orange Book), climate change is a problem of deep uncertainty (World Bank, 2012), which has led to the focus on DMUU methods (see next section). This was captured in the Green Book Supplementary guidance (HMT, 2009), but as highlighted above, this involved subsequent implementation challenges and there is little evidence that the guidance has been taken up.

What is more, in the private sector, these barriers are much higher. There is little financial justification for the private sector to adapt, as the private sector IRR effectively works with a much higher discount rate, and thus there is little attractiveness in investing in long-term resilience. When there is a public-private partnership, or where the private sector operates in a heavily regulated markets (which is often the case for infrastructure), it may be that appraisal guidance can specify the need to consider climate risks, or conditions or penalties can be included to try and help incentivize the internalization of resilience. However, there is still the underlying problem that financial appraisal will give lower weight to adaptation benefits, because of the timing issue (financial appraisal is much more focused on short-term returns).

Step 3. What are the economic costs of climate change - the effect on the outcome?

The infrastructure network in the UK is already exposed to climate-related risks (and floods in particular) that in the past have caused damage and disruption, negatively affecting service supply. There is well documented information on the costs of previous flood events (Environment Agency 2010; Frontier et al, 2013; CCRA2 Evidence report), as well as major hot summers (Metroeconomica, 2006) and some of the large storm events (ABI, 2017). There are also data collected on service costs delays by some sectors, such as Rail (as part of the schedule 8 costs), which break down costs by weather events, including the costs of service disruption (Network Rail, 2017), and show similar levels of costs for wind to floods. These reveal large economic costs on infrastructure currently, especially from extreme events.

As highlighted above, some climate risks are already being addressed, but where these are not, there could be additional costs. Therefore, not achieving the outcome would mean additional infrastructure related costs, affecting capital infrastructure, and also the services that infrastructure provides.

There are some estimates of future costs under climate change. These include assessment by climate risk, as well as assessment by infrastructure sector. There is some information on future economic costs to infrastructure, but it is difficult to split out the risk allocation between current infrastructure, and what will be added before the future time period of relevance. Nonetheless, the information provides a sense of the possible risks to current and new investment.

There are existing estimates of the costs of flood protection, though these are really a form of adaptation and tend to be focused on general flood defence rather than individual infrastructure protection (see adaptation costs and benefits section). Most of the economic cost studies are focused on the costs to residential and non-residential buildings. There are some estimates of the economic costs from flooding on infrastructure from CCRA1 and CCRA2. Ramsbottom et al., (2012) estimated the future costs of disruption on motorway and A roads in England and Wales due to fluvial and tidal flooding. Roads with an annual probability of 1.3% of flooding were considered. Sayers et al (2015) for CCRA2 does assess the indirect costs of flooding for the UK and for England, which includes infrastructure damage and knock-on effects, and shows similar levels of % increase in costs to building flooding, i.e. with a 25% to 75% increase in the 2050s (2 and 4°C scenarios respectively) and 48% to 140% in the 2080s for England. The report also projects much higher increases under the High ++ scenario (230% in 2050s and 470%in the 2080s). However, this is largely based on the current stock of infrastructure, and does not include new infrastructure development.

Some studies have looked more specifically at the impact on infrastructure, including to the service disruption. As an example, looking at the direct impacts, Frontier Economics et al. (Economics of Climate Resilience 2013) estimated that – without an increased level of adaptation – by the 2020s, up to 214 GWh of annual generation output could be lost due to flooding (75 year return period). This could rise to an annual output loss of between 30 GWh and 429 GWh per annum by the 2050s, depending on the duration of the outage period and the generation capacity at risk. To estimate the associated costs of such lost output, the study assumed that the shortfall in generation of CCGT plants would be met by using existing reserves - specifically, OCGT plants were assumed to be used instead of the affected plants. Given that the marginal cost of this type of plant is about 2.8 p/kWh higher than the marginal cost of gas fired CCGT plant, the incremental (undiscounted) expected average annual cost of flooding was estimated to range between £0.2 and £0.6 million per year in the 2020s, and £0.8 - £12 million per year by the 2050s. The ECR report also investigated the impact of a one-off flood event (as opposed to an average or 'expected' impact, as above), and estimated that the incremental one-off cost of the lost output during a six- month outage period would be approximately between £11.4 and £67.3 million in 2012 prices – though this sits within a wide range of uncertainty (Frontier Economics et al., 2013).

Wind storms are among the most damaging extreme events in England currently, in financial terms. Climate change has the potential to alter the frequency and intensity of these storms and thus affect the distribution of insured and insured losses. However, the projections of these changes are uncertain, particular whether the North Atlantic storm track could shift northward in the future, resulting in fewer mid-latitude storms (Vautard et al, 2014). Some studies have indicated a small increase in the number of windstorms affecting the UK with the frequency and intensity of the most extreme windstorms increasing during the winter months. ABI (2017), using the Representative Concentration Pathway (RCPs), projected the changes in frequency and intensity of windstorms, looking at the average annual loss (AAL), i.e. annual insured loss aggregated over an entire year, the 1.0% exceedance probability (100-year) loss, and the 0.5% exceedance probability (200-year) loss. The results indicated a change in the overall average annual loss of 11%, 23%, and 25% for the 1.5 °C, 3.0 °C, and 4.5 °C cases, respectively (corresponding to RCP 4.5 at 2050-59, RCP 8.5 at 2070-79 and RCP 8.5 at 2090-2099). The analysis also indicated a possible increase of up to 30% in the 100-year return level loss and up to 40% in the 200-year return period loss, though the distribution of these changes is not equal across the country. Note that much of this will be for buildings damage rather than other types of infrastructure asset, but the analysis shows the likely direction and magnitude of change.

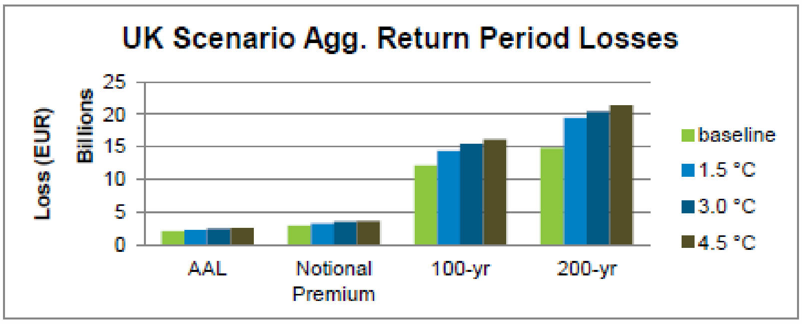


Figure 4 Average annual loss (insured), notional premium and 100 and 200 year losses for the UK.

