Climate Change Committee

Reviewing the latest methods and research for valuing the costs and benefits of climate change risk and adaptation policy

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clarity from complexity

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Executive summary

This report explores novel methodologies that exist for valuing the impacts of climate change risks and appraising adaptation policy packages, which could be used in economic assessments and/or form advice to risk owners within the next Climate Change Risk Assessment (CCRA4) Independent Assessment, due to be published by the Climate Change Committee in 2026. Specifically, this report focuses on methodologies which offer an alternative approach to conventional methods, which typically value the costs and benefits of climate risks, opportunities and adaptation policies through quantification or monetisation methods.

Establishing a framework for valuing risks and opportunities from climate change

Sectoral and central UK Government stakeholders could benefit from access to a more holistic narrative of climate impacts that can inform adaptation decision-making and safeguard against undervaluation of the risk of climate change on the UK economy.

Despite the limitations of quantitative valuation approaches, detailed monetary valuation of location-specific risks and opportunities resulting from climate change are key in providing inputs to planning activities conducted by risk owners.

We have identified the following needs for the development of a holistic valuation framework, which complements conventional quantitative valuation approaches, and addresses the additional information needs of sectoral stakeholders and central government. The proposed valuation exercise needs to:

- treat the UK central government and UK sectoral stakeholders as its proposed target audience;
- produce a well-structured and holistic overview of climate risk valuation;
- present an overview of expected direct and indirect climate impacts[1], with associated valuation, at a higher level of aggregation than individual risks;
- produce a socially accepted valuation of impacts by using a range of methods and acknowledging the trade-offs between them;
- complement other impact assessment exercises – for example, macroeconomic modelling and valuation activities performed by local government and other risk owners;
- build on key findings from CCRA3, addressing identified valuation gaps to the extent that it is possible.

This report proposes a framework, together with a set of valuation methodologies, that could address major climate change risk and opportunity

[1] Direct impacts can be defined as 'initial physical and socioeconomic consequences of changes in climate', while indirect effects can be described as 'the consequence of those direct impacts – materializing as a chain, or cascade, of impacts – compounding to impact a whole system, including people, infrastructure, the economy, societal systems and ecosystems' and include both cascading risks and international risks which have impacts on the UK.

valuation gaps identified in the CCRA3 (through the Monetary Valuation report). A mix of qualitative assessment methods and network analysis can complement existing quantitative best practices in climate risk impact assessment and valuation. For instance, qualitative methods with a strong deliberative component can address concerns related to the valuation of unmonetisable risks, missing quantitative data and uncertainty. This is expected to encourage the development of a holistic overview of climate risk valuations and safeguard against the undervaluation of climate risks.

In this report, CCRA3 climate risks are divided into a number of risk groupings, based on common valuation dimensions of individual climate risks, which can aid the identification of appropriate alternative valuation methods. To account for interdependencies between risks as well as cascading effects, it is useful to approach risk groupings through a multilevel framework that can consider the effect of international climate risks and cascading effects, together with the direct impacts of climate change to risk groupings. The report finds that a multilevel approach that relies on qualitative and network analysis assessment techniques can produce a holistic overview of the value of climate impacts, complementing detailed and technical narratives resulting from macroeconomic analyses and granular, quantitative risk valuations.

Appraising adaptation policy packages

Adaptation policy measures can help to alleviate the impacts of climate change at local, national or global levels. However, private and public entities face budget and resource constraints, and therefore must make choices about the best alternative adaptation measures or policy packages to implement.

Currently, policies are typically appraised by using monetary techniques, in particular Cost-Benefit Analysis (CBA). As the name suggests, this method is designed to assess the costs and benefits of different alternatives, and the ratio between them. However, while this method is appropriate in situations where the probability of future states is known or can be estimated with a high degree of certainty, its assumptions are often inadequate when it comes to analysing the role of adaptation packages in reducing the uncertain impacts of climate change. Despite a rapidly growing body of research and literature, there is a high degree of uncertainty around many climate change impacts, such as the exact amount of sea level rise, and the frequency and severity of different extreme weather events. Many monetary techniques simply estimate the probability of different future events and calculate net present values based on these – but these estimates are sensitive to changes in the estimated parameters and are therefore not very robust.

In this report, an in-depth evaluation of alternative adaptation policy appraisal methods is presented. Eight different methods were considered in detail;

- Real options analysis (ROA)
- Robust Decision Making (RDM)
- Info-Gap Theory
- Dynamic Adaptation Policy Pathways (DAPP)
- Multi-criteria decision analysis (MCDA)
- Agent-based social simulation (ABSS)

- Heuristics
- Horizontal evaluation

By analysing the methods in detail, several criteria, namely meeting policy objectives, resource requirements, time needed, accuracy, robustness, usability, communicability, distributional impacts, UK applicability, compatibility with the Green Book were assessed qualitatively (see Table 0.1**Error! Reference source not found.**). Adaptation policy appraisal methods were categorised into 'low', 'medium' or 'high' categories according to these criteria, where, except for the resource and time requirements, 'high' indicates a better quality assessment.

Table 0.1: Results of qualitative assessment of different methods, summary table

	ROA	RDM	IG	DAPP	MCDA	ABSS	Heuristics	Horizontal evaluation
Meeting policy objectives	Medium	High	High	High	High	High	High	High
Resource requirements	High	High	Medium	High	Medium	High	Low	Medium
Time needed	High	Medium	Medium	High	Medium	High	Low	Medium
Accuracy	High	Low	Low	High	High	High	Low	Medium
Robustness	Low	High	High	High	Medium	Medium	Medium	Low
Usability	Medium	Medium	Medium	Low	Medium	Low	High	Medium
Communicability	High	Medium	Medium	Low	Medium	Medium	High	High
Distributional impacts	Low	Medium	Medium	High	High	High	Low	High
UK applicability	High	High	High	High	High	High	High	Medium
Compatibility with the Green Book	High	High	High	High	High	High	Low	High

Understanding the uncertainties in valuing climate risk (and therefore related policy packages)

The CCRA3 explored several areas where climate change can have a significant impact, both risks and opportunities, and assessed its potential monetary values in the Monetary Valuation Report. This risk assessment is vital to understand the challenges the UK faces from climate change and to design the appropriate adaptation and mitigation policies. However, there are many uncertainties around the impacts of climate change, which are important to understand before being able to effectively appraise the impacts of adaptation policy packages. Using the broad groups of uncertainty identified in CCRA3, in this report we identify potential methods for handling these uncertainties (see Table 0.2), including through the application of some methods identified above.

Table 0.2: Summary of methods to address uncertainties in valuing climate risk

Broader group	Uncertainty	Potential method to deal with uncertainties
Uncertainty about future changes	Different socioeconomic pathways	
Impacts of policy packages	Uncertainty around the impact of policy packages	Scenario analysis (e.g. shared socioeconomic pathways), probabilistic approaches (e.g. Monte Carlo simulation)
Interdependencies	Non-climatic interlinkages	See Chapter 4, particularly robust decision making and sensitivity analysis
Valuation method choice	Appropriate choice of valuation techniques	See Chapter 3, combined scenario analysis
		See Chapter 4, particularly Multi-Criteria Decision Analysis, Dynamic Adaptation Policy Pathways, stakeholder approaches

Estimating the macroeconomic impacts of climate change

Climate change and the decarbonisation policies implemented by different governments and institutions will affect economic and financial systems, producing considerable impacts, some of which will be irreversible (NGFS, 2020). The increase in global temperatures is expected to increase the risk of floods, food insecurity and natural catastrophes and have negative impacts on ecosystems, biodiversity and other natural and economic systems like agriculture or tourism (IPCC, 2022). Despite an individual country's climate mitigation actions, its climate is dependent upon global warming and, even if emissions are stabilised, global temperatures are expected to continue rising, potentially for over a century (IPCC, 2001). In the UK, even if rapid targeted reductions in the level of greenhouse gas emissions are achieved, the impacts of global warming will continue to be experienced. For example, sea levels will keep rising after 2100, increasing the flooding risk of several areas and directly affecting multiple sectors such as farming and tourism (Met Office, 2018).

There is a broad literature base exploring the impacts of climate change on the economy, with multiple and different models producing results for the macroeconomic impacts of climate change across different indicators and sectors, and with a wide geographical scope (including the UK). The existence of these different approaches (and respective assumptions), results in widely varying estimates of the macroeconomic impact of climate change. This is an additional source of uncertainty for policymakers trying to understand the risk the UK faces from climate change.

Overall, the evidence shows that direct macroeconomic impacts from climate change are expected to be negative across most of the world (i.e. climate change will result in a loss of global GDP and a slowdown of GDP growth), including the UK, and most economic sectors. However, the literature/use of models to capture acute risks (caused by extreme climatic events) is scarce compared to approaches addressing gradual or chronic impacts of climate change. Quantifying these extreme impacts remains a gap to be filled with further research.

Different models make a range of assumptions which are open to challenge. There are also differences within seemingly common approaches, for example, the discount rate assumed by existing models reflects assumptions about the time preferences of different agents in the economy. The time preference component of the rate relies on ethical assessments and a normative (subjective) judgement. The rate of discount assumed in macroeconomic models dictates the present value the costs, both short- and long-term, of climate change (and/or climate change mitigation efforts) will pose on the UK economy.

In terms of modelling approaches, there is no "perfect" method to estimate the macroeconomic impacts of climate change, the uncertainty and multidimensionality of how climate change will impact the UK economy, what non-climate economic shocks may impact the UK in the future and how key economic variables will develop regardless of the changing climate all makes estimation challenging. Different models may be more useful depending on the aim of the exercise being conducted and therefore a suite of models may be the most appropriate way to present the range of potential macroeconomic impacts of climate change on the UK economy.

Ideally, the most robust model would be an enhanced IAM which has empirical properties of macro-econometric models (which offer a more evidence-based approach and are less restrictive than general or partial equilibrium economic models), detailed treatment of climate from climate specific models, and micro-foundations (depicting individual preferences and behaviours) from agent-based models. Such a combination currently does not exist in any single approach, however linking existing models with the relevant properties under a coherent framework could provide an imminent solution.

Concluding remarks

There are a number of challenges which are associated with valuing climate change risks and opportunities, including:

- a lack of underlying information or evidence on the physical impacts of climate change;
- high uncertainty about the future changes in climate and socioeconomic development;
- in some cases, simply assigning numerical, and particularly monetary, values to climate change risks and opportunities is particularly problematic

because of intangible non-market properties, independencies and resulting complexities around double-counting of values.

Relying on or considering conventional economic methods, which value climate risks and opportunities through a monetary lens alone, can lead to the costs of some climate change risks being substantially underestimated or not accounted for at all due to these challenges. Similarly, the impacts of the way in which we respond to climate change, through adaptation measures, can also be underestimated or mis-specified. Current modelling approaches intended to estimate the macroeconomic impacts of climate change have many associated uncertainties and limitations, and this is a field in which further research and model development is required. Not capturing or having a good understanding of the full value of climate risks facing the UK can lead to unsuitable or sub-optimal decisions or prioritisation of actions.

In this report, we consider alternative qualitative, and often novel, approaches to dealing with uncertainty, complexity and valuation challenges, arguing that these approaches should be used to complement quantification or monetary valuation methods to provide a more holistic overview of the impacts of climate change and adaptation policy. These additional approaches ensure that in cases where a monetary valuation is not possible, the value of certain risks are not ignored, and the true total value of climate change risk to the UK is captured. The Monetary Valuation Report of the CCRA3 highlighted the urgent need for a systematic, comprehensive and consistent economic analysis of risks and opportunities in the UK, improving upon economic analysis conducted as part of previous CCRAs (Paul Watkiss Associates, 2021). The key takeaways of this new report are intended to inform economic thinking and processes within the forthcoming CCRA4, and ultimately, to translate climate change risks into economics which speaks to policy- and decision-makers in future evaluations of the risk of climate change to the UK, and the measures used to respond to them.

1 Introduction

1.1 UK Climate Change Risk Assessments

The UK Government aims to address climate change mitigation and adaptation through a combination of policies aimed at reducing harmful greenhouse gas (GHG) emissions and preparing for current and future impacts arising from climate change.

As stipulated by the 2008 Climate Change Act, the UK government must publish a Climate Change Risk Assessment (CCRA) every five years, which assesses current and future risks to, and opportunities for, the UK from climate change. The Climate Change Committee (CCC) plays a pivotal role in producing the CCRA, being responsible for providing independent advice to the UK Government to inform the assessment. The third CCRA (CCRA3) was published in January 2022, identifying 61 individual risks and opportunities facing the UK as a result of climate change, categorised within the following sectors:

- Natural Environment and Assets
- Infrastructure
- Health, Communities and the Built Environment
- Business and Industry
- International Dimensions

Work is now underway to produce the fourth assessment (CCRA4), to be published in 2027, with the CCC's advice report due for completion by June 2026.

Improvements following the CCRA3

The structure of each CCRA and the methods applied to produce it follow the requirements set out by Defra and the devolved administrations, which feed into an initial method statement developed by the CCC (Paul Watkiss Associates, 2021). While the CCRA3 used the same approach as CCRA2, it incorporated lessons learnt to implement some refinements. Similarly, for the CCRA4, Defra and the devolved administrations, alongside the CCC, are considering ways in which the assessment could improve upon the limitations of the CCRA3. One area of focus is to consider different ways of presenting the economic consequences of climate change to the UK economy by using a more integrated approach than was possible under the previous CCRAs. Linked to this, the CCC is also interested in considering how potential adaptation policy packages can be appraised.

The Monetary Valuation of Risks and Opportunities in CCRA3

The Monetary Valuation of Risks and Opportunities in CCRA3 report was produced as part of the CCRA3 process and sought to estimate, where possible in monetary terms, the societal costs and benefits of each risk and opportunity identified in CCRA3. Valuing risks and opportunities in monetary terms helps to ascertain the relative importance of each individual risk or opportunity using a common metric (i.e. pound sterling) to 'compare direct impacts within and between sectors'. While the valuation report provides estimates of the economic costs and benefits for some of the risks and opportunities, there are many instances where a monetary valuation is not possible, or is produced with low levels of confidence. Furthermore, there are instances where the attempted valuation does not capture the full range of costs that exist under each risk. Gaps in valuations are particularly notable in the natural environment, health, and international dimensions themes and the principal reasons for these gaps in valuing risks are i) that the effects of climate change in question are highly uncertain; ii) that the costs/ benefits of the risks/ opportunities are intangible and therefore there are difficulties in assigning monetary valuations; or iii) that the effects are not sufficiently evidenced by scientific research (see Section 00 for a more in-depth discussion).

Given the potentially high economic cost of climate change risks facing the UK and the focus of key decision-makers on valuing this impact, the Monetary Valuation report highlights in its recommendations the urgent need for a systematic, comprehensive and consistent economic analysis of risks and opportunities for the UK, improving upon economic analysis conducted as part of previous CCRAs. As well as a more advanced and integrated economic assessment of risks to and opportunities for the UK of climate change, the report also recommends an improvement in the economic analysis of how current and planned adaptation is reducing these future risks.

1.2 The purpose of this report

The CCC commissioned this report to provide evidence on alternative or novel methodologies that exist for valuing climate impacts and appraising adaptation policy packages, which could be applied to economic assessments and/or form advice to risk owners within the outputs of CCRA4. Specifically, this report focuses on methodologies which offer an alternative approach to conventional methods, which typically value the costs and benefits of climate risks, opportunities and adaptation policies through quantification or monetisation methods. It is well documented that these valuation methods often lead to underestimates of the cost of climate change and fail to capture the breadth of impacts that climate change will likely inflict on the UK. This report identifies more holistic approaches which encompass qualitative valuation, either in isolation or in conjunction with quantitative approaches to address these methodological shortfalls.

This report has been produced following a series of extensive literature reviews covering valuation methods adopted both in the UK and internationally, but which could be applied in the UK-context. The reviews and findings were structured around the following themes, with a chapter dedicated to each:

- How can alternative valuation methods be used to add depth and fill gaps identified in the valuation of climate change risks and opportunities, and what are the strengths and weaknesses of some key approaches? (Chapter 32)
- What are the potential methods for appraising hypothetical adaptation policy packages, and what are the strengths and weaknesses of these approaches? (Chapter 4)

- How can uncertainties involved in valuing climate risk and policy packages be acknowledged and presented? (Chapter 54)
- What are the analytical options for estimating the macroeconomic impact of climate change on the UK economy? (Chapter 65)

2 Methodologies for valuing risks and opportunities to the UK from climate change

In this Chapter, a framework and set of valuation methodologies are presented. These aim to address major gaps in the valuation of climate change risk and opportunity identified in the CCRA3 (through the Monetary Valuation report) (Paul Watkiss Associates, 2021)**.** The Chapter begins by setting out the need for adopting an adapted framework for climate risk valuation, to address existing gaps. For the purpose of this research, individual climate risk valuation gaps which were identified in the Monetary Valuation report are grouped into broader categories, enabling the identification of alternative valuation techniques which can be applied to any risk within these categories, and which can complement quantitative valuations resulting from macroeconomic analyses and granular risk valuations. This chapter concludes with a presentation of valuation methods that can support the development of a holistic overview of climate risk, address current valuation gaps and safeguard against underestimation of climate risks.

2.1 Key challenges in valuing climate change risks and opportunities

The UK's most recent Climate Change Risk Assessment (CCRA3) identifies 61 individual and detailed risks and opportunities from climate change to the UK, spanning the Natural Environment and Assets; Infrastructure; Health, Communities and the Built Environment; Business and Industry; and International Dimensions sectors. These risks are present even under low warming scenarios, highlighting the importance for the UK to act now to be prepared for the impacts of climate change, regardless of the level of mitigation action. The impacts of these risks will be felt by the natural environment, the economy, and society.

While in some cases the impacts of these risks are well-researched or evidenced, in others, the future impacts of climate risks are far more uncertain. Furthermore, even if the impacts of climate risks are known, assigning a value to these impacts can be challenging. Valuation challenges may arise due to missing climate impact information required to make a quantitative valuation, or because a quantitative valuation is not suitable or ethical to apply. The valuation of climate risks associated with cultural ecosystem services presents a common example of a climate risk, for which ethical considerations will hamper the identification of an appropriate monetary value.