There is less evidence on heat related infrastructure costs. However, changing energy demand (reduced winter heating and increased summer cooling) will have implications for energy infrastructure and transmission and distribution. There is clearly also a large potential cost from the need to adapt infrastructure for heat extremes, although cost information in this area is not as advanced. On the energy infrastructure side, there have been several studies on the effects of climate change on renewables. Most of the focus has been on hydro-power generation. For Europe, most studies show a positive effect for northern Europe and a negative effect for Southern and Eastern Europe, though the overall change varies across studies from almost no effect to decreases of 5-10% by the end of the century. Tobin et al. (2014) assessed the potential impacts of climate change on wind generation, finding that mean energy yields could reduce by less than 5% by 2050 (2°C scenario), and as part of the same study. IMPACT2C, (2015) found limited changes in photovoltaic power potential and plants yields. For the UK, very moderate changes in wind generation were projected (+/- 5%).

There are some estimates for transport infrastructure. The WEATHER project estimated that the total costs from extreme weather events currently, noting these are dominated by road transport (Enei et al., 2011). The project estimated climate change could increase current costs by 20% by 2040-2050 (EEA, 2017), although, the costs from heat stress and flooding are large, but are offset by a large reduction in winter maintenance cost. For the rail sector, heat stress and heavy rainfall were estimated to increase costs by 72%. The impacts on air transport are very uncertain because they result from extreme wind and fog, but are estimated to increase by 38% (Przyluski, et al. 2012). For inland waterways, the main issues are low river flows, from drier summers. The PESETA II study (Ciscar et al., 2014) considered impacts on the road and rail network in Europe, estimating a 50% increase from the current baseline damage under a 4°C pathway, but around half of this under a 2°C scenario. More specific estimates also exist for road transport. There has also been a major focus on the potential risks to port infrastructure.

Finally, the JRC study on critical infrastructure (Forzieri et al. 2018) estimated the multi-hazard, multi-sector damage due to climate change across Europe, looking at several sectors.

The potential impacts to water supply infrastructure are covered in a separate outcome.

There is also an issue of how these climate risks cascade through to the private sector and final consumers. As highlighted earlier, properly accounting for physical climate risk could - on average – reduce company values by 2-3% due to the risk costs of insuring assets, and more than this in some sectors. This can be seen as one of the consequences of not adapting (i.e. the cost of inaction).

Step 4. What are the potential additional adaptation options to address impacts?

The starting point for this step is to review the existing adaptation in place, and then assess the additional actions that might be taken to reduce the outcome gap (investment decisions for new infrastructure). It is noted that adaptation action for the infrastructure sector includes not only technical (engineering) options but also regulatory, policy and community responses, which are crucial to enhancing the adaptive capacity of infrastructure systems.

The CCRA2 Evidence Report (Infrastructure chapter, Dawson et al, 2016) reported evidence that significant adaptation steps to manage climate change risks have been implemented, or are underway, across most infrastructure sectors. However, it also stated that where sufficient information is provided, these investments will maintain or, in some instances, reduce climate risks over the next decade or two. On longer timeframes, projected changes in climate are likely to outpace current adaptation plans.

The NAP2 sets out existing activities on infrastructure resilience. To summarise:

- The Cabinet Office has established a National Infrastructure Resilience Council (NIRC) to bring together utilities companies to share information about the locations of their assets and to take a coordinated approach to flood resilience.
- Road sector. HE is now developing its plans for delivering the second Road Investment Strategy (2020-25) with DfT. As part of this, HE will consider resilience to climate change across business activities to maintain a fit for purpose SRN and reduce its vulnerability to climate change events.
- Energy sector. River and coastal erosion continue to be monitored around infrastructure that is recognised to be at risk and investment strategies are implemented where needed. There is also a new Energy National Policy Statement (which require applications to consider climate change),
- DfT's High Level Output Specification for both the 2014-19 and 2019-24 periods contains specific requirements on Network Rail to "manage the resilience of the network to severe weather, taking account of the impacts of climate change, and to other potential threats".
- A new strategic policy statement (SPS) to Ofwat, published in September 2017 sets out Government's policy priorities, and the regulator has finalised the methodology for its 2019 price review (PR19) which instructs water companies as to what they will be able to charge customers from 2020 onwards. The statement has put long term resilience at the front and centre of business planning.
- Water UK's 21st Century Drainage Programme is driving work to improve the new long-term planning of drainage and wastewater services. This includes the development of a new planning framework for the production of water company Drainage and Wastewater Management Plans (DWMPs). DWMPs will help water companies manage their assets over the long-term and ensure that they are resilient to climate change. There is also the strategic policy statement to Ofwat (which includes long-term resilience thinking), and the National Policy Statement (NPS) for Water Resources.
- Ofcom's revised security guidance (published December 2017) contains explicit requirements for telecoms providers to ensure they meet NFRR obligations and to ensure all sites (not just those in scope of the NFRR) are adequately protected from flooding.
- There is a forthcoming policy statement on Flood and Coastal Erosion Risk Management (FCERM), which should sit alongside the Environment Agency's draft Flood and Coastal Erosion Risk Management Strategy.

Furthermore, Category A infrastructure (defined here as energy and water infrastructure) providers are increasingly recognizing flooding as a business risk and the importance of providing contingency plans and local protection to high risk sites. CCRA2 (2017) reports that transport and local authorities are also developing, and starting to implement, a range of actions to understand and map risks, inform users, and implement actions to manage risks (Transport for London, 2015; Newcastle City Council, 2016 in CCRA2, 2017).

Nonetheless, the analysis here identifies that much of the enabling environment for adaptation for new infrastructure is still missing and for the private sector, there is an emphasis on voluntary approaches. We therefore consider the potential for additional adaptation, using the priorities for early adaptation framework. This focuses on three types of adaptation that are considered together as a portfolio. The major focus for new infrastructure is on the central column, for early decisions, however, it is important to consider the overall portfolio at the same time, especially from a national perspective.

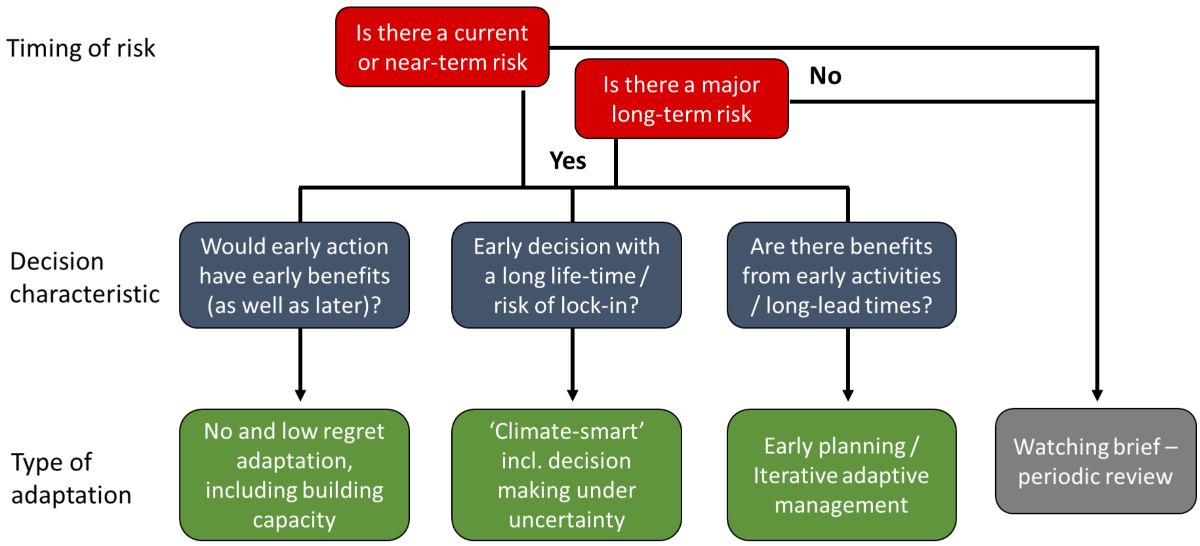


Figure 5 Early priorities for adaptation. Source CCRA3.

The main focus for this case study is on new infrastructure, and thus investment decisions that have long lifetimes and issues of lock-in, although for some major infrastructure, lead-times and future risks are relevant.

Type ii) Early decisions with a long life-time/ lock-in risks. Much of the existing literature on adaptation (especially with economics) has used a science-first approach (Ranger et al., 2010) in this area, looking at future projections and assessing technical adaptation response. However, this approach does not provide the information needed to make an adaptation decision for an investment today. This is because (OECD, 2015) as these studies provide information on the adaptation that is needed in the 2040s (not what to do now), they focus mostly on technical (engineering) adaptation responses and they do not consider adaptation decisions within the policy and organisational context (i.e. decisions are theoretical not applied). The framing of adaptation has therefore changed in recent years, to consider how to provide information and decision support for real and early adaptation decisions (as in this study, with investment decisions for long lived infrastructure decisions), but it is clear that this involves much more complexity than a predict and optimize (impact assessment based) approach.

A key challenge for effective adaptation is uncertainty (Wilby and Dessai, 2010). This arises in a number of forms. First, at the current time it is not clear what future emission pathway the world is going to be on, ultimately, i.e. whether a future 2°C or a 4°C world. This makes a major difference to the level of adaptation needed. Second, even if the future emission pathway were known, there is large additional uncertainty from uncertainties within and between different climate models. The range of outputs from alternative models (10^{th} to 90^{th}) is a significant driver of uncertainty especially in the next few decades, and for some climate parameters (e.g. precipitation), different models can even alter the sign of the change (i.e. whether there is an increase or decrease in rainfall). This makes investment decisions now very challenging. It is relatively straightforward to understand how to design a new investment to be resilient to a known future, but it is much more difficult to design it to cope with many unknown futures, especially where there is deep uncertainty (i.e. where there is not a good knowledge of the risk, i.e. no probability distribution). In this case, an early investment runs the risk of spending large resources (today) to prepare for future scenarios that might not occur, or it may exclude future scenarios that do subsequently arise, leading to large damages. This is particularly important because many early adaptation projects have either over-designed projects (to cope with the highest climate scenario and largest possible impacts) or do nothing (e.g. see ADB, 2014; Watkiss et al, 2018). Both of these involve the potential mis-allocation of resources and represent a risk of economically inefficiency.

As a result of the challenges above, a number of approaches have been advanced in recent years in the academic and grey literature to address the problem of uncertainty. This has focused on decision support tools and methods to address uncertainty, often called decision making under uncertainty (DMUU). The main approaches are summarised in the Appendix, drawing on an earlier review (Watkiss et al., 2014) and recent updates. These techniques address the economic and uncertainty challenges by using a set of principles, including learning, flexibility, robustness, hedging (risk spreading) and minimising regrets. While the focus has been on the tools, the principles they introduce are as important and have potential for less formal applications. What is clear is that it is difficult to implement DMUU approaches in practice (Watkiss, 2018). These approaches are rather complex for most investment analysis, and they take too much time and resources (when used in formal applications of the methods) for standard use (Watkiss et al., 2014: Bhave et al., 2015). For example, HMT (2009) recommends real options analysis (ROA) however, a review of uptake in UK Government (OECD, 2015) found no formal applications of the technique. Some of the MDBs have also tried to increase the adoption of these techniques by using external technical assistance (see ADB, 2015: Watkiss, 2018). However, such a level of TA is difficult to justify for all projects – and applications are usually limited to major investments (e.g. large hydro-electricity generation). For these reasons, there is interest in light-touch approaches that introduce an economic rationale and support the implementation of DMUU concepts, such as flexibility or iterative approaches, without the formal complexity and resource needs (See Watkiss and Wilby, 2019).