For the CCRA3, a Monetary Valuation of Risks and Opportunities report was produced, which estimated '*the economic value of risks and opportunities, in monetary terms as far as possible*', with the intention that by conveying the value of the risks and opportunities using a common numerical metric (i.e. pound sterling), the magnitude of the risks and opportunities could be directly compared, providing the justification for a prioritisation of risks and subsequent adaptation plans (Paul Watkiss Associates, 2021). The approach applied in the report focused on social or public value, therefore capturing the costs and benefits of climate change, both those with market prices and those without, '*that affect the welfare and wellbeing of the population*' including '*environmental, cultural, health, social care, justice and security effects*'. However, in many cases the resulting monetary estimation is produced with low confidence scores because of a number of challenges which are encountered with monetising climate change risks and opportunities:

- Valuation is only possible if there is underlying information/ evidence on the physical impacts of climate change. Therefore, if there is a lack of scientific evidence on the risks the UK faces from climate change, monetary valuation becomes difficult and relies heavily on assumptions.
- Future change in climate, and therefore the resulting risks and opportunities of a warming climate, are highly uncertain. While it is possible to attempt valuation under a variety of warming scenarios, for many risks and opportunities, how these scenarios actually play out in terms of changing weather, flood or drought risks, damage and disruption etc. is highly uncertain. There are also limits in the number of warming scenarios that can reasonably be examined so the wide range of plausible futures cannot be fully captured.
- The magnitude of climate change impacts on society and the economy will also vary with future socioeconomic conditions. Future socioeconomic conditions are uncertain and hard to communicate, which presents particularly pertinent challenges to accurately valuing the impacts of climate change. This is noted as particularly challenging in the CCRA3 Monetary Valuation report (Paul Watkiss Associates (2021)), which, due to resource and time constraints, relied on a review of existing evidence which did not have consistent underlying socioeconomic scenarios or assumptions.
- Assigning numerical, and particularly monetary, values to some climate change risks and opportunities is particularly problematic because of intangible non-market properties, independencies and resulting complexities around double-counting of values. This is especially true of risks and opportunities which relate to the impacts of a changing climate on the wellbeing of people or the natural environment.
- CCRA3 grouped identified risks into broader risk types compared to CCRA2. Less specificity when defining risks makes quantification of the value of the risks more challenging and less accurate.

Each of the challenges outlined above has implications for the resulting monetary valuation of climate change risk and opportunities. How the challenges are addressed, for example by applying assumptions or economic-theory-based techniques, can lead to valuations which could be either under- or over-estimating the risks and opportunities of climate change to the UK, presenting problems when making adaptation decisions or when trying to communicate to critical stakeholders.

2.2 Major valuation gaps considered in this report

This Chapter presents a potential framework, and set of valuation methodologies that could be used, to address a number of major climate change risk and opportunity valuation gaps identified in the CCRA3 (through the Monetary Valuation report). The first step was to compile a longlist of all valuation gaps from CCRA3, whereby either no valuation was provided or the value of the risk or opportunity was 'unknown' or where 'high impact' risks were valued, but the resulting valuation had a low confidence score[2] (see Table 2.1). In Table 2.1 the third column briefly describes the key underlying cause of being unable to value the particular risk (or only being able to produce a valuation with a very low confidence score).

The final column of Table 2.1 categorises the individual risks into broader groupings, whereby the risks have a common theme, and in most cases the costs of the risks have similar components or characteristics. Risks were grouped in this way so that alternative valuation methods could be identified within the scope of this report, which is not intended to determine valuation methods on a risk-by-risk basis.

Where individual risks could not be easily grouped and were quite distinctive compared to the other risks in the longlist, these were classified 'Distinctive risk' and were not considered any further in this study.

Table 2.1 Longlist of gaps identified in CCRA3 valuation of climate change risks and opportunities

Sector	Risk where valuation was unknown or valuation was scored 'low confidence'	The main underlying cause of quantitative valuation challenge	Broader grouping
Natural Environment	N1. Risks to terrestrial species and habitats from changing climatic conditions and extreme events	Lack of scientific evidence	N/A
Natural Environment	N2. Risks to terrestrial species and habitats from pests, pathogens and invasive species	Lack of scientific evidence	N/A
Natural Environment	N3. Opportunities from new species colonisations in terrestrial habitats	Lack of scientific evidence	N/A
Natural Environment	N5. Risks to natural carbon stores and sequestration	Lack of scientific evidence	N/A

[2] Such risks were identified and selected for the longlist in collaboration with the CCC.

Sector	Risk where valuation was unknown or valuation was scored 'low confidence'	The main underlying cause of quantitative valuation challenge	Broader grouping
Natural Environment	N10. Risks to aquifers and agricultural land from sea level rise, saltwater intrusion	Uncertainties, complexity	Distinctive risk
Natural Environment	N18. Risks and opportunities from climate change to landscape character	Intangible properties, potential for overlap with other risks (i.e. double-counting), inadequate quantified risk evidence, difficulty in monetising	Cultural risks
Infrastructure	I1. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures	Uncertainties, complexity, potential for overlap with other risks, lack of scientific evidence	Cascading risks
Infrastructure	I2. Risks to infrastructure services from river, surface water and groundwater flooding	Uncertainties, complexity	Damage or disruption to infrastructure and business
Infrastructure	I3. Risks to infrastructure services from coastal flooding and erosion	Uncertainties, complexity	Damage or disruption to infrastructure and business
Infrastructure	I9. Risks to energy generation from reduced water availability (cooling water of power plants)	Uncertainties, complexity	Damage or disruption to infrastructure and business
Infrastructure	I13. Risks to digital from high and low temperatures, high winds, lightning	Lack of scientific information	Distinctive risk
Health, communities and the built environment	H1. Risks to health and wellbeing from high temperatures	Uncertainties, complexity, intangible properties, difficulty in monetising	Risks to health and wellbeing
Health, communities	H7b. Risks to health and wellbeing from	Lack of scientific evidence,	Risks to health and wellbeing

Sector	Risk where valuation was unknown or valuation was scored 'low confidence'	The main underlying cause of quantitative valuation challenge	Broader grouping
and the built environment	changes in aeroallergens (air quality)	uncertainties, intangible properties, difficulty in monetising	
Health, communities and the built environment	H10. Risks to water quality and household water supplies	Uncertainties, intangible properties, difficulty in monetising	Risks to health and wellbeing
Health, communities and the built environment	H11. Risks to cultural heritage	Intangible properties, potential for overlap with other risks (i.e. double-counting), inadequate quantified risk evidence, difficulty in monetising	Cultural risks
Health, communities and the built environment	H12. Risks to health and social care delivery	Uncertainties, lack of scientific evidence, intangible properties, difficulty in monetising	Risks to health and wellbeing
Health, communities and the built environment	H13. Risks to education and prison services	Uncertainties, lack of scientific evidence	Distinctive risk
Business	B1. Risks to business from flooding	Uncertainties, complexity	Damage or disruption to infrastructure and business
Business	B4. Risks to finance, investment and insurance	Uncertainties, complexity, lack of data	Financial risks
Business	B6. Risks to business from disruption to supply chains and distribution networks	Uncertainties, complexity	Damage or disruption to infrastructure and business
International dimensions	ID1. Risks to UK food availability, safety, and quality from climate change overseas	Uncertainties, complexity	Cascading risks
International Dimensions	ID3. Risks to the UK from climate-related international human mobility	Uncertainties, complexity	International risks

Sector	Risk where valuation was unknown or valuation was scored 'low confidence'	The main underlying cause of quantitative valuation challenge	Broader grouping
International Dimensions	ID5. Risks to international law and governance from climate change that will impact the UK	Uncertainties, complexity, intangible properties, difficulty in monetising	International risks
International dimensions	ID8. Risks to finance sector from climate change overseas	Uncertainties, complexity, lack of data	Financial risks
International Dimensions	ID10. Risk multiplication from the interactions and cascades of named risks across systems and geographies	Uncertainties, complexity	Cascading risks

A final shortlist of risk valuation gaps to be explored in this study was derived from the longlist above. First, where the valuation of a risk is not possible because of missing scientific information, these gaps were excluded from the shortlist, as further scientific research outside the scope of this study is required. Second, risks not easily grouped into broader 'themes' of risks were mostly excluded from this research study, since focusing on broader themes of risks, rather than those that are somewhat individualistic, allowed for the greatest number of valuation gaps to be considered within the scope of this study. The risk valuation gaps within the following themes were therefore shortlisted for further investigation of alternative valuation methodologies:

- Risks to health and wellbeing
- Cultural risks
- Financial risks
- Damage or disruption to infrastructure and business
- Cascading risks
- International risks

In this chapter we consider whether alternative, in most cases qualitative, valuation methods could be used to add depth and fill gaps identified in the valuation of climate change risks and opportunities to better inform decision- and policy-makers, and their strengths and weaknesses.

2.3 The need for a qualitative valuation framework which complements existing quantitative risk valuations

The needs of stakeholders

At the UK-wide level, climate risks are often hard to identify and value. Therefore, climate risks are often under-considered by policy-makers. On-the-ground climate adaptation delivery is often the responsibility of regional or even sub-regional authorities[3], who have access to location- and context-specific data that enables them to value climate risks more effectively. However, risks that apply to the UK at national level also need to be considered as part of policy-making assessments. Therefore, the UK Government and sectoral stakeholders, who face challenges related to insufficient or incomplete valuation approaches, need access to a digestible, socially acceptable narrative of climate impacts that can inform day-to-day discussions. The remainder of this chapter addresses this challenge by discussing the shortcomings of the two levels of analysis. It then produces a blueprint for a valuation framework that safeguards against the undervaluation of climate change risks.

Macroeconomic models can be used to determine economic impacts, but there are limitations…

Macroeconomic models are commonly used in climate impact assessment exercises to provide estimates of the cost of climate change on the UK economy. These often use a range of warming scenarios for macroeconomic and distributional key performance indicators. Modelling outputs could feed into central government decision making, with the primary purpose to either build the case for, or justify existing, adaptation commitments. Macroeconomic simulations can offer insights into the evolution of indicators such as GDP, consumption, investment, employment, fiscal spending and disposable household income in such scenarios. Findings are often targeted to a specialist audience that is familiar with modelling constraints and capabilities. The estimation of macroeconomic impacts of climate change is often impaired by poor availability of quantitative data, underlying uncertainties, and the multidimensionality of the physical effects of climate change. Chapters 5 and 6 discuss this in greater detail by focusing on how assumptions, which are often used to address data availability, uncertainty or multidimensionality can impair results.

Often, neoclassical models directly compare individuals' choices through monetisation, without explicitly accounting for intangible and moral considerations of climate risk valuation. One of the key distinctions between neoclassical and ecological economics relates to how value and rationality are considered (Brown & Berry, 2022). Often, neoclassical models directly compare individuals' choices through monetisation, with peoples' choices or preferences valued through approaches such as willingness to pay. For example, the value of a natural habitat is derived by asking people how much they would be willing to pay to protect it. This contradicts real-world findings, where the underlying difficulties in quantifying intangible and often interconnected costs and benefits leads to individuals making what economic theory underlying macroeconomic models might consider 'non-rational' decisions.

[3] The UK government is currently working on the identification of risk owners for the different climate risks, as described by the 2022 Climate Risk Assessment: "The UK government recognises there are many barriers to effective adaptation that we must overcome. These include limitations in information and awareness of climate risk, lack of clarity on ownership of risks and responses, and the complexity of adapting for a future which contains innate uncertainty. (...) To support the development of NAP3, the UK government is conducting an internal exercise to establish ownership of risks...". This report uses the term to refer to entities that are responsible for observing climate risks and working on mitigation/adaptation strategies at the most granular and relevant level.

In the planning of adaptation, assessment of local climate risk may be conducted by regional or sub-regional authorities. This is because climate adaptation delivery is most often a responsibility of these actors.[4] National-level authorities need to perform additional work, e.g. data harmonisation, value transfer or aggregations, to scale up the valuation of climate risks, and obtain a holistic overview of climate risk valuation. In practice, this task faces significant challenges due to data availability, as well as the need to better accommodate for values that are non-commensurable, and that fact that the use of monetary values for value comparison is often not suitable. Missing climate impact data are expected to impede on the timely production of quantitative climate risk valuations. To address this challenge, national, regional and sub-regional authorities can leverage on qualitative methods of valuation.

Climate risk valuation can be improved by augmenting existing quantitative valuation approaches with novel qualitative approaches

The use of qualitative methods could help address some of the shortcomings identified in using quantitative methods to value climate risks. Qualitative valuation approaches can complement quantitative findings by addressing valuation limitations commonly associated with missing data and accounting for intangible and moral considerations of climate risk valuation. Despite the limitations of quantitative valuation approaches, detailed monetary valuations of location-specific risks and opportunities resulting from climate change are key in providing inputs to planning activities conducted by risk owners. However, when considering intangible and complex goods such as the ecosystem services provided by natural habitats or health and wellbeing, '*preferences and values can be incomplete and need to be formed through some sort of deliberation and learning process* '(Kenter et al., 2016, p. 194). Qualitative approaches, such as deliberative processes (see Section 2.7) which allow space for individuals to fully describe the true value of something in terms of broader wellbeing, cultural, moral and spiritual meanings, can be extremely important in eliciting a more accurate valuation than simply using conventional economic approaches, such as willingness to pay.

In collaboration with the CCC, we identified the following needs for the development of a holistic valuation framework. The starting point of this exercise was to safeguard against the underestimation of climate-risk impacts. The proposed valuation exercise needs to:

- treat the **UK central government** and **UK sectoral stakeholders** as its proposed target audience;
- produce a **well-structured** and **holistic** overview of climate risk valuation;

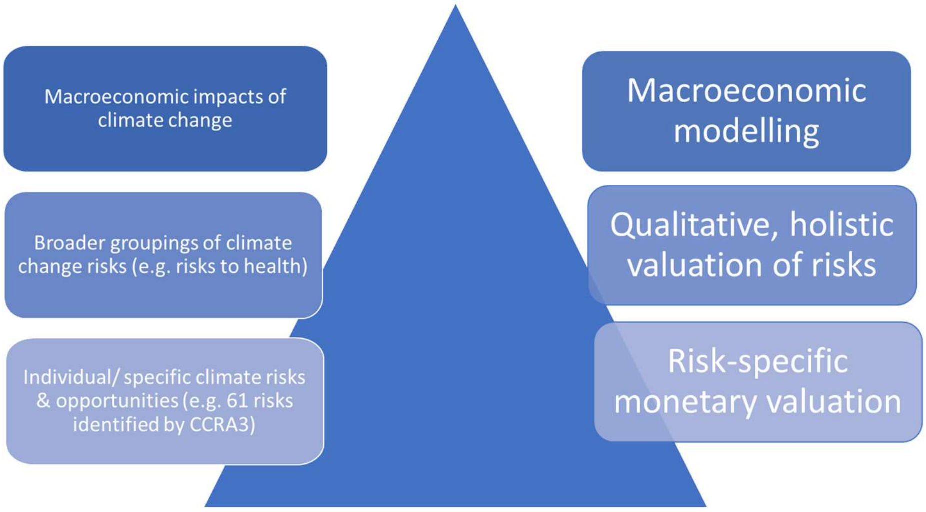
[4] The UK government is currently working on the identification of risk owners for the different climate risks, as described by the 2022 Climate Risk Assessment: "The UK government recognises there are many barriers to effective adaptation that we must overcome. These include limitations in information and awareness of climate risk, lack of clarity on ownership of risks and responses, and the complexity of adapting for a future which contains innate uncertainty. (...) To support the development of NAP3, the UK government is conducting an internal exercise to establish ownership of risks...". This report uses the term to refer to entities that are responsible for observing climate risks and working on mitigation/adaptation strategies at the most granular and relevant level.

- present an overview of expected **direct** and **indirect climate impacts**[5], with associated valuation, at a **higher level of aggregation than individual risks**;
- produce a **socially accepted valuation** of impacts by using a range of methods and acknowledging the trade-offs between them;
- **complement other impact assessment exercises** – for example, macroeconomic modelling and valuation activities performed by local government and other risk owners;
- build on key findings from CCRA3, addressing identified valuation gaps to the extent that it is possible.

The purpose of a qualitative assessment framework will not be to substitute existing assessment exercises, but to augment them. The proposed qualitative framework should focus on bridging climate impact data gaps or valuation gaps, as identified in CCRA3. Figure 2.1 visualises how macroeconomic analyses and granular risk assessments can be complemented by a qualitative assessment framework.

[5] Direct impacts can be defined as 'initial physical and socioeconomic consequences of changes in climate', while indirect effects can be described as 'the consequence of those direct impacts – materializing as a chain, or cascade, of impacts – compounding to impact a whole system, including people, infrastructure, the economy, societal systems and ecosystems' and include both cascading risks and international risks which have impacts on the UK (Quiggin et al., 2021).

Figure 2.1 How a qualitative valuation can complement other climate risk assessments



2.4 What are the underlying reasons for gaps in the valuation methods for certain groups of climate change risks?

A selection of broader risk groupings are identified in Section 2.1, based on a review of the most pertinent valuation challenges identified by the CCRA3 Monetary Valuation Report:

- Risks to health and wellbeing
- Cultural risks
- Financial risks
- Damage or disruption to infrastructure and business
- Cascading risks
- International risks

The purpose of grouping individual risks was to allow for common limitations to the development of a monetary valuation and key valuation dimensions to emerge. The appropriate identification of alternative methods can then enable the bridging of climate impact or valuation gaps in a way that provides a holistic overview of climate risks to relevant government and sector stakeholders; remains aligned with CCRA3 terminology; and can contribute to and draw from findings of macroeconomic assessment and granular assessment exercises.

Risks to health and wellbeing

Risks to health and welfare describe a wide set of risks to human health and wellbeing as a result of climate change impacts. Some examples of these risks include: risks to health and well-being from changes in aeroallergens (air quality); risks to health and well-being from high temperatures and risks to water quality and water contamination.

Impacts on human health and wellbeing are notoriously difficult to value through the use of monetary terms, due to the lack of observed market prices. CCRA3 proposes the use of the total impact on society's welfare as a means to value climate-induced health risks. Society's welfare, in terms of health risks, is commonly framed as a function of three variables: resource costs, opportunity costs and dis-utility costs.

The valuation of key health and wellbeing risk dimensions also presents challenges, due to value subjectivity and climate impact uncertainties. The CCRA3 identifies 3 key challenges linked to climate risk key valuation dimensions: resource costs, opportunity costs and dis-utility costs:

- Value of a Prevented Fatality (VPF) is not considered a holistic measure to describe dis-utility induced by poor health, even in instances of small changes in fatality risks, and particularly when it is age independent (Chilton et al., 2020).
- Quantitative approaches often result in an underrepresentation of the disutility associated with health risks, since many approaches are based on valuing the change in risk associated with fatality, but death is not the only outcome, discomfort or non-life threatening health effects also cause disutility.
- Variability and uncertainty at climate impact level (scientific assessment) present a barrier to the development of monetary valuations.

Not addressing these health and wellbeing risk valuation challenges can lead to health risk valuations that internalise uncertainty but are socially accepted. Qualitative techniques could present a solution to this challenge by accounting for subjectivity of dis-utility and eliciting expert/key stakeholder opinions to bridge current data gaps (Chilton et al., 2020).

Cultural risks

Cultural risks describe a large set of climate change risks associated with cultural assets, particularly the adverse impacts on cultural ecosystems services (CES) described as "non-material, normally non-rival and non-consumptive, outputs of ecosystems that affect physical and mental states of people" (Roy Haines-Young & Potschin, 2018b)**.** CES include the benefits environmental settings, locations and situations provide to the physical or mental state of people, through means of on-site or remote experience. The CCRA3 identifies 'risks to cultural heritage' and 'risks and opportunities from climate change to landscape character' as climate change risks where the value of impacts is unknown. Associated with this risk, the values of cultural assets can be described as option values (the value individuals place on being able to enjoy a cultural site or asset), existence (the value individuals place on simply knowing a cultural site or asset exists) and bequest value (the value individuals place on protecting a cultural asset or site for future generations).

The CCRA3 Monetary Valuation report emphasises that valuation exercises focusing on CES and other cultural assets need to carefully consider the economic and non-economic value of such assets. The CCRA3 does not identify an exhaustive or tightly structured list of key valuation dimensions for cultural risks.

Regarding CES, the need for both economic and non-economic values of the natural environment to be taken into account **echoes the recommendations of the Dasgupta Review,** which argues that natural capital needs to enter economic and finance decision-making in the same way as other economic sectors do (e.g. construction, services, manufacturing) (HM Treasury, 2021). There is a need to move away from economic success metrics such as GDP and towards the use of wider measures of inclusive wealth, which incorporate the value of produced capital, human capital, natural capital and ecosystem services to provides a more coherent measure of the well-being of current and future generations.

The impacts of climate change on cultural assets are difficult to quantify and report in monetary terms, due to their intangible non-market properties and lack of granular studies. CES valuation exercises for example, need to address the complexity of assessing non-economic values, and subjectivity features of many CES – impacts and values are often site-specific. Moreover, the lack of a harmonised approach to the conceptualisation and observation of CES can impair the ability to consolidate concepts commonly captured through quantitative metrics, such as utility or physical health, with qualitative concepts like mental and moral well-being, social cohesion or identity.

The key challenges that the CCRA3 Monetary Valuation reports and the literature highlights with respect to developing a holistic overview of the value of climate-induced risks to cultural assets include:

- There is limited consensus in academic and grey literature as to which should be the distinct cultural services that need to be considered when conducting a climate impact assessment.
- Natural capital accounting frameworks are not consistently used as a guide to developing an assessment of climate impacts on CES, leading to common disagreements at a conceptual level when discussing CES.
- Natural ecosystem categorisation is not consistently followed as a means to structure assessment of climate impacts on CES, often impairing the capacity to assess the completeness of the approach due to lack of adoption of a widely accepted framework.

The latest version (5.1) of the Common International Classification of Ecosystem Services (CICES) framework presents a guide for a classification of ecosystem services, which offers a solution to the promotion of commonly agreed set of valuation dimensions for CES (Roy Haines-Young & Potschin, 2018a)**.** CICES is increasingly becoming the main reference tool for the classification of ecosystem services by both national, e.g. Defra, and international organisation, e.g. the European Environment Agency. In October 2020, the EU published the “Mapping and Assessment of Ecosystems and their Services: The state and trends of ecosystems in the European Union” report, which used CICES as a typology for ecosystem services, which enabled inclusion in accounting frameworks. CICES divides ecosystem services into three distinct groups: provisions services, regulating and maintaining services, cultural services. CICES V5.1 presents roughly 15 (biotic and abiotic) CES. Out of the 15 CES, 7 are often described in quantitative or monetary terms – commonly related to recreation, science and physical health. The remaining 8 CES describe aesthetic experiences, symbolic/spiritual/ meaning, option/bequest or existence values, and mental health, which are more aptly represented in qualitative terms.

Challenges associated with valuing CES often lead to the overrepresentation of recreational benefits, which are easier to quantify or describe in monetary terms because of their market properties. Qualitative techniques applied on a widely accepted classification framework (such as CICES) could present a solution, by capturing other, more subjective or intangible benefits, addressing incommensurability of alternative values and strengthening value pluralism[6] (Crowder, 2021; Mason, 2023).

Financial risks

Financial risks describe a large group of climate risks associated with finance, investment and insurance, including access to capital. Based on this, the focus of financial risk assessments is commonly placed on banks and insurers, with the assessment of overall effects (or cascading effects) only discussing second degree impacts – from the financial system to the real economy.

Financial risks are considered difficult to quantify due to climate impact uncertainty and missing information relating to assets at risk from climate change in the UK banking sector. In 2022, the Bank of England published the results of the 2021 Climate Biennial Exploratory Scenario (CBES), which presented the first attempt to produce a detailed assessment of the impact of climate risks to the UK financial system. Currently, not all UK financial institutions – individual risk owners – produce detailed climate risk assessments. However, following the publication of the first exploratory scenario exercise on climate risk by the Bank of England, it has been working with large banks and insurers through dissemination of best practices and supporting initiatives to bridge important data gaps (Bank of England, 2023).

The CCRA3 Monetary Valuation report identifies two key valuation dimensions for Financial risks. These include climate risks and opportunities to the financial sector, and insurance risks – including insurance affordability.

The CBES highlights a lack of data on key factors at the level of banks and insurers as one of the key challenges in addressing current valuation gaps. This consequently presents a challenge in discussing the impacts of financial sector risks on the real economy – a task of direct interest to CCRAs. In line with current Bank of England activities that aim to harmonise data collection and reporting across the UK financial system. Future CCRA work could provide recommendations on the requirement of banks to collect and share relevant data with the Bank of England and other relevant organisations, thereby further supporting current Bank of England efforts.

[6] Value pluralism is often associated with the incommensurability of alternative fundamental values and can be most easily understood in contrast to value monism. Pluralistic approaches argue that several different values exists, which cannot be reduced to a single dimension - a sort of a supervalue. In contrast, monist approaches put forward that an ultimate value exists. A common example of a monist approach is the use of utility gained from the consumption of a given good or a service. As a supervalue, utility offers an easy to use framework for comparison. This solves the main challenge that most pluralistic approaches have to surmount – explain how different fundamental values relate to one another and which methodology can be used for comparison purposes.

Damage or disruption to infrastructure or business

The risks associated with damage or disruption to infrastructure or business represent a wide set of risks to the built environment, commonly identified for their capacity to interrupt supply and/ or production processes with impacts ranging from the local to national level. Some risk examples include: risks to infrastructure services from coastal flooding and erosion; risks to infrastructure networks (water, energy, transport, ICT) from cascading failures; risks to infrastructure services from river, surface water and groundwater flooding; risks to business from flooding; risks to business from disruption to supply chains and distribution. Climate-induced damage to infrastructure can lead to a series of cascading effects due to the reliance of the economy and society on the services it provides. The true impacts and associated costs of damage or disruption to infrastructure is therefore multiplied if these cascading effects are taken into account.

The CCRA3 Monetary Valuation report discusses a range of challenges associated with the valuation of risks associated with damage or disruption to infrastructure and business. Common barriers to the development of a valuation include: a lack of scientific impact data; uncertainty; the complexity of modelling interacting effects, avoiding double counting and fully understanding cascading failures and a lack of studies reporting impacts in monetary terms.

A supporting analysis to the CCRA3 'Interacting risks in infrastructure, the built and natural environments' investigates infrastructure risks through a complex system of key valuation dimensions that are seen through the lenses of an interconnected network (Munday et al., 2020)**.** Then, infrastructure is divided into critical and non-critical based on the importance it holds for the overall network and the type of service provided. The valuation results are based on a business function assessment, discussed in Chapter 6 of the CCRA3 Technical Report. This considers the impact of climate change along six dimensions (site location, capital, labour, supply chains, distributional networks and products and services), considering both direct and indirect effects.

In the lack of a detailed infrastructure system that considers all interdependencies, as discussed in Chapter 6 of the CCRA3 Technical Report, a holistic overview can only be based on a well-structured impact assessment framework that can identify direct and indirect climate-induced impacts (see footnote 55), without sacrificing system complexity (interactions).

To allow for the emergence of a more tractable valuation framework, infrastructure could be separated into a set of sector-specific broader groupings. Infrastructure should be split into the following groups: digital services; telecommunications services; electricity generation and distribution; natural water, water treatment and supply services; land transport services and transport services via pipelines, excluding rail and rail transport services. For each broader risk grouping the key valuation dimensions described by CCRA3 are in line with what can be found in academic literature: site location, capital, labour, supply chains, distributional networks and products and services.

Not addressing the challenges associated with valuing climate risks related to damage and disruption to infrastructure and business could

lead to monetary valuation figures that do not communicate the full complexity and magnitude of the risk impacts. Qualitative techniques could present a solution to missing impact or monetary valuation data. Different types of system analysis, such as network or systems mapping can offer a structured framework for the representation of interdependencies between the different sectors.

Cascading risks

Cascading risks represent spill over (or second degree) risks from one risk grouping to another. Cascading risks result from the knock-on impacts of direct climate risks, '*materializing as a chain, or cascade, of impacts – compounding to impact a whole system, including people, infrastructure, the economy, societal systems and ecosystems*'. For example '*a flood can cause direct damages to buildings, but also have knock-on effects on people's mental health, on business continuity and on supply chains*' (IPCC, 2021, Chapter Cascading impacts). The CCRA3 Monetary Valuation report presents cascading risks as a cross-cutting area, with key valuation dimensions varying widely between the risks included in this broader grouping.

The quantification of the likelihood, magnitude and impact of cascading risks is often not possible due to the complexity of the systems. Cascading risks require the development of complex systems modelling that can take into account non-linear effects. This undertaking presents further difficulties since there is little to no literature describing the non-linear features as a function of climate change, i.e. there is little to no literature on how cascading risks may change with climate change.

Common challenges associated with identifying and valuing cascading risks in quantitative terms may lead to an incomplete assessment of overall climate risks for the UK. An incomplete assessment is likely to mean that the true impacts of climate change are undervalued. A complete assessment of cascading risks can be viewed as particularly important given the potential high costs associated with this risk category. A carefully planned reduction in reliance on quantitative valuations, by leveraging on available qualitative techniques, could allow cascading risks to be explicitly considered and discussed as an additional layer of climate risk assessment. The use of a structured representation of the interconnections between various broader risk categories – similar to the aforementioned CCRA3 supporting analysis on interacting risks – could help in the investigation of cascading risks. Given the lack of quantitative data, a holistic overview or indicative impact assessment/valuation could be produced by leveraging on qualitative valuation techniques. Qualitative valuation techniques would still need to closely interact with climate impact assessment data and be able to leverage on a system mapping of interconnections for different types of cascade effects. In the absence of such a structure, it can be expected that qualitative valuations may yield incomplete results, due to the complexity of the valuation question itself.

International risks

International risks represent spillover or indirect risks[7] to the UK that originate from climate risks overseas. For instance, international risks

[7] See footnote 5 for a description of direct and indirect risks.

include risks to UK food availability, safety and quality as a result of climate change impacts overseas.

The CCRA3 Monetary Valuation report presents international risks as a cross-cutting theme, which touches upon a multitude of other broader risk groupings. As such, no exhaustive or tightly structured list of key valuation dimensions for international risks is identified.

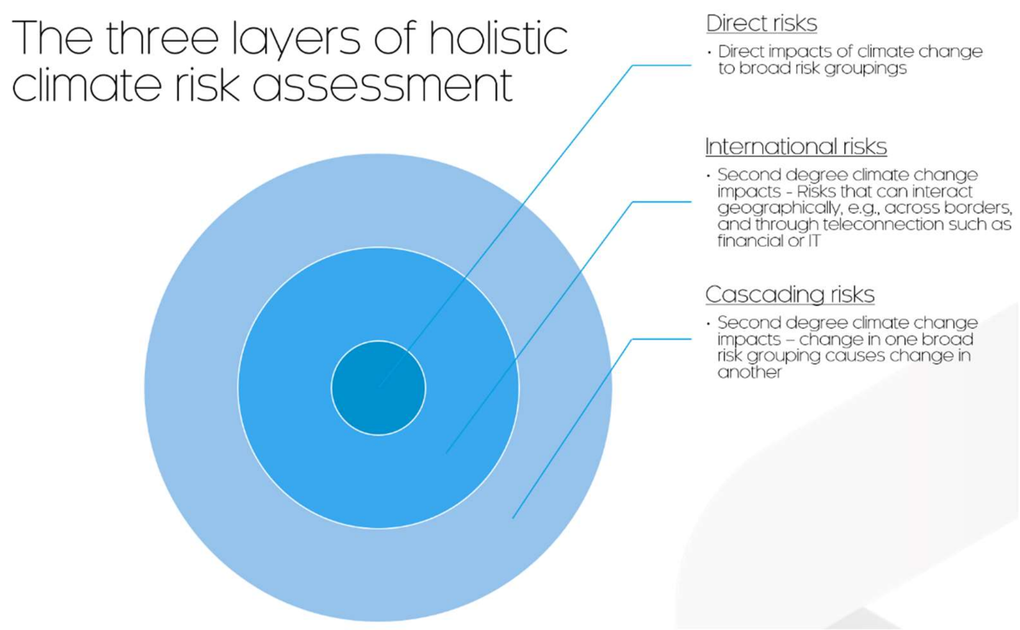
The CCRA3 Monetary Valuation report identifies as a key challenge the lack of a quantitative evidence base on international risks. The report highlights that information on the way these international risks affect the UK is also often missing.

If future evaluations adopt a singular focus on identifying a monetary value for international risks, it is likely that the full breadth of international risks will not be captured. A carefully planned move away from reliance on quantitative valuations, by leveraging on available qualitative techniques, could allow international risks to be explicitly considered and discussed as an additional layer of climate risk assessment.

Identifying and valuing direct and indirect risks within a multi-layered framework

A multi-layered assessment exercise may overcome the challenges associated with valuing direct climate impacts along with the indirect effects categorised as international risks and cascading risks. The first layer would involve the assessment of direct climate risks. Based on the broader risks discussed in this section, this would involve, for example, the valuation of risks to health and wellbeing, cultural risks, financial risks and damage or disruption to infrastructure and business risks. The second and third layer would involve the assessment of indirect climate risks, or second degree impacts. The second level will need to investigate international risks; the third level will need to investigate cascading risks, taking into consideration all relevant direct and international risks that may trigger tipping points or contribute to overall climate risk valuation for a given risk grouping or with a particular system.

Figure 2.2: A multi-layered risk assessment framework



The development of a holistic climate risk assessment for the UK requires the use of qualitative methods of research to complement monetary and quantitative valuations, with a focus on widening stakeholder engagement. A review of six broader risk groupings showed the need for addressing data limitations, uncertainty, incommensurable preferences, (individual or group) subjectivity and quantification complexity. Maintaining a singular focus on monetary valuations risks underrepresenting, if not misrepresenting, the social value of future climate-related risks. A coordinated adoption of qualitative techniques as a complement to macroeconomic assessments and granular risk assessments, may allow for a more complete picture of direct and indirect climate impacts by taking steps towards addressing many of the challenges mentioned in this section. Moreover, using qualitative techniques should facilitate the production of an overview of climate impacts by layering on top of direct risks, risks stemming from overseas and potential cascading effects.

Broader risk categories: the principal level of analysis

Key to the success of a holistic assessment exercise, that aims to give a detailed overview rather than a granular assessment, is identifying an appropriate level of analysis. This section has reviewed each broader risk grouping by identifying a set of key valuation focus dimensions, which allow an apt description of the ways through which a given broader risk grouping manifests. These dimensions were identified as common within a risk grouping following a detailed review of the risks included in each grouping. We propose that by performing this grouping exercise, UK central government and sectoral stakeholders can obtain a detailed overview that offers less granular information than the risk assessment performed by the risk owners, and more detailed narrative from what will be produced by the macroeconomic analysis.

The remainder of this chapter discusses alternative methods used in valuation and impact assessment exercises that could assist in bridging the risk gaps and challenges presented by this section.

2.5 The longlist of alternative valuation methodologies reviewed

A long list of methods was initially compiled consisting of 15 methods that were selected and described according to their relevance for meeting the needs of the valuation exercise described in Section 2.3**Error! Reference source not found.**. The full list of methods, with key information on application can be found in Annex A.

2.6 Deep dive evaluation into a shortlist of alternative valuation methodologies

The following sections review seven impact assessment and valuation processes that address in different ways the key challenges and risk valuation gaps presented in Section 2.2, and complement existing quantitative valuations, as discussed in Section 2.3. For each valuation method, a short description of the method is provided, together with key strengths and weaknesses. Then, how the valuation method addresses key gaps/challenges in producing a valuation of climate impacts at the level of broader risk categories is discussed. Concluding remarks provide a view of how this method can be used for climate impact assessment, which entails a discussion on whether the method is appropriate for the identification and/or valuation of impacts, a topic that relates to how/whether the valuation method can aptly account for the uncertainty of future climate risks.

Within the seven valuation processes, five are qualitative assessment approaches and two are network type analyses. The qualitative assessment methods are recommended as a complement to current quantitative methods, regarded as best practices. The qualitative methods presented in this chapter promote value pluralism and can address data gaps through different ways: primary data collection; value transfer[8]; qualitative methods of analysis or complementing or leveraging on other (quantitative or qualitative) analyses. The network methods presented in this chapter are discussed as a means to process the complexity of interacting risks can be used together with other quantitative or qualitative techniques. The purpose of this deep dive evaluation is not to offer an exhaustive assessment of all available impact assessment and valuation methods. Instead, out of a long list of best practices, these methods were selected to demonstrate alternative paths to undertaking a holistic valuation of climate risks, subject to current challenges.

2.7 Deliberative approaches

Deliberative approaches rely on participation processes, social exchange, reflection, learning and meaningful debate to perform risk valuation (Kenter et al., 2016)**.** Deliberative approaches present a structured framework that, unlike traditional valuation practices, can bridge the views of citizens, sectoral stakeholders, government and academia. Deliberative approaches are inter-disciplinary and support value pluralism by presenting processes that accommodate value conflict and incommensurability. They can contribute to the formation of a more apt description of climate risks, that strikes a good balance between escaping the constraints of strict monetary valuation, relaxing some constraining assumption of macroeconomic models, and presenting a higher-level description of climate risks compared to granular analyses by risk owners.