One way this can be introduced is by considering what levels of climate appraisal detail is needed, noting this depends on the type of infrastructure decision. As highlighted above, there are three key issues that are important in this choice. First, the lifetime of the decision or type of policy/programme. Interventions or decisions that are very long lived (e.g. many types of infrastructure) could have more exposure to larger, future climate change and warrant more consideration of future climate. Conversely, there is less need to build long-term adaptation thinking into an investment or policy with a short life-time. Second, the 'lock-in' involved. As highlighted above, some investments involve irreversible choices now. This could be due to the costs of retrofit (for a major bridge) or the land-use change involved for new housing policy. Decisions that are harder to change later may warrant more action earlier. Third, the level of precaution required. Some investments need a precautionary approach, i.e. there are major downsides in getting it wrong. For example, critical infrastructure or projects that involve major safety issues (large storage dams) already build in design criteria to avoid failure, and they would be therefore more likely to consider an over-design for climate risks. This is already starting to appear: for example, there is some draft guidance on making hydro-projects climate resilient, recognizing the high potential risk for these investments.

It is also highlighted that there is ongoing work on the economics of infrastructure adaptation in the MDBs and IFIs, which highlights that there are different approaches for building resilience, with different costs. For example, faced with a possible risk, the options that could be considered are (Watkiss and Wilby, 2019):

- Introduce no and low regret options;
- Over design the project (if cost-effective options exist or there is precaution needed);
- Introduce robustness in design (to better cope with many future options);
- Introduce flexibility, primarily to allow later changes more easily and cost-effectively;
- Look at non-technical alternatives (risks spreading and insurance, legislative);
- Monitor and upgrade later if needed;
- Do nothing (live with the risk).
- Fix later.

The decision on which of these to do is determined by particular climate risk and economics, as well as lifetime, degree of lock in (cost of retrofitting later) and level of precaution. Emerging work is looking to standardize in sector, to aid this decision-making process. This is also strongly linked to the economics of adaptation for climate smarting infrastructure – see the next section.

As highlighted earlier, individual risk assessment may not be sufficient, i.e. that individual CRM and sectoral guidance is important, but there is a need to consider the integrated infrastructure system.

Type iii) Early actions to address long-term risks. At the national level, there is clearly a need for an iterative programme to start addressing long-term risks. This includes both the climate resilience of planned infrastructure, but also the need to increase the pipeline of dedicated adaptation infrastructure that addresses climate risks. This includes monitoring, research and awareness raising. There has already been work progressed under the National Infrastructure Resilience Council (NIRC) and as part of the National Flood Resilience Review, but given the scale of the challenge, the need to scale this up is highlighted. The CCRA2 Infrastructure chapter (Dawson et al., 2016) highlighted some of the knowledge gaps:

- Research and monitoring dedicated into understanding and mapping existing and future interdependencies and cascading effects;
- Research to take a robust, forensic and consistent approach to monitoring and recording the performance and thresholds of failure of infrastructure over the long term in order to construct a comprehensive database of infrastructure fragility
- To assess the vulnerability of the UK's ICT networks and systems, and its interdependencies particularly with the energy sector, to a changing climate
- Research to understand the potential of climate risk on UK infrastructure as a result of international interactions
- Improvements in understanding of wind, lightning, offshore and inshore waves and currents, and sub-hourly rainfall intensity, should subsequently be translated into future UK design guidance for infrastructure designers and operators.

What is also critical is to translate this research into the enabling environment for adaptation.

Possible options to create an advancing enabling environment for infrastructure adaptation

There are major barriers to adaptation (Cimato and Watkiss, 2017), and in particular to infrastructure resilience, that need to be addressed to encourage uptake. Sources of distortion include misaligned policies, including regulatory frameworks, and unpriced externalities (OECD, 2017). Recent analysis of successful infrastructure resilience reports that action is required across a number of areas (Vallejo and Mullan, 2017: Watkiss 2018, ADB, 2019):

- Supporting decision-making by providing tools and information;
- Screening climate risks (climate risk management) in public investments;
- Screening climate risks (climate risk management) in private sector investments;
- Enabling infrastructure resilience through policy and regulation;
- Encouraging the disclosure of climate risks/uptake in commercial finance
- Supporting innovative risk spreading (insurance);

Tools and information

Access to information, knowledge and availability of capacity is fundamental to effective climate action. Decision makers, investors and practitioners for infrastructure development require access to actionable information and knowledge that enables them to take action. The UK has led the way in producing climate information, most recently with UKCP18. However, given the complexities on future uncertainty and thus the effective management of climate and disaster risks, all infrastructure development stakeholders need to be assisted in strengthening their capacity to plan, develop, design and implement climate resilient policies and programs/projects. This includes data and information required for understanding climate and disaster risks; analytical methodologies, methods and tools for assessing climate risks and adaptation interventions; and original analyses and insights that contribute to the broad knowledge base and understanding.

Dawson et al., 2016 highlighted a number of tool priorities:

- A common and internally coherent framework for risk analysis that enables different risks to be fairly compared.
- Analysis of the impact of persistent climatic events (e.g. repeated sequence of storms or floods, in the same or multiple locations) and joint hazard events (e.g. wind storm coupled with flooding).
- A national database of the location, function and design of assets, and a record of any adaptation to these assets and its effect on risk reduction that is updated under the ARP.
- Assessment of a range of impacts to the economy, environment and society. First order impacts on the infrastructure itself, as well as higher order and longer-term impacts need to be considered to gain the richest possible understanding of risk.
- A common baseline and a number of standardised adaptation scenarios to provide a set of common reference points, as well as the capability to develop and test further scenarios

In addition, it is highlighted that there is a need for

- Better information and knowledge on how technical, non-technical, and capacity building resilience options perform;
- A greater focus on the economics of resilience. This includes the need to strengthen economic appraisal of investments, and to build the evidence base on the costs and benefit of resilience

It is also stressed, however, that making data, information and knowledge available will not, on its own, lead to the uptake or application of such knowledge products. Previous review of adaptation implementation (Hegger et al., 2014: COACCH, 2018) identify a number of critical success factors, identify the need for resources, support, and identify a key role for intermediaries (knowledge brokers) to transfer science into practice (joint knowledge production).

Screening climate risk into public investments

As highlighted above, the MDB (MDB, 2017) have introduced climate risk management systems and now climate screen all new infrastructure projects for climate risks, for example with the existing activities in the European Investment Bank and European Bank for Reconstruction and Development.

This is also undertaken for all European Commission funds, e.g. for structural, cohesion funds, with support from the JASPERS programme. In general, these approaches (e.g. ADB, 2014) include an initial climate risk screening, which assesses whether a project is a low, medium or high climate risk. Projects that are assessed as medium and high risk are then investigated with a more detailed climate risk and adaptation assessment.

OECD (2017) reports that only 9 countries – less than half of the G20 – have integrated both mitigation and adaptation considerations into infrastructure planning. The UK reported (to OECD) that it had integrated both adaptation and mitigation into infrastructure plans. There is existing guidance on adaptation in the supplementary guidance for the Green Book, but as highlighted above, this is now considerably out of date (HMT, 2009) and would benefit from a revision and greater dissemination and uptake, given that the OECD itself could find no evidence of uptake. There are many sector activities being undertaken to address climate risks, but there is a lack of direct guidance, and in line with evolving practice, there is perhaps a need to consider mandatory climate risk screening in all public infrastructure projects. This would include the cascade from national Government down to regional and local Government for major infrastructure projects. It is stressed that this does not mean expensive resilience options, but merely that all projects should undergo a level of climate risk screening, with those that are identified as being at risk subject to more detailed analysis.

It is noted that a similar conclusion – on the imperative to develop a national capability for performing infrastructure climate change risk assessments – was presented in CCRA2.

A key focus of this is to enhance the economic analysis of resilience, noting the challenges involved (see above). It is noted that in many sectors, more detailed guidance is emerging on managing climate risks and the role out of more formalized guidance, including economic analysis, could help reduce costs and increase uptake. There is also a recognition (Watkiss 2018) of the need to differentiate projects by sector, reflecting different risk levels, and standardising where possible - but recognizing some projects will need detailed analysis and require incremental resilience measures.

One other thing that is highlighted is the need to move 'upstream', i.e. to move away from individual project level analysis to a more harmonized analysis at the national level of infrastructure resilience, and in developing pipelines of infrastructure.

Screening climate risk into private investments and PPP

As highlighted above, a large part of the UK's future infrastructure will be financed by the private sector (50% of the NIDP pipeline). As the discussion set out earlier, there are greater barriers to the uptake of adaptation in the private sector, because of the lower benefits of future adaptation when considered as part of an IRR analysis. In short, building resilience has an additional cost, and it is not clear that generates a positive IRR, especially for benefits that arise towards the end of a project's financial lifetime. There is therefore a need for public (government) action to consider the barriers to private sector investment. At the initial level, this can be by creating the enabling conditions for the private sector through awareness raising and information, technical assistance support and demonstration studies to address risk perceptions.

One area of focus is also through public private partnerships. PPPs are already a major part of English infrastructure development including the role to maintain and operate projects to enhance their economic and physical performance. There is therefore an important role for PPPs in terms of enhancing climate resilient infrastructure investments, however, this is challenging due to their highly prescriptive performance payment regimes. The consideration of climate resilience in PPPs is at an early stage, and it will involve some challenges concerning the level of risk transfer (noting climate risks are often not considered explicitly or allocated to a specific party in a standard PPP risk allocation framework). However, introducing PPP schemes with an appropriate allocation of risk could help, and there are opportunities to consider risk sharing and risk transfer and to help integrate climate risks for PPPs. This would require some policy and institutional reforms in PPP frameworks. It might include the need to translate the public climate risk screening and resilience building processes (and lessons) into private and PPP projects, greater use of land-use planning policy to avoid high risk locations, and design standards. There might also be some role for insurance protection (see later).

It is also stressed that there is a major financing gap for future new infrastructure for adaptation, i.e. dedicated adaptation infrastructure, as well as mitigation infrastructure. Public finance will remain critical for proactive planned adaptation (resilience). However, given the size of the gap, there is a need, particularly in the short term, to incentivize investments to accelerate investments in resilience. To meet the financing gap in infrastructure resilience financing, efforts will be needed to engage the private sector, which is responsible for constructing and managing a significant fraction of the infrastructure pipeline above. This will involve using government funding to leverage private sector finance, as well as new and innovative approaches to finance that expand resources beyond the existing funds and modalities.

Enabling infrastructure resilience through policy and regulation
There can also be institutional and/or policy barriers to designing resilience in infrastructure projects, especially when it comes to future climate change: one such example is engineering standards. The UK has existing engineering design standards, building codes, etc. that set mandatory safety and performance criteria for new construction, but these are typically based on historic weather extremes and do not take account of the changing climate. These standards can act as a barrier to future climate resilience, because exceeding the current engineering standards (with higher levels of resilience) is not required under existing practice, and there are issues enough with compliance and enforcement of existing standards (CCC Housing Report, 2019). This can be addressed by working at the national level with the use of climate change allowances, which are incorporated within existing national engineering design standards to ensure they include climate change (Wilby and Keenan, 2012). Such an approach has been included in the UK for some sectors with respect to flood risks. This approach addresses the institutional barriers, and it also has an advantage in that it removes the need for a detailed technical climate risk study for each individual project whilst enhancing consistency across investments. The role for further work on standards and norms is therefore highlighted.

Encouraging the disclosure of climate risks/uptake in commercial finance
As above, one area is to raise awareness on climate risks, so that these issues become integrated in financial markets, commercial lending, due diligence, and company risk analysis. The incentives for financial markets to price in climate change risks have increased recently with initiatives such as the Task Force on Climate-related Financial Disclosure (TCFD), highlighted earlier. As highlighted above, public banks in Europe are already undertaking due diligence on climate risks as part of investments analysis and lending. An important extension of this would also be to consider the role for climate resilient standards and norms for the commercial banking sector. These could be important for incentivising the uptake of resilience in commercial bank lending.

Risk spreading (insurance)
There are also opportunities to support infrastructure resilience through enhanced insurance, which could provide an important source of leveraging to the private sector. Insurance is a risk spreading mechanism. It can build resilience through a more efficient allocation of resources to address high impact, probabilistic events and by supporting rapid recovery after climate-related extremes, and is therefore an important part of a layered risk management strategy. It also plays a valuable role in helping to identify and quantify risk. It is also a complementary tool to adaptation for future climate change. However, while insurance spreads the financial risks of probabilistic extreme events, it cannot insure against climate change trends, as the risk spreading mechanism breaks down and premiums become unaffordable. It is also highlighted that increasing risks due to climate change could be

factored into premiums by insurance providers, and markets are likely to want to different pricing, which may make it harder for affordable insurance for more vulnerable infrastructure (UNEP, 2018).