The key assumption in deliberative processes is that valuation is a social undertaking. During a valuation exercise, values are discovered, constructed and reflected in dialogue. Deliberative processes are commonly used to elicit the willingness to pay for a certain change with respect to an activity of interest (Kelemen & Saarikoski, 2014). The remainder of this section discusses the key features of deliberative approaches and how they can be applied to the valuation of climate risks through the use of two examples, the Deliberative Valuation Method and the Deliberative Value Formation.

Deliberative Valuation Method

The Deliberative Valuation Method uses open discourse and processes of deliberation with different stakeholders to identify and value impacts. Deliberative valuation (hereafter Deliberative Valuation Method or DVM) can be considered as an assessment framework or template, rather than a single,

[8] Refers to alternative methods used to transfer estimates from one valuation study with focus on a given site (e.g. a city) to another. For effective use of value transfer methods, it needs to be demonstrated that the sites discussed are similar enough (Brander, 2013).

strictly defined method. Data collection is the result of deliberation, thus the use of focus groups is central to deliberative approaches.

The design and purpose of focus group engagement may vary greatly from one deliberative approach to another. DVMs can function as a data collection framework used to provide inputs to other qualitative, mixed-methods or semi-quantitative techniques, or as a standalone assessment exercise. For instance, Multiple Criteria Decision Analysis may allow the formulation of qualitative results to quantitative values (see Chapter 3 for more discussion) or systems mapping can rely on deliberative findings for the validation or development of impact propagation mechanism. DVMs can also source inputs from existing analyses (i.e. literature) or indirectly contribute to other assessments through the use of value transfer methods[9].

DVM has been commonly applied to decision contexts that involve mediation between conflicting interests and opening up institutional mechanisms to bottom-up decision-making processes and public engagement. The deliberative features of this method can contribute to balancing the power asymmetries between stakeholders through giving voice to more marginalised groups or (when necessary) empowering them; integrating different forms of knowledge, such as local, traditional, expert, or scientific and promoting social learning and value plurality (Isacs et al., 2023).

DVM is particularly well suited for the valuation of changes to common goods, where consequences are also experienced by other people, including future generations and people living in other places. DVM enables the capture of willingness to pay information that may go beyond self-oriented values, accounting for others-oriented values that follow collective rationality. However, DVM is unlikely to lead to quantitative results, for this it often needs to be paired with other approaches such as Multiple Criteria Decision Analysis (IPBES, 2023).

Deliberative Value Formation Model

Deliberative Value Formation (DVF) presents a variation of a DVM. It focuses more closely on how values are formed though 'translating' values which represent our overarching principles and life goals into 'contextual' values represented by indicators such as willingness to pay. DVF offers a theoretical and methodological framework for more rigorous monetary and non-monetary deliberative valuation. DVF enables the extensive integration of social learning and plural knowledges and values in valuation and decision-making. Its principal contribution involves the identification of a range of potential positive (e.g. learning) and negative (e.g. social desirability bias) outcomes of deliberation processes and key factors that influence the outcomes (e.g. ability to deliberate, institutional factors, power dynamics).

The principal contribution of DVF is a detailed understanding of the key factors that influence how deliberation forms values. Similar to DVM, DVF:

- can aid participants in performing moral and political considerations as part of the value formation process

[9] See footnote 8.

- functions as a data collection framework used to provide inputs to other qualitative, mixed-methods or semi-quantitative analyses;
- is commonly applied to topics where it is valuable to overlay different science disciplines, and bridge the views of citizens, sectoral stakeholders and academia
- is particularly well-suited for the valuation of changes to common goods, where consequences are also experienced by other people, including future generations and people living in other places.

The DVM and DVF can help to fill climate risk valuation gaps

DVM and DVF can be used to address future uncertainties relating to broad categories of climate risks. Both methods can leverage on public dialogue to develop a description of the type of future impacts, the magnitude or the value that individuals and different social groups ascribe to the risk associated with a given climate impact. The methods can be applied to the development of an impact narrative that fills data gaps or aptly communicates spatial or social idiosyncratic components, e.g. subjectivity, associated with certain broader risk groupings, e.g. CES.

Table 2.2 How DVM and DVF approaches address key data gaps for 4 broader risk groupings

Broader risk grouping	Impact valuation
Risks to health and wellbeing	DVF and DVM can accommodate for subjectivity associated with disutility of health impacts, potentially offering more nuanced data than VPF. The methods can also contribute in assigning a social value to resource costs. A value for opportunity costs can also be determined through inputs from stakeholders, such as different types of employees and employers. DVF can also lead to a deconstruction of the value formation process in a way that describes how shared values influenced contextual values and resulted in value indicators.
Risks to cultural ecosystem services (CES)	DVM and DVF can apply the classification of CES from the CICES framework to attribute a value to climate impacts on CES. Data generated through processes of deliberation can permit an apt representation of subjective/geography-specific features of CES that have been identified as challenging to observe. DVF can also lead to a deconstruction of the value formation process in a way that describes how shared values influenced contextual values and resulted in value indicators.
Damage to infrastructure by sector	Both methods could be used to identify and value risks faced by each infrastructure sector, based on interviews with the directly affected population. The deliberative methods will probably need to be

Broader risk grouping	Impact valuation
	paired with network or system analysis methods to handle the complexity introduced by sector interactions.

Future evaluators can leverage on the deliberative features that both DVM and DVF offer, and their flexibility to interact with other valuation/impact assessment methods to identify direct risks, and attribute a value that reflects social perceptions. Future evaluators can draw on existing literature on climate impact risks to identify a causal impact pathway or alternative causal impact pathways that can be expanded or validated using deliberative methods.

Both approaches are particularly well suited to handle uncertainties associated with new or different impact types or risks. Furthermore, DVF can deconstruct the value formation process in a way that describes how shared values influenced contextual values and resulted in value indicators, such as willingness to pay. Future evaluators can make explicit use of the public dialogue undertaken as part of a deliberative assessment to address uncertainty – mainly qualitatively, unless paired with Bayesian methods. Both approaches can contribute to direct, international and cascading risks analysis. Table 2.3 offers an overview of how future evaluators could use DVM or DFV for the assessment of direct, international and cascading risks.

Table 2.3 How DVM or DVF can inform broader risk assessment at the 3 levels of climate impact analysis

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
Direct risks	Future evaluators can leverage on focus group data gathered as part of a deliberation process to identify the type or magnitude of climate risks, and communicate qualitative information relating to uncertainties. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative.	Future evaluators can use either method to assign value or sense-check perceptions relating existing valuations assigned to direct risks. Resulting values, subject to needs, can be in narrative or quantitative format. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative.
International risks	Future evaluators can leverage on focus group data gathered as part of a deliberation process to	Future evaluators can use either method to assign value or sense-check perceptions relating existing

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
	identify the type or magnitude of climate risks, and communicate qualitative information relating to uncertainties. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative. Dependency models and systems mapping or similar methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.	valuations assigned to direct risks. Resulting values, subject to needs, can be in narrative or quantitative format. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative.
Cascading risks	Future evaluators can leverage on focus group data gathered as part of a deliberation process to identify the type or magnitude of climate risks, and communicate qualitative information relating to uncertainties. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative. Dependency models and systems mapping or similar methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.	Future evaluators can use either method to assign value or sense-check perceptions relating existing valuations assigned to direct risks. Resulting values, subject to needs, can be in narrative or quantitative format. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative. Dependency models and systems mapping or similar methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.

Deliberative methods such as DVM and DVF are a particularly useful method for the assessment and valuation of climate impacts when there is a need for integration of different forms of knowledge, e.g. local, traditional, expert, or scientific, and/or it is valuable to safeguard social learning and value plurality. Deliberative valuation approaches are also appealing in a climate impact setting, since they offer an opportunity to (re-)consider uncertainties and flesh out the effect of differences in values between social/cultural groups.

An example of the DVM or DVF approach in practice

For example, future evaluators want to better understand CES risks associated with climate-induced ocean acidification. The main challenge so far has been the lack of a structured framework for the assessment of CES and the limitations presented by the use of purely quantitative metrics for the valuation of impacts on CES. For tractability purposes, the proposed example focuses on presenting how DVM can be implemented by describing the steps involved in the assessment of ocean acidification impacts on CES through deterioration of shell integrity of plankton classifiers, leading to adverse impacts on shellfish population and aquacultures (impact) in the North Sea (Kelemen & Saarikoski, 2014).

DVM or DVF can leverage on the CICES framework for the description of CES to identify the key valuation dimensions (Roy Haines-Young & Potschin, 2018a).Through the following three broad steps both approaches offer an opportunity to understand better how CES changed and what influenced the perceived changes:

The application of a deliberative framework (i.e. either DVM or DVF) starts with the framing of the changing features. The purpose of this step is to understand the main features related to the focus of the study. A mixture of qualitative analysis techniques can be used for this. The future evaluators can start by performing a detailed review to identify limitations of existing estimates. For this example, future evaluators are likely to find that the literature can offer a good description of the climate impacts on CES (type and magnitude); the main challenge lies in valuing the impact. Based on this, future evaluators could start by performing a validation step that looks into how key stakeholders view the literature-founded description of climate impacts on CES, and whether they find that the CICES is fit for purpose. This will promote alignment and ground theory to observed reality. Standard stakeholder analysis, and in-depth interviews can be useful at this stage. This step can also be used for the expansion of the stakeholder list (academia, sectors, civil society) - here not described explicitly.

Knowledge co-generation revisits the framed changing features with the aim to reach a holistic shared understanding of the experienced or expected change. For the DVF method, here it is key to collect information that describes the conceptualisation of deliberative value formation as a translation of shared values into contextual values and value indicators. Key components that constitute this process will need to be underscored for later reporting. For both methods, stakeholders will be invited to engage once again with the issue of climate acidification, but this time in a deliberative way. Different types of stakeholders, experts, citizens from directly and indirectly affected communities can come together to co-generate knowledge by sharing their perceptions relating to the issue of ocean acidification. Then, the evaluators will need to steer activities towards preferences to elicit the community's shared valuation of the resulting changes to CES. Citizens' science applications, photovoice or storytelling with art methods, focus groups variations, including concept mapping groups, can present useful at this stage (Flum et al., 2010).

The output of the co-generation stage is a decision-support report. After having engaged with different types of stakeholders, experts and general public and identified a shared notion of the adverse impact of ocean acidification on CES, future evaluators are called to synthesise all information into a report. The CES risk valuation is expected to be in narrative format.

The findings of the CES risk report can easily be used as inputs to other exercises. For instance, they can be used as inputs to the assessment of cascading risks resulting from the change in CES, or can be translated to quantitative format by leveraging on appropriate methods of analysis. In general terms, the integration of deliberative features as part of a structured valuation or impact assessment process aimed at informing and appraising decisions can inform individual and group value. This can contribute to breaking through individual-type concerns by attaining or identifying broader shared and social understanding of values and impacts.

Choosing between DVM and DVF approaches

Future evaluators are likely to choose DVF over DVM or other variations of deliberative processes if there is an expressed aim to investigate CES risks in a way that explicitly focuses on the importance of shared values and beliefs for value formation. DVF will explain how knowledge was gained – through learning based on information exchange – and how shared values and beliefs were eventually exchanged in the formation of reasoned opinions.

In general terms, DVF and DVM outcomes can include proposed changes to the previous systemic understanding; improved understanding of the value attribution process, including appreciation for contextual and shared values; a move towards the social good in terms of value orientation; individual or social willingness to pay and a ranking of alternatives and narrative-based valuation.

2.8 Qualitative Impact Assessment Protocol

The Qualitative Impact Assessment Protocol (QuIP) collects evidence on the impact of a project based on narrative causal statements. Statements are collected directly from individuals affected by an intervention or an event (e.g. climate change risk). Respondents are requested to reflect on the principal changes they experienced in their lives. QuIP permits the selection of multiple sources, as selected drivers of change, it links cause and effect subject to a certain set of prevalent structural circumstances, and leverages on effective use of triangulation for robust inferencing (Better Evaluation, 2022).

QuIP is backward looking exercise, thus it not well-equipped to account for uncertainty commonly associated with unknown future events. QuIP is designed as a means to determine how an event has affected or is affecting a group of people. While QuIP is not tailored to investigate the impact of future events, it is particularly well-suited to the development of an independent reality check of theories that describe how and why an observed change took place within a given context. QuIP can be used to define the magnitude, type and value of experienced impacts, as well as to develop an impact narrative that fill data gaps or effectively communicates the idiosyncratic components of value formation, such as subjectivity.

QuIP offers a process of controls that safeguard against common biases found in qualitative assessment methods, such as interviewer or selection bias. Interviewer bias relates to the situation where interviewers (unwittingly) influence the responses collected. Selection bias relates to the selection of respondents. Response panel composition can influence both the type of information and the quality of information collected.

Table 2.4 How QuIP addresses key data gaps for 4 broader risk groupings

Broader risk grouping	Impact valuation
Risks to health and wellbeing	QuIP can accommodate for subjectivity associated with disutility of health impacts, potentially offering more nuanced data than VPF. QuIP can also contribute by assigning a social value to resource costs. A value for opportunity costs can also be determined through inputs from those affected, e.g. company/organisation stakeholders.
Risks to cultural ecosystem services (CES)	QuIP can apply the classification of CES using the CICES framework to attribute a value to climate impacts on CES. Interview data gathered from the affected population can permit an apt representation of subjective/geography-specific features of CES that have been identified as challenging to observe.
Damage to infrastructure by sector	QuIP could be used to attribute a value to risks faced by each infrastructure sector, based on interviews with the directly affected population. QuIP cannot address the complexity challenge (discussed also in the level of analysis table), but it can assist by bridging the gaps and providing a reality of quantitative findings.

Future evaluators can leverage on the qualitative assessment framework that QuIP offers to identify the magnitude of experienced direct risks and attribute a qualitative value (in the form of a narrative) that reflects the perceptions of society members affected by the risks in different degree. Future evaluators can draw on existing literature on climate impact risks to identify a causal impact pathway or alternative causal impact pathways that can be validated through QuIP. QuIP is not well placed to handle the complexity of open-ended thinking processes, such as uncertainties linked to different impact types or risks not experienced yet. However, similar to other qualitative approaches, the value transfer method can be used to generalise QuIP findings.[10]

[10] See footnote 8.

Table 2.5 How QuIP can inform broader risk assessment at the 3 levels of climate impact analysis

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
Direct risks	Future evaluators can leverage on interview data gathered and processed using QuIP to fill missing data relating to the impact magnitude of different types of experienced direct risks or perform a reality check on the proposed causal pathway describing the emergence of the risk, thereby discussing the risk itself.	Future evaluators can use QuIP to sense-check perceptions related to existing valuations assigned to experienced direct risks or assign a value (most effectively, in narrative terms) to the direct risk.
International risks	Future evaluators can leverage on interview data gathered and processed using QuIP to fill missing information relating to the impact magnitude of different types of international risks or perform a reality check on the proposed causal pathway describing the emergence of the risk, thereby discussing the risk itself.	Future evaluators can use QuIP to sense-check perceptions relating to existing valuations assigned to experienced international risks or assign a value (most effectively, in narrative terms) to the experienced international risk.
Cascading risks	Future evaluators are likely to face challenges in employing QuIP for the identification cascading risks. The identification of the type and magnitude of cascading risks requires a framework that can handle the complexity involved in processing interacting causal impact pathways. Application of QuIP would involve the segmentation of cascading risks into a set of risk grouping that can be	Future evaluators can use QuIP to sense-check perceptions related to existing valuations assigned to decomposed cascading risks. The reliance on interview data, which then need to be coded and compared/contrasted may present a barrier to assessing the multitude of cascading risks.

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
	studied in turn. This could only be assessed through repeated use of QuIP, which seems coplex and inefficient.	

An example of the QuIP method in practice

QuIP is a particularly useful method for the assessment and valuation of experienced impacts when no appropriate baseline exists, the affected population is not well-defined to allow for the identification of a counterfactual group, and impacts cannot be easily or holistically captured quantitatively.

Using the previous example of valuing the risks associated with climate-induced ocean acidification, the QuIP method can be applied using the following steps, to better understand the impact of this risk.

Development of questionnaire and sampling strategy: QuIP questionnaires include open ended questions with supplementary prompts and closed questions. The questionnaire covers various areas of respondents' ways for which CES are relevant. Questions are framed around outcomes to collect information more broadly about what has changed and capture any unexpected outcomes – focus can be placed on perceived/experienced outcomes and/or valuation of outcomes.

Case selection from a long-list of affected individuals: purposive and random sampling can be mixed for the identification of a relevant and representative sample of individuals. However, QuIP recommends the use of purposive sampling as a means to sample to 'saturation', where every additional story adds little to the existing set of information.

Data collection based on interviews and focus groups: semi-structured individual interviews and focus groups discussions can be mixed as forms of data collection. QuIP prescribes 24 semi-structured interviews and four focus groups, subject to sampling and research question. Central to controlling for some of the caveats of QuIP is the interviewer blindfolding – interviewers are not aware who has commissioned the research or the exact focus of the assessment.

Analysis relies on the use of thematic coding for the identification of type/magnitude of impact on CES and value attribution. QuIP focuses on stories of change, rather than the entirety of interview/focus group material generated. The result should allow the emergence and analysis of key narratives of change with respect to CES. Here, analysts will look for trends common in different respondent types.

Reporting entails the communication of results from the coded qualitative data through the use of static text and interactive visual elements. QuIP does not provide an average effect or a unique monetary value of impact. Instead, the change in CES as a result of ocean acidification in the North Sea will be communicated in the form of rich, detailed stories of change. This output format intends to allow individual stories to contribute to the results.

2.9 Q-methodologies

Q-methodology

Q-methodology is a mixed methods approach, which is often used to investigate perspectives that represent different stances on a given issue (Admiraal, 2015)**.** The approach entails the ranking and sorting of a series of statements performed by participants/respondents. As part of Q-methodology, the evaluator needs to use qualitative judgments to define a problem, develop statements to investigate participant perspectives and select study participants. Q-methodology also uses quantitative options of analysis, most commonly factor analysis.[11] The use of ordinal ranking for subjective values addresses issues relating to incommensurability. Value incommensurability is often linked to the use of monetary values in investigating non-utilitarian anthropogenic, intrinsic or moralistic values. Ordinal rankings are also a useful tool to communicate uncertainty - cardinal scales and point estimates are often associated with a false sense of accuracy (Maniatakou et al., 2020).