The insurance industry already provides coverage for engineering and asset risk through to third party liability risk coverage for infrastructure. There are opportunities for innovation and implementation of market-based solutions, such as expanding risk coverage across the infrastructure lifecycle, and extended to innovative risk transfer solutions. It has a role in facilitating (ex-ante) disaster risk finance solutions through the transfer of residual risk to the private insurance re/industry and capital market, but also enhanced financing of disaster risk reduction adaptation measures. It can provide additional financial headroom, for instance loan repayment obligations can be waived in case of extreme disaster events creating headroom for public and private borrowers/lenders but also the sustainability of investments can be enhanced, i.e. de-risked and ensured against residual risk and lack of performance, making such projects more bankable and attracting more private investors. There are now more advanced and innovative approaches that are being considered, with a range of insurance instruments (Lloyds, 2018), such as insurance–linked loan packages (infrastructure loans which include built–in insurance) resilience impact bonds (pay–for–performance contracts) and resilience bonds (risk–linked financing mechanism similar to catastrophe bonds, but which take account of resilience measures).

Step 5. What are the benefits and potential costs of adaptation?

This final section investigates the potential costs and benefits of adaptation.

Simple climate investment and financial flows analysis

In the early run up to the Copenhagen Conference of the Parties in 2009, a set of studies emerged that estimated adaptation costs, primarily focused on infrastructure investment, usually referred to as investment and financial flow (IFF) analysis. These were implemented at the national to global scale. These studies used a different approach that assessed existing sector investment and financial flows, and then estimated the increase needed (the adaptation cost) to cope with climate change (e.g. UNFCCC, 2007). These usually derived estimates by applying a generic adaptation 'mark-up' on current investment/finance levels that is judged to be sufficient to reduce impacts effectively (Agrawala et al, 2011). These studies have the advantage of grounding the analysis in current policy and plans, but they have a less direct link to future climate change, and importantly, they do not quantitatively assess adaptation benefits.

It is possible to apply these approaches to the infrastructure pipeline identified above, using evidence from different sectors. The earlier assessments typically applied standard mark-ups of 10% to all climate sensitive infrastructure. More evidence is now emerging on the likely costs of infrastructure, although this shows a greater variation on costs. Ranger et a (2014) estimated that accounting for future climate in high-risk projects today could potentially increase project costs by between 5% and 15%. In contrast, Hughes, Chinowsky and Strzepek (2010) estimated the cost of adapting infrastructure at no more than 1-2% of the total cost. Note that these studies do not estimate the benefits that this would deliver.

More recent analysis provides some ex post information for major projects. In the road sector, for example, the uplift required to deliver resilience varied from 0.5 – 10% of the total project investment cost (ADB, 2014): this value appears to be robust in that similar findings emerge from European investment banks. Applying this approach to the NIDP economic infrastructure pipeline would mean a total adaptation cost of £2.1 billion to £42 billion (primarily over the period to 2021), and an annual cost of £0.2 billion to £4.8 billion. Some of this may already be factored into the costs, but it is likely there could be an additional finance gap. This adaptation would also lead to economic benefits, which are not captured in the analysis.

Estimates of costs for adaptation to flooding

While there are multiple risks for infrastructure, most of the focus has been on flooding. The National Infrastructure Commission (2018) analysed the investment that would be required to provide a range of resilience standards across different settlement types for river and sea flooding. Average annual capital costs between 2020 and 2050 were based on a climate change scenario equivalent to a 2°C increase in global mean temperatures. The baseline assumes that current resilience is maintained, broadly following the Environment Agency's Long Term Investment Scenario. The modelling produces estimates of the costs of a national standard of resilience to flooding with 1 per cent, 0.5 per cent or 0.1 per cent annual probability. The Commission recommended that higher standard should be provided for the largest cities, with populations over half a million. This is justified by the lower cost per property for protecting densely populated areas, the potential for natural disasters in cities to result in cascading failures, and the range of economic and social services provided to their region as a whole, not just to those who live within them (NIC, 2018). The benefits of achieving a resilient infrastructure sector could be estimated as the value of the 'avoided' or 'mitigated' damage and disruption caused by climate-induced events thanks to adaptation.

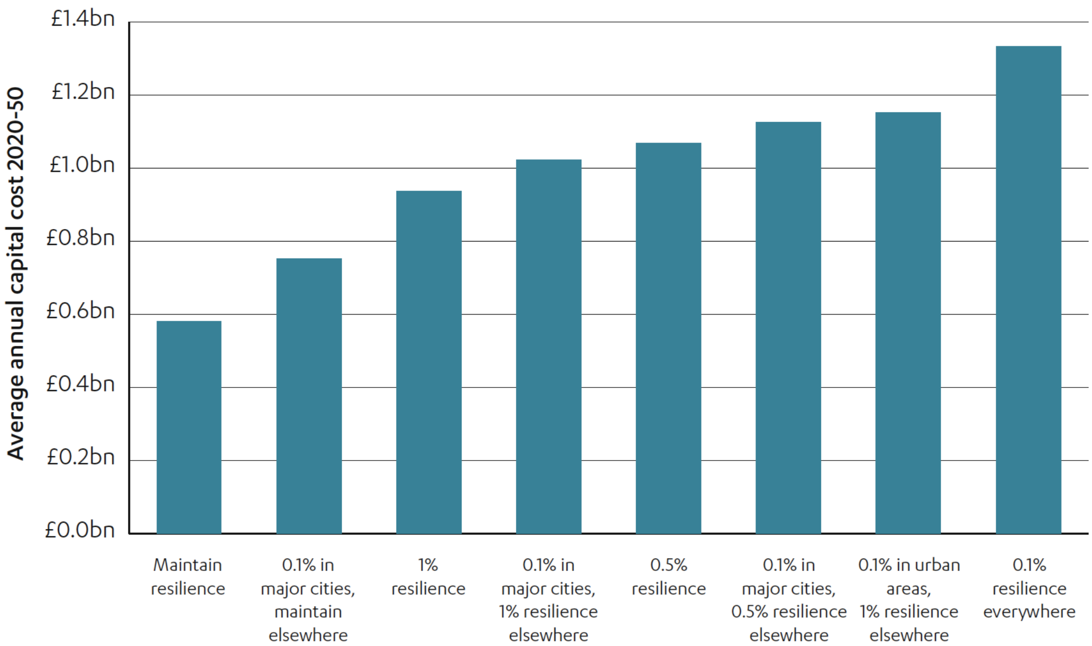


Figure 6 Estimated average annual public capital costs for different standards of resilience to flooding from rivers and the sea, 2°C increase in global mean temperatures climate scenario, 2017 prices, in England (NIC, 2018)

Similar analysis was undertaken by the EA (LTIS 2014), who estimated that the net present value of the optimised long-term investment in flood and coastal erosion risk protection is £102 billion over 100 years, providing an overall benefit to cost ratio of about 5 to 1. Benefits are valued according to the economic damages avoided by making the investment, including the benefits of protecting homes and businesses, farmland and infrastructure. The EA estimated that this would lead to a 12% reduction in flood damages over the next 50 years. This does not include economic growth benefits that could be achieved in areas where the standard of protection against flooding is improved over time, or other benefits such as health or reduced risk to life.