Q-methodology can be particularly useful in investigating the degree of individual or group subjectivity with respect to valuation of various climate risks. Q-methodology can be a particularly useful approach for validating or investigating the prevalence of a given set of views or perspectives on a given topic, without requesting participants to articulate clearly these perspectives themselves (Armatas et al., 2014).

Q-methodology can be used as a way to address future uncertainties relating to the type of broader risk grouping impacts caused by climate change – impacts that have yet to be experienced. Q-methodology can leverage on survey data and statistical analysis to discern the main ordered patterns in opinions relating to impact type, magnitude or valuation. Results can show which aspects are contested, which are less so and why. This can fill data gaps and communicate the importance of the idiosyncratic component, such as subjectivity, associated with certain broader climate risk groupings, such as health and wellbeing risks and risks to CES (Sneegas et al., 2021).

At its core, Q-method is a flexible approach that can be used alongside other techniques, such as semi-structured interviews. The Q-method's purpose is to understand varying attitudes with respect to a given topic (e.g. value of a given climate impact or types of expected climate impacts). It leverages on quantitative analysis techniques to identify variation in subjective perspectives. Q-method utilises a type of factor analysis to systematically identify groups that share common attitude features (factors). It identifies what individuals consider significant by prompting individuals to rank a set of subjective statements. The result is a distribution of columns that shows what individuals consider as significant (considering frequency and relative ranking).

[11] For more details on the use and application of Q-methodology see the section below, on Deliberative Q-methodology.

Q-methodology can also improve the replicability and credibility of valuation studies. Valuation is based on indicating the attributes that are considered more valuable than others. This presents a framework that can handle effectively both trade-offs and uncertainty, leading to better informed, transparent and socially accepted valuation findings.

Deliberative Q-methodology

Q-methodology's reliance on statistical aggregation of individual values for the production of final results can limit its ability to promote value pluralism[12]. The simple Q-method does not have deliberative features, producing final results based on statistical aggregation of individual values. This limits its ability to elicit shared or social values and/or to acknowledge the diverse forms of human communication (e.g. anecdotes and arguing).

The deliberative Q-methodology combines deliberative focus groups and Q-methodology to develop a holistic understanding of shared (group) values (Khirfan & Peck, 2021)**.** The statistical analysis of Q-methodology weighs competing values to better understand polarized and consensus views. The additional deliberative features of deliberative Q-methodology enhance value plurality, promoting mutual learning through results that are informed by socially robust knowledge.

The use of focus groups leverages on group interaction and deliberation to explore human knowledge and experiences. Deliberation helps to identify shared values and value plurality, as well as control for different forms of human communication.

Table 2.6 How Q-methodology addresses key data gaps for 4 broader risk groupings

Broader risk grouping	Impact valuation
Risks to health and wellbeing	Q-methodology can accommodate for subjectivity associated with disutility of health impacts, potentially offering more nuanced data than VPF through the use of frequency rankings. Q-methodology can also contribute in assigning a more widely accepted value to resource costs. Alternative values for opportunity costs can also be determined through inputs from stakeholders, such as different types of employees and employers, at the stage of statement development, and in the case of deliberative Q-methodology, at the stage of deliberation .
Risks to cultural ecosystem services (CES)	Q-methodology can apply the CICES classification of CES to attribute a value to climate impacts on CES. Data generated through Q-sorting (and deliberation in the case of deliberative Q-methodology) can permit a more detailed representation of the degree of subjective/geography-specific features of CES that have been identified as challenging to observe.

[12] For an explanation of value pluralism, see footnote 6.

Broader risk grouping	Impact valuation
Damage to infrastructure by sector	Q-methodology could be used to identify the likelihood of alternative risks from materialising and the value of these risks by infrastructure sector, based on Q-sorting. Q-methodology will probably need to be paired with network or system analysis methods to handle the complexity introduced by sector interactions.

Q-methodology can be used to address climate risk valuation gaps

Q-methodology is particularly well suited to handle uncertainties associated with new or different impact types or risks. Following the identification of alternative outcomes or valuations for different aspects of a broader risk grouping, it can identify which aspects are contested by stakeholders, which are less contested and why this is the case. Value formation as part of a sorting process is be based on individual ranking decisions (or group ranking decisions in the case of deliberative Q-methodology). Factor analysis is used to give a quantitative representation to the results for each aspect. Table 2.7 offers an overview of how future evaluators could use Q-methodology (either in its standard form or deliberative Q-methodology) for the assessment of direct, international and cascading risks.

Table 2.7 How Q-method can inform broader risk assessment at the 3 levels of climate impact analysis

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
Direct risks	Future evaluators can leverage on statistical analysis of sorted alternative outcomes to identify the type or magnitude of climate risks most widely recognised as appropriate.	Future evaluators can leverage on statistical analysis of sorted alternative outcomes to identify the valuation of climate risks most widely recognised as appropriate.
International risks	Future evaluators can leverage on statistical analysis of sorted alternative outcomes to identify the type or magnitude of climate risks most widely recognised as appropriate. Dependency models and systems mapping or similar	Future evaluators can leverage on statistical analysis of sorted alternative outcomes to identify the valuation of climate risks most widely recognised as appropriate.

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
	methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.	
Cascading risks	Future evaluators can leverage on statistical analysis of sorted alternative outcomes to identify the type or magnitude of climate risks most widely recognised as appropriate. Dependency models and systems mapping or similar methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.	Future evaluators can leverage on statistical analysis of sorted alternative outcomes to identify the valuation of climate risks most widely recognised as appropriate. Dependency models and systems mapping or similar methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.

An example of the Q-methodology in practice

Q-methodology is a particularly useful method for the assessment and valuation of climate impacts when there is a need for consolidation of different forms of knowledge, e.g. local, traditional, expert, or scientific.

Future evaluators are likely to choose Q-methodology over other methods if the aim is to investigate CES risks in a way that explicitly focuses on a certain set of predefined alternatives of impact type, magnitude and valuation. Unlike the conventional Q-methodology, which is an activity undertaken by individual participants, the deliberative Q-methodology performs the rank-order exercise in groups. By adding deliberation to the ranking exercise, the value pluralism component is strengthened.

Using the previous example of valuing the risks associated with climate-induced ocean acidification, the Q-methodology can be applied using the following steps, to better understand the impact of this risk.

The first stage involves the development of a set of statements on each aspect of study, which will later be sorted by the respondents. The development of statements is usually based on a literature review, expert opinion, or investigative practices such as interviews or focus groups. The final result should resemble the Q-set example shown in Table 2.8. Each row is dedicated to one CES category based on CICES Version 5.1, where ocean acidification may have a direct impact. The second column is dedicated to statements relating to the type and magnitude of impacts. The third column is dedicated to statements relating to valuation. For indicative purposes, each cell is marked to include n statements, however this may differ from cell to cell.

Table 2.8 Example of Q-set: Full list of alternative statement describing ocean acidification impact on CES risks

Cultural ecosystem service at risk	Impact type and magnitude	Valuation
Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	Alternative impact and magnitude scenarios Number of statements: n	Alternative valuation options for each impact and magnitude scenario Statements: n
Characteristics of living systems that enable aesthetic experiences	Alternative impact and magnitude scenarios Number of statements: n	Alternative valuation options for each impact and magnitude scenario Number of statements: n
Elements of living systems that have sacred or religious meaning	Alternative impact and magnitude scenarios Number of statements: n	Alternative valuation options for each impact and magnitude scenario Number of statements: n
Characteristics of living systems that enable education and training	Alternative impact and magnitude scenarios Number of statements: n	Alternative valuation options for each impact and magnitude scenario Number of statements: n

Stage 2 involves the use of sorting programmes, such as QSortWare, to sort the statements included in each cell. In the standard Q-methodology the sorting of statements of each respondent is then transformed to quantitative data and inter-correlated with the arrays of all other respondents. In deliberative Q-methodology sorting is a group exercise performed within focus group, which rely on deliberation for the identification of a shared rank. The sort of statements of each group is then transformed to quantitative data and inter-correlated with the arrays of all other respondents.

Stage 3 involves the use of factor analysis to obtain groupings of statements that correlate (factors). Factors that explain the most variance and factors that form the descriptions of the discourses will be extracted.

Stage 4 focuses on reporting of the most salient CES risks among the surveyed population (respondents). Supportive evidence such as the degree of consensus/conflict and polarisation of opinion can be reported through the use of consensus charts. Information on the characteristics of respondents or inclusion of statements relating to contextual or shared characteristics can help interpret the results.

2.10 Network analyses

Qualitative Network Analysis

Qualitative Network Analysis (QNA) is a tool of analysis that can be used in conjunction with valuation methods to perform complex valuation exercises. QNA approaches the study and representation of networks through a qualitative perspective, this often involves the use of interviews, focus groups or literature review. QNA relies on two key tools of analysis: network maps and expert interviews/focus groups. Expert interviews can be easily replaced with a more structured assessment framework, such as DVM.

The development of network maps is an essential part of QNA. Unstructured maps are free-style drawings, developed by interviewees. Thus, they reflect the individual's view on the structure of the interactions, based on own-narrative. An alternative to unstructured maps is standardised or non-standardised structured maps. Here, interviewees are presented with a fixed definition of circles or sector of circles that they are invited to populate with information. In this setting, resulting network maps of different persons are highly comparable. For the mapping of climate impacts, a structured approach may be more appropriate – subject to the type of participants (Roca et al., 2018; Ryan & Dahinden, 2021).

QNA is commonly applied to topics where it is valuable to visually communicate the complexity of interacting risks. QNA is specifically designed to investigate phenomena that can be represented as a complex system of interactions, such as a network. The flexibility of this method allows it to be paired with deliberative methods such as DVM. Thereby, QNA can be used to portray the full complexity of interacting risks, without sacrificing the ability to tackle changes to common goods, where consequences are also experienced by other people, including future generations and people living in other places.

QNA can address uncertainties relating to interacting or cascading risks and fill quantitative data gaps, in terms of tipping points, through qualitative means such as expert judgment. As the focus of QNA is singularly placed on the representation of interconnections, the method does not have an explicitly defined framework that allows it to handle future uncertainties relating to the type of broader risk grouping impacts caused by climate change. The same applies to valuation uncertainties. To address these challenges, QNA needs to draw on other valuation techniques, some of which are presented in this section.

For all broad risk groupings considered in this report, QNA can provide a framework for the representation of interactions between specific risks and other risk groupings. QNA could also provide a framework for a geospatial approach to risks, by treating the risk dimension as a system of entities spread across the UK space. To address other challenges relating to direct effects, the method needs to rely on other valuation tools.

Future evaluators can leverage on the visual representation features than QNA offers, and its flexibility to interact with other valuation/impact assessment methods to identify cascading risks, and attribute a value that reflects social perceptions.

QNA is particularly well suited to handle uncertainties associated with cascading risks. Future evaluators can make explicit use of the public dialogue undertaken as part of a deliberative assessment to address uncertainty linked to interactions between broader risk groupings and use QNA as a means of visual representation. Table 2.9 offers an overview of how future evaluators could use QNA for the assessment of direct, international and cascading risks.

Table 2.9 How QNA can inform broader risk assessment at the 3 levels of climate impact analysis

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
Direct risks International risks Cascading risks	Future evaluators can leverage on focus group data gathered as part of a deliberation process to identify the type or magnitude of climate risks, and communicate qualitative information relating to uncertainties. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative. QNA could be used to handle uncertainty and process the complexity of attributing impacts to	Future evaluators can use QNA to assign value or sense-check perceptions relating existing valuations assigned to direct risks. Resulting values, subject to needs, can be in narrative or quantitative format. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative. QNA could be used to handle uncertainty and process the complexity of attributing impacts to

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
	multiple broader risk groups.	multiple broader risk groups.

An example of the QNA method in practice

Using the previous example of valuing the risks associated with climate-induced ocean acidification, the QNA method can be applied using the following steps, to better understand the impact of this risk.

QNA is a particularly useful method for the representation of cascading risks. By leveraging on methods such as DVM, QNA fits well in settings where there is a need for integration of different forms of knowledge, e.g. local, traditional, expert, or scientific, and/or it is valuable to safeguard social learning and value plurality. Deliberative valuation approaches in QNA are appealing since they offer an opportunity to (re-)consider uncertainties related to cascading effects and flesh out the effect of differences in values between social/cultural groups.

The application of a network analysis starts with the development of a structured mapping. Future evaluators will be splitting the nodes in two groupings, based on type of risk. Health and wellbeing risks will be represented by 3 nodes, resource costs, productivity costs and disutility. CES risks will be represented by the full set of CICES CES classes.

Future evaluators will need to access information on the impact of ocean acidification on CES, which will then be shared with respondents responsible for identifying cascading impacts. Once access is given, individual respondents or groups will be asked to identify and value resulting cascading effects. Future evaluators may rely on DVM or other valuation processes to obtain appropriate results.

The output of the co-generation stage is a decision-support report, which communicates the prevalent features of the cascading effects mapping. After having engaged with different types of stakeholders, experts and general public and identified a shared notion of the adverse impact of ocean acidification on health risks through CES risks, future evaluators are called to synthesise all information into a report. Visual mapping aids in the communication of the causal pathway that links CES risks and health risks.

Dependency modelling mixed with systems mapping

The use of Dependency modelling together with systems mapping was identified as a relevant technique for the valuation of interacting climate risks following the review of the CCRA3 report on the study of interacting risks (Munday et al., 2020)**.** The approach relies on two key parts. Part I, involves the use of an iterative process, which leverages on workshop-style engagement and a literature review, to develop and validate systems maps. Part II, involves the employment of Bayesian Belief Networks. This report follows the wording used in Munday et al. (2020), referring to this type of Bayesian Belief Networks as Dependency models.

Systems maps visually communicate the process through which a top level cause (e.g. climate variable) has a direct associated impact (e.g. biophysical effect). At the next level, the previously identified effects are treated as causes investigating whether a second-degree impact (effect) can be identified. This can be repeated for third and fourth degree impacts.

Dependency models provide a quantitative description of nodes and the relationship that exists between them. In Munday et al. (2020), nodes can take the form of climate drivers, hazardous events, or impacts. Relationships between nodes (on various states) are represented through conditional probability tables that are based on event frequencies or expert judgment. In this way, dependency models can also handle uncertainty. For each node an indication of relative impact is attached, where impact values can be expressed in appropriate units (not necessarily the same units). The expression of overall risk is based on an aggregation process, which relies on standardisation – various units are transformed to a common unit using weights that which comparability and aggregation.

The joined use of dependency modelling and systems mapping can present an effective way to summarise the complexity of climate risk interactions and quantify the relative size of risk interactions. Based on the literature review presented In Munday et al. (2020):

- Dependency models present a distinct advantage over alternative approaches. They promote a clear visual representation and communication of model parameters, inputs, and interactions. They also give the freedom to turn qualitative outputs into semi-quantitative models, i.e. it is possible to develop qualitative visualisations of the structure of system/network interactions, which can be augmented with quantitative data to develop the model and produce an overall risk figure.
- Dependency models can investigate system components and perform well in evaluating the capacity of systems to cope with events that potentially lead to large impacts.
- Dependency models can support the identification, description and testing of interconnected events, however to achieve this they need a large quantity of input data to run. This can prove costly and challenging to do.

Dependency models do not accommodate an easy quantitative assessment of feedback loops. This can present an important caveat for the study of natural environments, where feedback effects can be particularly important to capture. One way to account for this challenge is by aptly describing these effects in the outputs (e.g. systems maps) to communicate where feedback dynamics are expected to appear. Using a reduced form depend model, that has a narrow scope primarily relying on the visual communication of results and the description of impacts (type and magnitude) through qualitative means may also present a shortcut to portraying a complete picture.

The combined use of dependency modelling and system maps offers a detailed framework that can describe cascading risks. Framework limitations such as the representation of feedback loops or identification of tipping points can be addressed through the use of qualitative valuation methods such as DVM.

For all broad risk groupings considered in this report, dependency modelling mixed with systems mapping can provide a framework for the representation of interactions between specific risks and other risk groupings.

Dependency models are particularly well suited to handle uncertainties associated with cascading risks. Future evaluators can make explicit use of the public dialogue undertaken as part of a deliberative assessment to address uncertainty linked to interactions between broader risk groupings. Table 2.10 offers an overview of how future evaluators could use dependency models and system maps for the assessment of direct, international and cascading risks.

Table 2.10 How dependency modelling and system can inform broader risk assessment at the 3 levels of climate impact analysis

Level of analysis	Identification of climate risks and associated impacts (type and magnitude)	Impact valuation
Direct risks International risks Cascading risks	Future evaluators can leverage on focus group data gathered as part of a deliberation process to identify the type or magnitude of climate risks, and communicate qualitative information relating to uncertainties. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative, if necessary. Dependency models and systems mapping or similar methods could be used to handle uncertainty in a quantitative way and process the complexity of attributing impacts to multiple broader risk groups.	Future evaluators can use DVM to assign value or sense-check perceptions relating existing valuations assigned to direct risks. Resulting values, subject to needs, can be in narrative or quantitative format. Multiple Criteria Decision Analysis or similar methods could be useful in transforming qualitative values to quantitative, if necessary. Dependency models and systems mapping could be used to handle uncertainty and process the complexity of attributing impacts to multiple broader risk groups.

Systems mapping is a particularly useful tool for the representation of cascading risks. By leveraging on methods such as DVM, future evaluators can attempt to fill literature gaps that present challenges to the use of dependency modelling. Moreover, by incorporating deliberative features the framework can fit well in settings where there is a need for integration of different forms of knowledge, e.g. local, traditional, expert, or scientific, and/or it is valuable to safeguard social learning and value plurality. Moreover, deliberative valuation approaches in systems mapping can be applied to the mapping process as an extra round of validation, and a means to identify potential differences in maps produced by different stakeholders.

A reduced form of this framework could involve application between the system and broader risk categories or the valuation dimensions of each broader risk category. Subject to needs, the dependency model could be used in its full form, a probability table, or in a reduced form involving a mapping of interconnections and indication of relative impacts. In Munday et al. (2020), the level of detail that is deemed appropriate is between the system and assets. This was decided to allow the identification of key interdependencies between sectors and safeguard the identification of most CCRA3 descriptors. Quantitative estimates were derived using OpenMarkov, a probabilistic graphical modelling software.