The new LTIS (Environment Agency, 2019) updated the economic assessment showing what flood and coastal erosion risk management (FCERM) could look like over the next 50 years in England. LTIS sets out the total national level of investment if we invest in all the places where the benefits are greater than the costs (the optimum level of investment for FCERM. Evidence from the new scenarios shows the overall economic optimum level of investment is higher than previously estimated. The new optimum is a long-term annual average of over £1 billion. This compares to an annual average of around £860 million for the LTIS 2014 baseline. The new best estimate is higher because it uses the range across medium and high climate change scenarios. It also includes a better understanding of the wider impacts of flooding and the investment needed to manage surface water. A large proportion of this investment is required to maintain and renew existing FCERM assets; there are over 10,000km of raised defences in England.

LTIS 2019 includes medium and high climate change scenarios which are similar to the 2˚C and 4˚C scenarios used by the Climate Change Risk Assessment (2017). With medium climate change, risk can be reduced 12%. With high climate change risk reduction is only 4%, and with the plausible extreme high++ climate change scenario, risk increases 7%. LTIS 2019 states that policy choices also affect the optimum level of investment.

There are also recent studies looking at the costs and benefits of shoreline protection (Jacobs, 2018) as an input to the CCC Coastal report. However, none of these are focused specifically on benefits to infrastructure. There are some studies that provide some estimates for these.

Thacker et al. (2018) presents a national-scale analysis for investment in flood protection measures of major electricity substations in England and Wales (107 assets in total). The study looked into the direct and indirect economic losses that could occur due to the failure of major electricity assets within England and Wales. Based on the authors' calculations, the two sectors that are affected the most are the telecommunication and electricity sectors; the smallest direct losses occur due to disruptions of airline passengers. The largest indirect sector impacts correspond to the business services and real estate sectors as well as the mining sector. This emerges due to the large role that these sectors play in the national economy and their strong reliance on infrastructure, for example, the service sectors' dependency on the telecommunications sector and electricity sector. Using a CBA framework[8], and taking direct and indirect impacts into account, Thacker et al (2018) found positive NPV values (up to £20 million) highlighting the business case for adapting these substations through the installation of permanent flood protection walls to reduce hydro- meteorological hazard risks. A sensitivity analysis shows that this option performs well under a range of future uncertainties, including the direct damages and the duration of disruption, which are the most sensitive parameters in the analysis. The study also found that investment in high-cost adaptation options such as raising the substations and relocating the substation are cost beneficial in only a limited number of cases.

However, it is highlighted that the analysis of the costs and benefits of adaptation for individual infrastructure resilience is very challenging. Following on from the discussion on Decision Making Under Uncertainty above, there are range of possible options:

- Introduce no and low regret options;
- Over design the project (if cost-effective options exist or there is precaution needed);
- Introduce robustness in design (to better cope with many future options);
- Introduce flexibility, primarily to allow later changes more easily and cost-effectively;
- Look at non-technical alternatives (risks spreading and insurance, legislative);
- Monitor and upgrade later if needed;
- Do nothing (live with the risk).
- Fix later.

[8] NPV was calculated for the three different adaptation measures at 2060 (45 years asset life from implementation in 2015), assuming that the flood disrupts services for three days, that direct asset damages are £4,500,000, and that cash flows are discounted at a rate of 3.5% (Thacker et al. 2018).

Some organisations have produced decision rules, to assess which of these should be taken forward. For example, the Asian Development Bank produced *Economic analysis of climate proofing investment projects* (ADB, 2015). This uses a decision typology that takes into account the challenges of discounting and uncertainty (building on the adaptation and DMUU literature). The guidance recommends that analysis should quantify the economic costs of climate change and the costs and benefits of adaptation, and then based on this information, it should identify one of three different types of decisions: (i) climate proof now; (ii) make the project climate-ready; or (iii) wait, collect information and data, and revise if needed (a shorter version of the list above). If the project lifetime is short, then there is no need for iterative or flexible design: the focus should be on immediate options (technical or non-technical) that are low-regret. In contrast if the lifetime is long and there is lock-in involved (for example future retrofitting is very expensive or impossible) this would suggest iterative and flexible options could be more important, while if the benefits of climate proofing now and the future costs are not prohibitive, it makes more sense to wait and upgrade later if needed. This operationalises the DMUU approach in a decision tree, but requires extensive information.

Issues of implementation and evaluating success

Finally, one further issue that concerns is the fact that the different adaptation approaches are not equally easy to implement, due to the ease of implementation and financing (programming). Indeed, practical experience in MDBs (Watkiss, 2018) has shown that project teams will gravitate towards overdesign as this is easiest to appraise and implement: as an example, the ex post analysis in ADB has shown all road projects either overdesign or do nothing, because this is a simple engineering decision (ADB, 2014b). At the opposite extreme, complex options (e.g. flexible and iterative learning) are particularly difficult to implement through the current financing modalities. For example, if an adaptation pathway is used with a recommendation to upgrade infrastructure later, there is a question on who does the actual monitoring and who makes the decision on when to act later. These issues are not insurmountable, for example, it might be possible to include monitoring in the loan conditions, but this still requires a cycle of monitoring and evaluation. Similarly, if there is a need to upgrade infrastructure in 20 years' time, then how exactly is this packaged up in financing agreements and structured. Experience from some existing MDB projects has identified that iterative adaptation can cause new problems: for example, the upgrade later in time would mean a period of downtime (for adaptation) and this could break contract conditions, such as for BOOT contracts on hydro-electricity stations (Watkiss and Cimato, 2015). There is therefore a need to think how to program adaptation options and provide material to make these more complex adaptation options easier to implement (using examples). This would include guidance on how to structure the finance for these options.