Using the previous example of valuing the risks associated with climate-induced ocean acidification, systems mapping can be applied using the following steps:

Similar to Munday et al. (2020), nodes will take the form of climate drivers, hazardous events and impacts. In this example, climate acidification, CES based on the CICES Version 5.1 definition, and the three valuation dimensions of health and wellbeing risks (opportunity costs, disutility, and productivity costs) will be represented with nodes. Relationships between nodes will be represented through conditional probability tables that are based on event frequencies or expert judgment or focus group engagement methods – similar to those described earlier in this section. In this way, dependency models can also handle uncertainty. For each node an indication of relative impact is attached, where impact values can be expressed in appropriate units (not necessarily the same units). The expression of overall risk is then based on a weighting factor, which can represent equivalents between different units. Identification of impact values can be derived through literature review and validated through qualitative analysis methods similar to those described earlier in this section.

2.11 Key takeaways

- **Chapter 3 proposed a framework, and a set of valuation methodologies, that could address major climate change risk and opportunity valuation gaps identified in the CCRA3 (through the Monetary Valuation report).** Chapter 3 argued that by performing a grouping of climate risks, common key valuation dimensions can emerge that allow for a more structured approach to identifying alternative valuation approaches. The mix of qualitative assessment methods and network analysis can complement existing quantitative best practices in climate risk impact assessment and valuation, contributing to the development of a holistic overview of climate risk valuations and safeguarding against the undervaluation of climate risks.

- **Climate risk groupings that are based on common key valuation dimensions can accommodate the development of an overview of climate risk valuations**. At national level, climate risks are often harder to identify, value and incorporate in day-to-day decision-making and can often be under-considered by policy-makers and sectoral decision-makers. On-the-ground climate adaptation delivery is often a responsibility of regional or even sub-regional authorities and many of the 61 risks identified in the CCRA3 could be assessed (identified and valued) by regional or sub-regional authorities. Risks, that apply to the UK at national level are often considered as part of macroeconomic planning. A climate risk valuation overview that follows risk groupings rather than individual risks, and can account for interdependencies between risks as well as cascading effects, could complement the more detailed and technical narratives resulting from macroeconomic analyses and granular risk valuations to improve overall economy-wide estimates.
- **Qualitative assessment methods and network analyses can complement existing quantitative best practices in climate risk impact assessment and valuation, safeguarding against the undervaluation of climate risks.** Macroeconomic models commonly used in climate impact assessments offer insights that are often targeted to a specialist audience and often rely on neoclassical modelling assumptions, which impose some form of value commensurability – a very restrictive assumption when accounting for intangible and moral considerations of climate risk valuation. Qualitative valuation approaches can complement quantitative findings: they allow for interdisciplinary approaches; they address intangible and moral considerations of climate risk valuation, without disregarding value conflict and incommensurability; they bridge common data gaps associate with climate risks through primary data collection, value transfer, qualitative methods of analysis, or by complementing or leveraging on other (quantitative or qualitative) analyses.
- **Qualitative methods with a strong deliberative component offer the possibility to uncover individuals' true valuation.** They can elicit information on broader well-being, cultural, moral, or spiritual meanings, as well as the importance of shared values in climate risk value formation. Deliberation offers a structured framework to bridge the views of citizens, sectoral stakeholders, government and academia.
- **A multi-layered assessment exercise may overcome the challenges associated with valuing direct climate impacts along with the indirect effects categorised as international risks and cascading risks.** The first layer would involve the assessment of direct climate risks – 'initial physical and socioeconomic consequences of changes in climate', such as risks to health and wellbeing, cultural risks or financial risks (Quiggin et al., 2021, p. 35). The second (international risks) and third layer (cascading effects) would involve the assessment of indirect climate risks – 'the consequence of direct impacts – materialising as a chain, or cascade, of impacts – compounding to impact a whole system, including people, infrastructure, the economy, societal systems and ecosystems' and include

both cascading risks and international risks which have impacts on the UK (Quiggin et al., 2021, p. 35).

- **A holistic overview of climate risk valuation needs to be able to identify and compound direct climate impacts along with indirect effects.** Similar to direct risks, the valuation of indirect risks is often associated with a lack of scientific impact data; uncertainty; the complexity of modelling interacting effects, avoiding double counting and fully understanding cascading failures and a lack of studies reporting impacts in monetary terms. Qualitative techniques could present a solution to missing impact or monetary valuation data. Different types of system analysis, such as network or systems mapping can offer a structured framework for the representation of interdependencies between the different climate risks.

3 Methodologies for appraising adaptation policy packages

3.1 Introduction

As the adverse impacts of climate change become more frequent and severe, adaptation policy measures can help to mitigate impacts at local, national or global levels. However, private and public entities face budget constraints, and therefore must make choices about the best alternative adaptation measures or policy packages to implement. In addition, the future impacts of climate change are deeply uncertain: it is not known how severely different future outcomes will affect our societies and economies, when tipping points will be reached, and how many other non-linear effects remain unidentified or insufficiently assessed. This makes the decision on the most appropriate adaptation policies to implement particularly challenging.

This chapter introduces and elaborates on different approaches to help public and private decision-makers select adaptation policy packages. Most commonly, policies are appraised by using monetary techniques, in particular Cost-Benefit Analysis (CBA). As the name suggests, these methods are designed to assess the costs and benefits of different alternatives, and, often by defining a ratio between costs and benefits, the most cost-effective option, as identified by the appraisal exercise, can be selected. However, while these methods are appropriate in situations where the probability of future states is known or can be estimated with a high degree of certainty, their assumptions are often inadequate when it comes to analysing the role of adaptation packages in reducing the uncertain impacts of climate change. Despite a rapidly growing body of research and literature, there is a high degree of uncertainty around many impacts, such as the exact amount of sea level rise, and the frequency and severity of different extreme weather events. Many of the monetary techniques simply estimate the probability of different future events and calculate net present values based on them – but these estimates are sensitive to changes in the estimated parameters and are therefore not robust.

In the rest of this chapter, the focus is on the identification of methods which are designed to overcome the weaknesses of traditional monetary techniques. First, the identification approach is described in detail, and a longlist of methods is set out. Eight methods were then selected for deeper evaluation.

3.2 How policy appraisal approaches were identified

This chapter explores potential approaches that might be appropriate for appraising hypothetical adaptation policies or policy packages. Both academic and grey literature were used to identify options. Multiple combinations of the two main types of keywords were searched for, primarily on Google Scholar.

Table 3.1: Search terms for the identification of methods

Keyword - adaptation policy	Keyword - valuation
Climate change adaptation	Valuation
CCA policy	Evaluation
Adaptation policy packages	Assessment
Adaptation measures	Estimate
Adaptation preparation	Forecasting
Preventive adaptation	Appraising
Adaptation strategy	Projection
Adaptation approach	Anticipation
	Calculation
	Prediction

These terms were generally accompanied by the search term 'method' to provide a better focus.

Identifying methods that can deal with uncertainty was a top priority, as the most commonly used methods, such as cost-benefit analysis, are often not appropriate for situations of deep uncertainty. (As described in section 3.1).

In addition, novel approaches were explored, particularly by searching the grey literature. Such methods have not previously been used in the assessment of adaptation policies, instead being used in the assessment of organisational change, business projects or innovations. However, they may have useful application in the area of adaptation policy appraisal.

3.3 The longlist of policy appraisal approaches reviewed

A long list of 33 methods was initially compiled and described across a number of aspects, such as whether they are qualitative or quantitative, their appropriate use, the types of policies or sectors that can be analysed with them, time scales, the costs and benefits that can be assessed, their required inputs, their resource requirements (length of application, level of human capacity, cost), the counterfactual (if any), and whether the method is cross-referenced with the UK Green Book (guidance issued by HM Treasury on how to appraise policies, programmes and projects) (HM Treasury, 2022). The output of the method is separately attached to this report in the form of a Microsoft Excel spreadsheet.

3.4 Deep dive evaluation into a shortlist of policy appraisal approaches

In this section, nine selected methods from the longlist are presented in detail. The description of the approaches is structured as follows.

1. A brief description of the method.
2. A step-by-step guide defines the main points of implementation.

3. Resource and time requirements qualitatively assess the level of expertise and time required to implement the method. This is complemented by a well-defined list of inputs required to use the method.
4. Accuracy and robustness are assessed: the first indicates how accurately the appraisal can capture the costs and benefits of the adaptation policy packages (e.g. how well potential damages and risks are assessed when after the adaptation policy is implemented), while the second indicates how well the method can handle uncertainties and how robust the results are.
5. Usability and communicability refer to a qualitative assessment of the ease with which the evidence can be translated into policy action and the methodology and assumptions can be communicated to stakeholders.
6. An indication of how well socioeconomic values, and therefore distributional impacts, of policy packages can be incorporated is considered. UK applicability refers to whether any issues have been identified in applying the method in the UK – here some studies are presented that have applied the approach in the UK or elsewhere.
7. Consistency with the UK Green Book is analysed (for instance, whether the method is cross-referenced with it or supporting guidance).
8. Finally, the conclusion summarises the main strengths and weaknesses of the method, based on the above points.

The methods have been divided into two main groups, depending on whether they are ex-ante or ex-post evaluation methods. Methods in the former category are suitable for appraising hypothetical adaptation policy packages and selecting the most appropriate. The latter provides valuable feedback to decision-makers on how effective the policy has been, whether its application is recommended in different situations (e.g. in different geographical areas), or how the policy should be modified to achieve policy objectives. There are some methods which are hybrid in the sense that they include some monitoring activities and dynamic decision-making (for instance, an initial plan is prepared where trigger points are agreed on and when they are reached, the plan might be revised), particularly in the case of dynamic adaptation policy pathways (DAPP).

Methods appraising policies ex-ante

As described above, ex-ante policy assessment methods are suitable for appraising hypothetical adaptation policy packages without implementation and they can support decision-making by selecting the most appropriate measures based on the pre-agreed criteria. The majority of the methods fall into this group. DAPP, which is a hybrid method, is also presented here.

Real options analysis

Real options analysis (ROA) is an extension of cost-benefit analysis (CBA), which allows uncertainty to be incorporated to some extent by assessing the timing, flexibility and future opportunities of some measures. While CBA supports decision-making on which alternative to choose or whether to invest or not, ROA can answer the question of whether to invest now, later, or not at all, or just a little while keeping open future opportunities for a larger investment (Kwakkel, 2020). In other words, ROA evaluates also the delay of an investment and its flexible implementation, in contrast to CBA (Kalra et al., 2014).

The term ‘options’ refers to the ability, but not the obligation, to undertake a project with uncertain future benefits at known costs (Kalra et al., 2014). The ‘real’ part refers to the fact that the value of future options is expressed in real terms (present value), which allows the comparison but requires an agreement on the value of the discount factor.

This method is suitable for situations where (1) the decision is irreversible (e.g. infrastructural changes), (2) there is some flexibility in when the decision is implemented (e.g. in single or multiple steps), and when (3) postponing the decision allows new information to reduce the level of uncertainty, which might also affect policy implementation (Watkiss et al., 2015).

As ROA is an extension of the CBA approach, it shares and cannot overcome some of its weaknesses. Both methods require the estimation of future probabilities, which is particularly difficult if climate change impacts need to be incorporated. Similarly, the agreement on which discount factors to apply can vary widely, taking into account the different stakeholders affected by climate adaptation measures, their preferences and risk assessments. Furthermore, the assessment of some non-monetary values is also challenging (Kwakkel, 2020). In contrast, ROA performs better than CBA as it is able to incorporate the value of future options, such as changing the timing of investments, changing plans at different decision-points in the future, or enabling further opportunities which could not otherwise be realised (Watkiss et al., 2015).

Although the origin of the method is from finance, it has been widely used to appraise climate adaptation measures. This is due to the fact that adaptation measures often require high-value investments, i.e. the construction of new infrastructure, such as dams against flooding, the creation of water reservoirs, or redesign of urban areas.

ROA is not always the most efficient approach to achieving policy objectives for adaptation to climate change, as it is mainly intended to be used in situations where impacts are realised only in the long term, but the method is not robust. Conversely, ROA cannot overcome the weaknesses of CBA, such as being highly sensitive to the assessment of discount factors and probabilities of future events. Adaptation to climate change requires the engagement of multiple stakeholders with widely differing preferences, and future impacts are deeply uncertain. Although ROA is designed to evaluate the value of delay and flexibility, due to poor parameter estimates, it is not well suited to achieve policy objectives with high certainty.

Table 3.2: Comparison of different evaluation criteria in the case of real options analysis

Evaluation criterion	Assessed value
Meeting policy objectives	Medium
Resource requirements	High
Time needed	High
Accuracy	High
Robustness	Low
Usability	Medium
Communicability	High
Distributional impacts	Low
UK applicability	High
Compatibility with the Green Book	High

By design, ROA can be used to provide very accurate estimates of the costs and benefits of adaptation measures compared to other methods, as it is an extended version of CBA. Additionally, the outcome of the method is easy to communicate, as most stakeholders can compare monetised values without deep understanding of the methodology. The method can be combined with decision trees relatively easily, which can assist with communication (however, other, more formalised options are also available, such as Monte Carlo simulation). The method has been widely applied in the literature, while the adaptation of several sectors in different countries and regions, including the UK, is often evaluated by ROA. The UK Green Book recommends the use of the method explicitly.

On the other hand, the method cannot overcome the weaknesses of the CBA approach. Primarily, it is sensitive to the estimation of different parameters, such as the discount factors and probabilities of future events – this reduces robustness significantly. Furthermore, the method has relatively high resource and time requirements, as experts and different stakeholders may be involved to estimate the mentioned parameters. Considering that the method is intended to be used to appraise adaptation policy measures which have long term impacts and are often irreversible, the lack of robustness is identified as a serious drawback to achieving stated policy objectives.

Robust Decision Making (RDM)

Robust Decision Making refers to a group of approaches which aim to support decision-making under deep uncertainty[13]. RDM helps its user to (1) identify robust strategies and (2) characterise the few deep uncertainties that are the most relevant to the choice between alternatives (Groves and Lempert, 2006). Rather than optimising the outcome under different future scenarios, this method focusses on the robustness of different alternatives relative to each other. In other words, RDM can identify those strategies which are insensitive to all or most of the key uncertainties. However, this strategy may not lead to optimal outcomes, i.e. the same result could have been achieved at lower cost (e.g. smaller dikes could have provided sufficient flood protection), or higher impact could have been achieved at the same cost (e.g. a greater number of less drought-resilient trees could have been planted, which would have

[13] Deep uncertainty refers to the situation where decision-makers are unable to know or agree on the system model that relates actions to consequences.

achieved the same outcome), but the required policy objectives will be achieved in (almost) all future states (e.g. to mitigate flood risk below a certain level or to increase the proportion of green urban areas with climate-resilient species). RDM is also suitable for dealing with non-linearities and other threshold responses that may occur. It is also able to capture trade-offs between different policies (unlike, for instance, the precautionary principle approach) (R. J. Lempert & Collins, 2007). Some other methods listed and described in this report fall under the definition of this method, such as information-gap decision theory or dynamic adaptation pathways (Bhave et al., 2016).

RDM can be particularly useful for designing or appraising different adaptation policy packages, as not only is the path of global warming unknown, but the magnitude of its impacts is poorly understood. Additionally, global warming involves tipping points and non-linearities, such as the impact of melting ice caps and glaciers on sea level rise, the increase in the severity and frequency of extreme weather events, and so on. Adaptation measures should be designed to perform well under these uncertain conditions, while policy-makers face other constraints, such as limited budgets, changing socioeconomic factors, etc.

Table 3.3: Comparison of different evaluation criteria in the case of robust decision making

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	High
Time needed	Medium
Accuracy	Low
Robustness	High
Usability	Medium
Communicability	Medium
Distributional impacts	Medium
UK applicability	High
Compatibility with the Green Book	High

The robust decision making (RBD) approach has been developed to deal with deep uncertainty and to support decision-making when the probability of future events, the scenarios and the outcomes are hard to assess. It can identify trade-offs and easily compare different alternatives. By design, the method is robust and policy objectives can be achieved with a high degree of certainty compared to other methods. However, the outcome might not be optimal in the future – in other words, when climate and other impacts are realised, there could be other adaptation policies which would have produced the same outcome at lower cost, or a higher impact at the same cost in that future state. The use of RDM is recommended by the UK Green Book.

The main weaknesses of the method are its relatively high resource and time requirements. As it is a complex method involving simulation, it is not easy to use and to communicate the evolution of the results. Similarly, the method is not suitable for estimating the costs and benefits of adaptation policies accurately, but it can mitigate potential risks below a certain threshold (for example, if there is an agreement in the intolerable level of climate impacts, such as freshwater availability which should not fall below a certain level, robust decision making would achieve these policy objectives with high degree of certainty).

Info-gap theory

Info-Gap (IG) is a decision theory which was developed by Ben-Haim and aims to prioritise alternatives and support decision-making under deep uncertainty (Ben-Haim, 2006, 2010). The theory has two main concepts: the robustness and the opportuneness. The first concept aims to mitigate potential risks arising from uncertainty as much as possible (e.g. due to the unknown change in processes, due to the uncertain impacts of climate change, or when updated data will be released later, but a decision has to be made immediately), while the second concept seizes opportunities (e.g. which adaptation policy has the greatest chance of achieving some socioeconomic goals, while still increasing the ability of adaptation above a certain level). More formally, the robustness of an alternative refers to the greatest horizon of uncertainty on which the critical outcome is achieved. The opportuneness refers to the lowest horizon on which a better-than-anticipated outcomes can be achieved (Marchau et al., 2019, Chapter 5).

By using the IG approach, short- and long-term decisions and the combination of them (adaptive strategies) can be made (Marchau et al., 2019, Chapter 5). The method can be formalised and give a quantitative appraisal of alternatives, or can be implemented qualitatively, using verbal evaluation.

If a robustness approach is applied, policy objectives can be met with the highest certainty possible. In other words, robustness IG supports decision-making by evaluating and selecting different alternatives which are the most insensitive to the change of our current knowledge (to the *information gap*[14]).

Table 3.4: Comparison of different evaluation criteria in the case of info-gap theory

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	Medium
Time needed	Medium
Accuracy	Low
Robustness	High
Usability	Medium
Communicability	Medium
Distributional impacts	Medium
UK applicability	High
Compatibility with the Green Book	High

As the IG approach has been developed to support decision-making under deep uncertainty by prioritising robust policies, its robustness is high. The results of the method can be communicated relatively easily, as minimum performance requirements are easy to understand, and results are often a priority list. Furthermore, it has some easier applications when expertise is

[14] Formally, info-gap is is the disparity between what is known and what needs to be known for a responsible decision (Ben-Haim 2019, p. 94)

less necessary, also reducing resource requirements. Although the IG approach is not explicitly mentioned in the UK Green Book, its use can be considered as recommended since the method falls under the definition of robust decision making (which is recommended by the Green Book).

Its weaknesses include the relatively wide range of inputs that need to be collected, and the need to understand the system in which the policy is intended to produce results before implementation. If a quantitative, more sophisticated, result is expected the resource and time requirements can be relatively high.

Dynamic Adaptation Policy Pathways

Dynamic Adaptation Policy Pathways (DAPP) is designed to support decision-making under deep uncertainty. It is robust (achieves its objective in most future scenarios), dynamic (includes monitoring and can incorporate new information) and adaptive (can be adjusted based on new information). The method is highly effective in appraising different adaptation policies as it is designed to deal with uncertainties arising from climate change.

It combines the advantages of some other methods, such as Adaptive Policymaking (APM), Adaptation Tipping Point (ATP), Adaptation Pathways (AP) and Robust Decision Making – moreover, the method falls under the definition of the latter (Bhave et al., 2016). In order to understand the implementation of DAPP, APM, ATP and AP are also introduced briefly below.

The DAPP method is designed to meet two main requirements: (1) to produce a robust plan and (2) to enable dynamic planning. For more details on robust planning, see the section on 'Robust Decision Making'. Dynamic (robust) planning means that at certain points (*signposts* and *triggers*) the plan should be reconsidered, and action taken to avoid failure to achieve the original objectives.

DAPP is based on the *Assumption-Based Planning (ABP)* approach. This method includes *signposts* (events or thresholds at which the vulnerable assumptions of the policy are realised and actions need to be taken), *shaping actions* (intended to control the future by mitigating risks and protecting the uncertain assumptions) and *hedging actions* (actions for the case when the assumption fails despite the implementation of the shaping action – insurance is a typical example).

APM (or Dynamic Adaptive Planning, DAP) consists of two main parts: the design phase (in which the dynamic adaptive plan, the monitoring activity and other actions are planned) and the implementation phase (the implementation of the plan and monitoring and taking actions if necessary).

The *ATP* and *AP* approaches focus on timing. ATP is designed to deal with new information (e.g. incorporating the data from new climate scenarios): when this becomes available, the timing of the actions is changed to keep the ability to achieve the original objectives. AP extends ATP by reconsidering actions which should be taken when certain tipping points are reached (rather than just changing the timing), thus creating pathways. As a result, this approach can build in flexibility. This can be also particularly useful in situations where innovation can have significant impacts, which are hard to be considered in the original plan (e.g. agricultural innovation might explore new, more adaptive species or radically change the production by using vertical farms with significantly lower water need). The method supports policymaking by exploring opportunities and no-regret actions, revealing lock-ins and suggesting the timing of actions. AP therefore contains anticipatory (actions that need to be taken now) and reactive (actions need to be taken in the future when tipping points are reached) elements (Marchau et al., 2019, Chapter 3&4; Walker et al., 2013).

As DAPP combines the merits of the aforementioned methods, policy objectives are likely to be achieved with high certainty, even under deeply uncertain future.

Table 3.5: Comparison of different evaluation criteria in the case of DAPP

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	High
Time needed	High
Accuracy	High
Robustness	High
Usability	Low
Communicability	Low
Distributional impacts	High
UK applicability	High
Compatibility with the Green Book	High

As DAPP supports decision-making under deep uncertainty by developing policy pathways and assessing the value of future flexibility and opportunities, it is a robust evaluation method. When different pathways are designed and assessed, a scorecard often supports the analysis by identifying trade-offs, such as evaluating costs, benefits and other, even non-monetised, factors. On top of that, the design of the method allows the incorporation and response to new information (i.e. it is dynamic). As a result, the method can relatively accurately assess the costs and benefits of adaptation policies. Similarly, socioeconomic impacts can be considered, and different pathways might be selected based on that criterion. Available actions are planned in advance and can be implemented when trigger points are reached (monitoring activities are included). As a result, the method can handle non-linear changes, explore opportunities and no-regret actions, and identify potential lock-ins. It is easy to visualise, which makes it easier to communicate. The method has been widely used, including the planning of climate adaptation policies. Although this approach is not explicitly mentioned in the UK Green Book, its use is compatible with it since the method falls under the definition of robust decision making (which is recommended by the Green Book).

The weaknesses of the method arise from its complexity: it has relatively high resource and time requirements - however, it is generally used in situations where the upfront costs are also high. This complexity also reduces the usability and communicability of the method.

Multi-criteria decision analysis (MCDA)

Multi-criteria decision analysis (MCDA) refers to a group of approaches which incorporate several inputs, both quantitative and qualitative, and evaluate them jointly. As a result, this method is useful in situations where it is difficult or impossible to quantify some aspects, such as acceptability, safety, etc., but they are important factors in the evaluation of a policy. This is a particular problem for adaptation policy implementation which often has consequences on sectors where monetisation of impacts is challenging. These issues materialise when analysing climate adaptation measures: policy implementation might fail if, for instance, the local acceptance of new dikes is low, if a new, more resilient type of crop is invasive and affects local biodiversity adversely, etc.

As MCDA is only a collective name for different approaches, there are multiple options available for evaluation, depending on the objectives of the policymakers. Some commonly used methods are:

- Multi-attribute utility theory or multi-attribute value theory (MAUT/MAVT) scores different options (both quantitative and qualitative) and then aggregate them. The result can be a priority list, the most appropriate approach or a group of acceptable policies can be selected.
- The analytical hierarchy process (AHP) is based on the fact that people are better at making relative judgements than absolute ones, and therefore, one-to-one comparisons are more efficient (e.g. method 1 is better than method 2 and method 2 is better than method 3, etc., rather than stating which is the best method).
- The outranking method does not assume that all criteria are equally important (e.g. cost may be more important) and it compares all criteria at once, selecting the best performing alternatives in the most important categories (while all factors are considered). This method is particularly useful when units are hard or impossible to compare, measurement scale is very wide, or the aggregation of criteria metrics is difficult. (Kiker et al., 2005)

Other advantages of MCDA are that it is suitable for dealing with some degree of uncertainty, for making decisions at group level instead of individual, and for not ignoring available information just to simplify the complexity (Kiker et al., 2005).

By applying this method, policymakers have great flexibility to include any type of criteria to meet their objectives, such as both quantitative and qualitative inputs. MCDA is widely applied in environmental economics, for instance, to appraise adaptation policies (Huang et al., 2011).

Table 3.6: Comparison of different evaluation criteria in the case of MCDA

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	Medium
Time needed	Medium
Accuracy	High
Robustness	Medium
Usability	Medium
Communicability	Medium
Distributional impacts	High
UK applicability	High
Compatibility with the Green Book	High

As MCDA evaluates multiple criteria, both quantitative and qualitative, jointly (e.g. ethical issues, land and water use, the costs of adaptation, acceptability), the method is relatively accurate in estimating the costs and benefits of adaptation policies. Similarly, socioeconomic impacts can be included and assessed. One of its strengths is its flexibility: as several methods are included in the MCDA category, policymakers can apply the most appropriate one, for example, to select the best method, to rank the alternatives or to exclude some policies. MCDA is recommended by the UK Green Book; in addition to that, a supplementary manual was released to support the use of the method (Department for Communities and Local Government, 2009).

On the other hand, the relatively high resource requirements are one of the method's weaknesses (however, it depends on the policy objectives): a consistent qualitative or quantitative assessment of different factors is necessary which might require the involvement of experts and stakeholders. This also results in a relatively long implementation time. In addition, the use of the aggregation method and the communication of the methodology can be complex (although the results can be easily understood by most of the stakeholders). Generally, the method has been designed to support decision-making by creating a framework which allows the comparison and aggregation of different (and sometimes controversial) information and preferences. As a result, the focus is often not on dealing with uncertainty, while its quantification is necessary to some extent and there are some methods which prioritise robustness (e.g. non-expected utility or scenario-based MCDA approaches (Durbach & Stewart, 2012)).

Agent-based social simulation

Agent-based social simulation (ABSS) is a relatively formal, computer-based modelling approach which allows users to realistically model the actions and interactions of different agents under different assumptions (scenarios). In general, agent-based methods are designed to incorporate multiple (realistic) assumptions about the agents, such as environmental values, responses to economic and regulatory policies, etc. (UNFCC, 2004a) .

The actions of agents can be described by 3 main types of features: (1) by the given set of rules which determine their behaviour and interactions; (2) by their ability to incorporate new information through cognitive capabilities and (3) by their ability to consider their environment (Alam & Geller, 2012). It is also important to note that ABSS are mainly based on hypotheses or on the estimation of several parameters (Gilbert, 2004), which need to be verified, tested or realistically assumed.

Social simulations enable the modelling of complex issues, which are sometimes not feasible (or would be unethical) in the real world. Complexity also refers to the fact that the human interactions involve non-linearities, and societies are the result of dynamic processes (Gilbert, 2004). For example, implementing adaptation policies only in one sector or in one region might affect different groups of people and different economies (e.g. raising dikes along the upper parts of a river can worsen the situation in the downstream parts). Simulations also contribute to the modelling of some problems which cannot be calculated analytically (or would be complicated) (Richiardi et al., 2006).

The method can realistically model agents' decisions under different scenarios which helps to achieve the objectives of policymakers. However, due to its complexity, the method is appropriate for appraising a set of adaptation policies rather than individual ones.

Table 3.7: Comparison of different evaluation criteria in the case of agent-based social simulation

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	High
Time needed	High
Accuracy	High
Robustness	Medium
Usability	Low
Communicability	Medium
Distributional impacts	High
UK applicability	High
Compatibility with the Green Book	High

As ABSS is a computer-assisted simulation method, it can realistically model the actions and interactions of different agents. As a result, this approach can estimate the impact of adaptation policies relatively accurately under different scenarios. This also contributes to meet policy objectives and design their implementation. Due to its high resource requirements and complexity, the method is recommended to analyse a group of policies and not individual ones. However, even though the communication of the method and assumptions are not always simple, stakeholders are often familiar with understanding the results of simulations, which increases the method's communicability. By design, ABSS is appropriate to model distributional impacts and social interactions. Agent-based simulation modelling is compatible with the UK Green Book as it is mentioned in the Magenta Book, which is the specific guidance for carrying out evaluations (HM Treasury, 2020).

The main weaknesses of the method come from its complexity. In order to model agents realistically, there are high resource and time requirements: often expertise in policy analysis and analytical abilities are necessary to set up the simulation. These also result in relatively poor usability, as inputs are hard to be transformed to outputs. Furthermore, the method is not designed to work under deep uncertainty, however, sensitivity analysis can be incorporated to increase robustness. This shows how changing some parameters affects the main outcomes (how sensitive the modelling results are to changing the parameters), which is particularly useful if the modelling involves uncertain assumptions.

Heuristics

Heuristics refer to simplified, generally rule-based decision-making process. It considers only a few inputs (which are usually the most important) and ignores some part of the available information (Meyer, 2018). Different options are available under this framework which includes, for instance, the following:

- 'Tallying', where all the inputs are weighted equally (Meyer, 2018).
- 'Take-the-Best', where different alternatives are compared based on one metric at a time and the first outstanding option is chosen based on any metric (Meyer, 2018).
- ‘Take-the-first’, where the first option is chosen which can reach a given threshold, without analysing its optimality (e.g. which can reduce risks under a given level) (Siders & Pierce, 2021).

Using heuristics in appraising adaptation policies is a novel approach, however, their use is widely applied in many parts of people’s life. This is due to the fact that people are often unable to handle all available information or complex situations and, therefore, they use ‘cognitive shortcuts’, such as heuristics (or rule of thumb). The application of heuristics is now widely examined in cognitive sciences, such as psychology (Gigerenzer & Gaissmaier, 2010).

This method is appropriate for the elimination of complex decision-making processes and for choosing strategies which fit the most important policy objective or objectives. However, due to its simplicity, it is hard to evaluate multiple options at the same time. Heuristics are particularly suitable in situations where rapid decision-making is required (e.g. in the case of current disasters, heatwaves) or the cost of rational (or thought-to-be-rational) decision-making outweigh its benefits (e.g. the decision about the re-design of some urban places).

Table 3.8: Comparison of different evaluation criteria in the case of heuristics

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	Low
Time needed	Low
Accuracy	Low
Robustness	Medium
Usability	High
Communicability	High
Distributional impacts	Low
UK applicability	High
Compatibility with the Green Book	Low

The main strength of using heuristics is that it can enable rapid assessment of different alternatives and reduce the complexity of decision-making. As a result, the method works well if decisions have to be made quickly. Moreover, the results in cognitive sciences have shown that the method works efficiently and robustly under deep uncertainty. Further advantages come from its simplicity, such as its easy usability (compared to other methods) and communicability, and (relatively) low resource and time requirements.

Among its weaknesses, the shortage of decision criteria (which can be considered at one time) should be mentioned. As the method cuts complexity, fewer aspects, such as distributional impacts, can be taken into account, which runs contrary to the advice of the UK Green Book. Similarly, its accuracy in assessing the costs and benefits of adaptation policy measures is also lower, as decisions are made based only on the most important factors.

Methods appraising policies ex-post

As described earlier, methods which appraise policies ex-post are suitable for evaluating policies which have been implemented to guide future decision-making and suggest (or indicate to avoid) using adaptation policies in different situations, such as in different geographical locations or in different socioeconomic groups. They can significantly contribute to adjust current policy framework, to improve efficiency, robustness or optimality. In the case of this report, only horizontal evaluation approaches have been categorised as ex-post.

Horizontal evaluation

The horizontal evaluation approach was designed to merge the experience of local participants and the knowledge of peer experts. Originally, it was developed to support agricultural innovation in developing countries in the Andes, but it has the potential to be used in other (Thiele et al., 2007).

This method is appropriate for giving an early evaluation of a policy when significant modifications are still possible, but the basic concept has been designed or even initial results are already available. Usually, it consists of 2+1 types of participants and stakeholders: (1) the local participants, which refer to the local team who is developing and implementing the policy; (2) experts who owe important knowledge and expertise, but were not involved in the project before; (+1) local stakeholders (beneficiaries) who do not participate in the evaluation process directly, but their views are built in through interviews and field visits.

The essence of the method is a multi-day workshop, which also contains a field visit. The responsibility of the local team is to collect and present the context, the outcomes and all available information in a structured way and to be constructive to reconsider their ideas and implementation process. Peers' responsibility is to assess the strengths and weaknesses they can identify and make constructive suggestions. Local participants (stakeholders) are interviewed and their living and working circumstances are observed on the second day, during the field visit.

Policy objectives can be achieved with a relatively high degree of certainty, as the horizontal evaluation should be applied in a situation where significant changes are still possible, but the initial work has already started. The approach is suitable for evaluating different adaptation policies and incorporating experience from early implementation.

Table 3.9: Comparison of different evaluation criteria in the case of horizontal evaluation

Evaluation criterion	Assessed value
Meeting policy objectives	High
Resource requirements	Medium
Time needed	Medium
Accuracy	Medium
Robustness	Low
Usability	Medium
Communicability	High
Distributional impacts	High
UK applicability	Medium
Compatibility with the Green Book	High

As horizontal evaluation combines the merits of applying local and peer experts, and incorporates the view of the intended beneficiaries, a comprehensive evaluation of the policy is possible, while stakeholders are also engaged. The latter mitigates the risk of not accepting the suggested solutions. Moreover, the method's output is a clearly defined list of suggestions (beside the explored strength and weaknesses), which further improve the method's communicability. Even though horizontal evaluation can analyse complex projects and policies, its time and resource requirements are not particularly high. This is due to the fact that local project members – if they use monitoring activities – can collect and present inputs relatively easily as they are involved in the implementation of the process. Distributional and socioeconomic impacts can be easily included, for instance, through integrating the view of intended beneficiaries who were interviewed and whose problems and activities were observed during the field visits. Even though this method is not cross-referenced with the UK Green Book, it incorporates several suggestions of it, such as to use surveys and interviews to understand the different view of stakeholders, and to monitor and evaluate the implementation (when the workshop needs to be held).

Among the method's weaknesses are its low robustness. Horizontal evaluation is not designed to handle uncertainties; however, robustness can be included among the shortlisted criteria. Furthermore, long-term impacts of the adaptation policy are also not supposed to be estimated accurately, as the method rather focusses on current and short-term problems and stakeholders' engagement. As the method has not been used in developed regions yet (or at least no evidence has been identified as doing so), the methods' applicability in the UK is assessed to be only medium.

3.5 Key takeaways

- The in-depth evaluation of the adaptation policy appraisal methods set out above makes it possible to compare the different methods and to explore possible trade-offs between them. By analysing the methods in detail, several criteria were assessed qualitatively (see Table 3.10**Error! Reference source not found.**).

Table 3.10: Results of qualitative assessment of different methods, summary table

	ROA	RDM	IG	DAPP	MCDA	ABSS	Heuristics	Horizontal evaluation
Meeting policy objectives	Medium	High	High	High	High	High	High	High
Resource requirements	High	High	Medium	High	Medium	High	Low	Medium
Time needed	High	Medium	Medium	High	Medium	High	Low	Medium
Accuracy	High	Low	Low	High	High	High	Low	Medium
Robustness	Low	High	High	High	Medium	Medium	Medium	Low
Usability	Medium	Medium	Medium	Low	Medium	Low	High	Medium
Communicability	High	Medium	Medium	Low	Medium	Medium	High	High
Distributional impacts	Low	Medium	Medium	High	High	High	Low	High
UK applicability	High	High	High	High	High	High	High	Medium
Compatibility with the Green Book	High	High	High	High	High	High	Low	High

Note: In the case of resource and time requirements, 'low' indicates a better score while in all other cases, 'high' is the best assessment

- **In terms of meeting policy objectives, all methods except for ROA received the highest score**. This is a consequence of the design and purpose of the methods: they are efficient in meeting their policy objectives. However, it is important to note that meeting policy objectives does not always imply an *optimal* outcome in the future, as policymakers may choose to prioritise robustness or rapid decision-making. For example, heuristics aims to support rapid decision-making through simplifying complexity, but it does not focus on selecting the optimal outcome. In contrast to the other methods, only ROA was given a medium score in this category: it is efficient when different parameters can be assessed with a relatively high degree of certainty (e.g. the probability of different scenarios, the magnitude of impacts); however, under deep uncertainty (when the parameters are poorly or not at all assessed), the method may fail to achieve its policy objectives because it is not robust.
- **The majority of the methods perform score well in terms of their applicability in the UK**. The horizontal evaluation method is the only method scored 'medium', as it is specifically used in developing countries to support local R&D and agricultural projects.
- **Resource and time requirements are strongly correlated with each other**, which can be explained by the fact that more complex methods tend to require more resources (e.g. more expert judgement or the need to use simulations). As a result, data collection, their analysis and the implementation take more time *relative to other methods* – however, this does not mean that the method would always take a long time to be implemented: if policymakers want to include a few factors in their analysis for which data are readily available, it can be much easier to apply. Only

heuristics were scored low here, as the method is based on reducing complexity and making rapid assessments.