Mitigation and Adaptation Trade-offs

There is an existing literature that looks at the potential linkages between mitigation and adaptation in national and sector policy and planning. This (Watkiss et al, 2015) identifies four linkages:

- Strategies or options that are beneficial for mitigation and adaptation (win-win or synergistic);
- Mitigation strategies or options that make adaptation more difficult e.g. that reduce resilience;
- Adaptation strategies or options that make mitigation more difficult (i.e. increase GHGs);
- Strategies or options where there is a trade-off between the two, i.e. where prioritising one (e.g. mitigation) is counter-productive for the other (e.g. adaptation) and vice versa.

A recent review (GIZ 2018) finds that long-term emission reduction strategies include little integration of adaptation and little analysis of how the changing climate could affect low emission plans over time. Where links are mentioned, it is mostly in the forestry and natural resource management sectors. Part of the reason for the low level of integration is because these countries have separate adaptation plans. In general, these are more focused on adaptation, though some include low carbon development including synergistic plans in agriculture and forestry. The reason is that there are barriers that make it difficult to plan and deliver integration or take advantage of synergies in practice.

The UK also shows this trend of insufficient consideration of adaptation in long-term mitigation policies, and lack of consideration of mitigation in adaptation policies (such as the 2nd NAP). There is some discussion in the NAP, primarily for soils and peatlands, and some generic mention for agriculture. There is also some discussion on buildings - but while this outlines some aspects, there is nothing in place to deliver these (e.g. mitigation and adaptation measures need to be combined when promoting the implementation of energy efficiency and ventilation interventions). In practice there are known barriers to taking these more holistic approaches. For example, planned passive alternatives to air conditioning (AC) involve major barriers to implementation, due to higher up-front capital costs and institutional barriers: passive technologies need to be built at the design phase by one actor (the construction firm) to generate benefits for another (the household owner). There has been some consideration of potential trade-offs and synergies in the CCC land-use and housing reports (CCC, 2017: CCC, 2018), and most recently in the new net zero report (CCC, 2019): the latter will require major considerations of these factors.

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Appendix Additional information

DMUU methods include.

- Real option analysis (ROA);
- Robust Decision Making (RDM);
- Decision scaling;
- Portfolio Analysis;
- Dynamic adaptation pathways.
- Rule based decision support criteria.

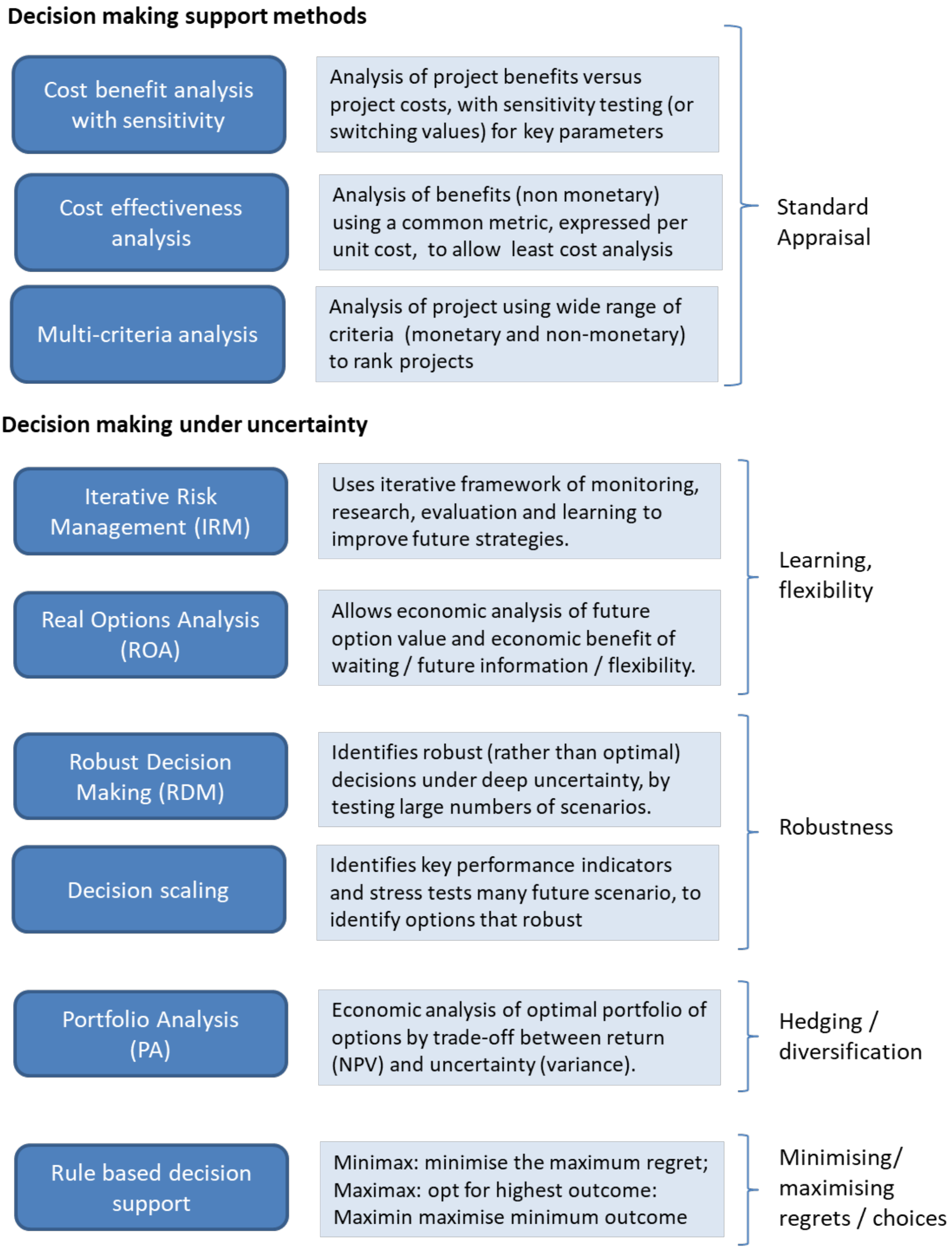

Figure 7 Decision making under uncertainty tools and concepts. Updated from Watkiss et al, 2014.