- **In some cases, there is a trade-off between accuracy and robustness**. In the case of RDM and IG, this is because the model optimises for robustness but does not focus on the cost or optimality of the strategy (e.g. the same results might be achieved at lower cost, but in fewer cases). Conversely, in the case of the ROA, the costs and benefits of the adaptation policy are estimated relatively accurately, but the method has not been found to be robust. Some methods (e.g. DAPP or ABSS) can address both issues simultaneously through dynamic planning or scenario design.
- **Similar to resource and time requirements, usability and communicability are linked to complexity.** Usually, if it is easy to transform inputs into outputs then the model is not complex, and the transformation is therefore easy to interpret. Communicability also depends on the objectives of policymakers (e.g. whether they want to select an optimal or robust method) – often it is not necessary to communicate how the method was selected (i.e. it is not important for most of the stakeholders), but doing so may make the result easier to understand. Hence, communicability refers to the *relative* ease of the communication.
- **The potential inclusion of distributional impacts varies across methods.** Those methods achieved higher scores on this criterion which can easily include socioeconomic aspects as one or more inputs (in the case of MCDA, DAPP); simulate social characteristics (ABSS); or where stakeholder interviews and field visits are the essential part of the implementation (horizontal evaluation). In the case of RDM and IG, it is possible to include, for instance, distributional impacts or to define the intended outcome in different socioeconomic groups, but this is often not focus of the method. Heuristics and ROA are not appropriate for including distributional impacts due to simplifications, or, in the latter case, due to the fact that monetised costs and benefits are often generalised to society as a whole.
- **The majority of the methods assessed in this report are compatible with the UK Green Book.** MCDA, RDM and ROA were directly referenced in the Green Book, while ABSS appears as a recommended method in the Magenta Book (which serves as a guide to conducting evaluations). Although horizontal evaluation, IG, and DAPP are not directly cross-referenced in the Green Book, their methodologies are broadly consistent with the recommendations. Conversely, in the case of heuristics, inconsistencies were found due to its simplifications, lack of transparency or objectivity in some cases of application.

4 Presenting the uncertainties involved in valuing climate risk and policy packages

4.1 Introduction

The CCRA3 explored several areas in which climate change leads to both risks and opportunities and assessed the potential monetary values of these risks and opportunities in the Monetary Valuation Report. A risk assessment is vital to understand the challenges the UK faces from climate change, and to design appropriate adaptation and mitigation policies. However, several uncertainties are associated with assessing the impacts of climate change, which are relevant in understanding climate risks and appraising the impacts of adaptation policy packages. This chapter summarises the uncertainties which were acknowledged in CCRA3 and identifies what needs to be given further consideration in CCRA4 (i.e. what the limitations were that CCRA4 can try to overcome).

To identify the main types of uncertainties involved in valuing both climate risks and the outcomes of adaptation policy packages, the CCRA3 Technical Report and the Research and Supporting reports were carefully reviewed to identify the approaches followed to communicate uncertain economic and other types (e.g. societal, technological) of estimates. Particular emphasis was placed on reviewing Chapter 2 of the Technical Report (Methods) (Watkiss & Betts, 2021), and the Monetary Valuation of Risks and Opportunities in the CCRA3 report (Paul Watkiss Associates, 2021). From these sources, numerous different types of economic and other non-climatic uncertainties were explored, which, in this report, have been categorised into four broader groups. While there are many uncertainties associated with climate scenarios or pathways and climate modelling, the focus of this chapter is how to present socio-economic related uncertainties.

4.2 What are the uncertainties around the present and future estimates of climate change risks and around their evaluation?

The following uncertainties have been identified:

- Uncertainty about the evolution of different socioeconomic and technological changes
- Uncertainty about the impacts of adaptation, both autonomous and policy driven
- Uncertainty about the interdependencies of climatic and non-climatic interlinkages and cascading effects
- Uncertainty about the appropriate valuation method choice

Uncertainty about future change

A major **uncertainty concerns the evolution of socioeconomic and technological changes**, i.e. it is not known how the future will develop, and what socioeconomic, technological and other changes affecting socioeconomic dynamics will occur. There is therefore additional uncertainty about the impact our society and economy might have on the potential for mitigating emissions and adapting to climate change impacts in the future, with implications for the adaptations needed to plan for and manage climate risks. For example, population and demographic changes leading to increased urbanisation will have implications for adaptation measures such as the required location of flood defences. Similarly, the number of people living, and therefore buildings located, in areas threatened by sea level rise, or the increased risks of river flooding, determines the assessment of potential risks and the costs of adaptation at local, national and global levels. Globally, diminished rivalry between different regions may mean that they are more willing to work together to limit the adverse impacts of climate change. However, less global collaboration, potential characterised through trade and physical wars, worsens the opportunities for cooperation. This will impact the rate of global emissions reduction (and therefore the rate of temperature change) and the capability to sufficiently adapt to the changing climate.

The situation of vulnerable groups is an important factor when considering the impacts of climate change, such as the impact of heatwaves on the elderly population or the adverse effects of extreme weather events on poorer communities with fewer resources to respond to the catastrophe. In the context of socioeconomic uncertainties, the key influential factors are political systems, demographic changes (e.g. population growth, urbanisation), income distribution both locally and globally, and the level of economic growth and its main contributors (e.g. further globalisation or smaller resource needs of some technologies). Socioeconomic development creates the framework in which policy-makers can adopt policy measures and assess their own climate risks, and in which different policies can work efficiently and achieve their objectives.

Uncertainty around the impact of policy packages

Another uncertainty arises from the **unknown impacts of adaptation and mitigation policies and autonomous adaptation**, to which a lack of evidence and information around the design and delivery of policies is a key driver of uncertainty.

The efficiency of policies (how rapidly and to what extent emissions can be reduced and to what extent resilience against climate change can be increased) is often uncertain. This is often the result of different, poorly considered effects. For instance, there can be a lack of evidence about how the policy should be implemented and how the impacts should be monitored. Furthermore, behavioural impacts are not (correctly) considered (e.g. models do not represent the heterogeneity of the population sufficiently due its simplifications and limitations – for more details, see Chapter 5). This affects the planning of different mitigation and adaptation policies and the assessment of risks and opportunities.

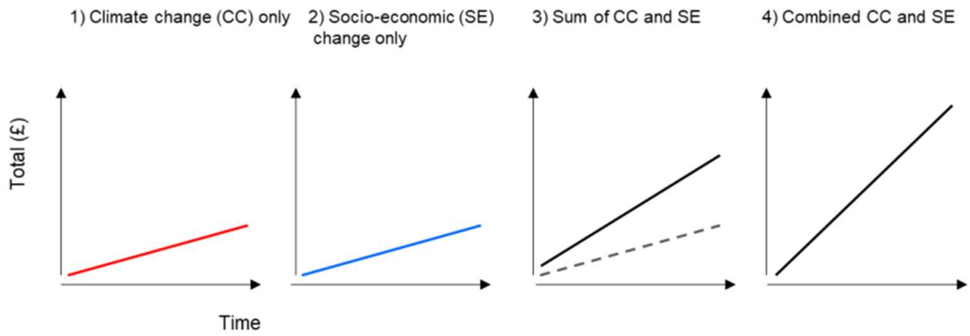
The lack of certainty around potential future adaptation action which could happen autonomously or as a result of policy measures makes predicting the future consequences of climate change particularly uncertain. The same applies to the impact of mitigation policy measures which is a key driver of the rate of global warming.

Interdependencies with other risks

The **interdependencies of climate risks with other non-climatic risks** are equally important to assess since the single, isolated evaluation of one risk might underestimate, if not incorrectly specify, the risks and opportunities associated with climate change.

Uncertainty arises when the linkages are recognised but their joint impacts are uncertain, or when attempts are made to disentangle climatic and non-climatic impacts. Chapter 2 of the Technical Report focusses on the combination of climatic and socioeconomic uncertainties and illustrates clearly that, if they are combined, the magnitude of risks is larger than the sum of climatic and socioeconomic risks (see Figure 4.1[15]). Another issue is to *separate climatic impacts from non-climatic ones*. For instance, the biodiversity of oceans is not only influenced by climate change, but also with the level of pollution and trade patterns. Therefore, it can be challenging to isolate the different impacts and assess only the risks of climate change (Paul Watkiss Associates, 2021, p. 52).

Figure 4.1: Illustration of the interlinkage between climate and non-climatic risks



Source: Watkiss and Betts, 2021, Box 2.6. Figure 1 (p. 49)

Valuation method choice

Finally, the **appropriate choice of valuation techniques** might substantially change the results of valuation exercises. Uncertainty results from different views of how to evaluate different assets, services, etc., particularly if they are hard to monetise (e.g. the evaluation of life lost due to air pollution or heatwaves) (for a more in-depth discussion see Section 2.1). The appropriate choice of methods may vary across different sectors, depending on the specific types of risks and climatic impacts that need to be considered. The aggregation of these outputs is also problematic, for instance due to interdependencies between different sectors. As the impacts of climate change (e.g. the resultant change in GDP) are often expressed *relative to the baseline*, it is also essential to define and frame the baseline appropriately. When values (e.g. potential losses) are expressed in real terms, an agreement on discount rates is necessary.

The quantification of different risks and opportunities often fails to consider the current/future level of adaptation (i.e. the baseline is assumed to be a “no adaptation” scenario). However, adaptation is a dynamic process that is

[15] This figure illustrates the difference between the sum and the combination of different risks. The first two graphs on the left show the estimated costs of climate change (CC) and socio-economic changes (SE) over time. The third graph shows how the costs change when only the CC and SE costs are summed up, without considering the linkages. Finally, the fourth graph includes the interlinkages of CC and SE costs, which are significantly higher over time than the sum of the costs.

already occurring, and often happens in the absence of policy intervention (i.e. with the private sector or individuals acting of their own accord). This ‘autonomous adaptation’ includes, for example, a steady but slow shift in agriculture towards more resilient crops, as a decision by farmers who are experiencing lower yields due to higher temperatures and less precipitation; the decision by financial institutions not to finance new buildings in areas which could be flooded due to sea level rise; the redesign of public spaces, as a decision of local governments and/or residents who prefer more green spaces and trees, and the reduction of concrete surfaces to mitigate the effects of heatwaves (this can occur besides other objectives, such as revitalisation of streets). Not incorporating these dynamic impacts could result in an overestimation of the cost of climate change on the UK economy. However, autonomous adaptation also entails costs that will need to be financed and borne by some actors (e.g. the private sector, local or national governments or households).

Additionally, when estimating the macroeconomic impacts of climate change, the choice of modelling approach (e.g. partial, general or non-equilibrium models) also affects the estimated impacts (see Chapter 5 for an in-depth discussion).

4.3 How can the identified uncertainties be dealt with?

The literature on dealing with uncertainty is extensive and several approaches have been developed to support decision-making, even under deep uncertainty. Some of these methods have already been introduced in previous chapters, for example through the analysis of the robustness of the methods in Chapter 4. Now, the focus is on a consistent presentation of those methods which may be the most suitable for supporting decision-making on climate policies.

Methods that have already been presented in detail are only briefly described in this section, while some additional approaches are described in more detail. Table 4.1 summarises the identified potential methods to deal with uncertainties.

Table 4.1: Summary of grouped uncertainties and potential methods to deal with them

Broader group	Uncertainty	Potential method to deal with uncertainties
Uncertainty about future changes	Different socioeconomic pathways	Scenario analysis (e.g. shared socioeconomic pathways), probabilistic approaches (e.g. Monte Carlo simulation)
Impacts of policy packages	Uncertainty around the impact of policy packages	See Chapter 4, particularly robust decision making and sensitivity analysis
Interdependencies	Non-climatic interlinkages	See Chapter 3, combined scenario analysis
Valuation method choice	Appropriate choice of valuation techniques	See Chapter 4, particularly Multi-criteria decision analysis, Dynamic Adaptation Policy Pathways, stakeholder approaches

Uncertainty about future changes

Both probabilistic (e.g. Monte Carlo simulation) and non-probabilistic (e.g. scenario analysis) approaches can be effective tools to address uncertainty in the evolution of socioeconomic pathways when assessing potential climate risks and opportunities and to support policy-making.

Scenario analysis

Scenario analysis is often used as a solution for presenting uncertainty about the evolution of future socioeconomic and technological changes. This method is widely used to model the differences between multiple (but generally realistic) assumptions. The creation of scenarios also provides coherent narratives, which enable the description and understanding of complex information and can therefore aid policy-making (Polasky et al., 2011). Scenario modelling involves examining a range of possible futures, instead of attempting to predict just one single future. Some strengths and weaknesses of scenario analysis (with a focus on appraising adaptation policy packages) are listed under the method of agent-based social simulation (see Chapter 4 and the ‘Annex B: Detailed description of the short-listed methods which appraise adaptation policy packages and measures’).

The most commonly used representation of possible socioeconomic futures are the **shared socioeconomic pathways (SSPs)** (Kriegler et al., 2012; O’Neill et al., 2017a). The global SSPs, used in IPCC assessments, are five different storylines of future socioeconomic circumstances, explaining how the global economy and society might evolve over the next 80 years. Crucially, the global SSPs are independent of climate change and climate change policy, i.e. they do not consider the potential impact climate change has on societal and economic choices (UK Climate Resilience Programme, 2021). Instead, they are designed to be coupled with a set of future climate scenarios, the Representative Concentration Pathways or ‘RCPs’. When combined within climate research (in any potential combination), the SSPs and RCPs can tell us how feasible it would be to achieve different levels of climate change mitigation, and what challenges to climate change mitigation and adaptation might exist.

O'Neill et al. (2017) provides an analysis of the socioeconomic challenges within different SSPs when implementing adaptation and mitigation measures (O'Neill et al., 2017b). In the case of SSP3, characterised by regional rivalry, limiting global warming below 1.5°C at the end of the century is particularly challenging, if not impossible. However, in SSP1, which is characterised by sustainable growth, socioeconomic challenges to adaptation and mitigation are significantly lower. Many modelling exercises do not consider the challenges of different socioeconomic trajectories, but rather assume the development of a single scenario.

UK-SSPs

A set of downscaled SSPs have been developed for the UK, the UK-SSPs (UK Climate Resilience Programme, 2021). The UK-SSPs are consistent with the global SSPs and are intended to provide the basis for UK research on climate risk and resilience. In line with the characteristics of the global SSPs, the UK-SSPs are independent of climate change and climate change policy. Essentially, the SSPs represent five baseline scenarios in which socioeconomic factors such as population, economic growth and technological development could lead to very different future outcomes, even without climate policy.

Additionally, in order to reduce the uncertainties around future climatic and socioeconomic changes, different scenario analysis can be combined – this can address the cascading effects of different impacts. More details are presented under the subsection of 'Interdependencies'.

Scenario analysis, particularly the use of SSPs, is a common method for representing future socioeconomic change. However, scenarios do not assign probabilities to different future states, or the assessment of probabilities is difficult and requires the use and combination of additional methods (Polasky et al., 2011). Similarly, scenario analysis is not designed to report error bars and confidence intervals, which can be of important use to decision-makers. Another limitation of a scenario approach is that it can only explore a very limited number of combined assumptions, which also limits the range of possible outcomes. Additionally, there may be a degree of bias in the scenario design, as the assumptions used in the different scenarios are based on the judgement of the policy-makers (or modellers). As a result, the uncertainty space can only be partly explored (Morris et al., 2022). This can make communicating this approach to addressing socioeconomic uncertainty particularly challenging to policy makers and other interested parties.

Monte Carlo simulation

To overcome the limitations of a scenario approach, **probabilistic approaches** can instead represent socioeconomic uncertainty and estimate the distribution of key outcomes. The most commonly used probabilistic method is the **Monte Carlo simulation**. This stochastic method is based on available historical data and predicts the range of outcomes of uncertain events. It involves creating distributions of the underlying parameters, drawing samples from them, and running a large number of simulations (e.g. thousands) to observe the range of outcomes and estimate the underlying distribution function. The inputs can vary widely, depending on the purpose of the modelling exercise and preferences of the policy-makers; for instance, inputs may include socioeconomic (e.g. population growth, productivity, inequalities, levels of urbanisation) or technological changes (e.g. energy efficiency, resource requirements and potential shortages or elasticities of substitution for labour) (Morris et al., 2022; Refsgaard et al., 2007).

Quantifying uncertainty using Monte Carlo simulation can overcome the weaknesses and limitations of scenario modelling. The method is well suited to exploring a wider uncertainty space in a systematic manner by modelling a large number of combinations of inputs. This reduces the risk of omitting important areas of the uncertainty space and reduces the bias in the scenario design. Furthermore, Monte Carlo simulation is also suitable for reporting error bars and its combination with other methods, such as multi-criteria decision analysis (MCDA) can enhance usability for policy-makers, e.g. by prioritising alternatives (Baudry et al., 2018).

However, the Monte Carlo method has some limitations. It requires the collection of a large number of inputs, often subject to assumptions and constraints, which need to be updated as new information becomes available.

Moreover, a major problem is that the method requires the estimation of input parameters (and their distribution), which are often poorly understood and difficult to assess (Refsgaard et al., 2007). Experts often disagree on when parameters can be described by distribution functions and when uncertainties are too great (i.e. there is a lack of information on how to assess parameters based on historical values) (Morris et al., 2022). In the case of deep uncertainty, scenario analysis and robust decision making (which are often combined) are more appropriate methods (Chapter 3 discusses decision-making under deep uncertainty in detail).

Since a Monte Carlo simulation assesses the distribution of an outcome individually, the link between different outcomes, or the relationship of the same outcome over time, may be lost. For example, if the same outcome is achieved in different years (e.g. in 2030 and in 2050), its 90^{th} percentile may not come from the same combination of input parameters (in other words, from the same scenario). Similarly, when assessing the distribution of different outcomes (e.g. the energy generated from different energy sources, such as renewables and fossil fuels), they are likely not consistent across each percentile. As a result, Monte Carlo simulation is inappropriate for exploring the links between different outcomes and creating frameworks and storylines – scenario analysis is designed to address this. (Morris et al., 2022)

Table 4.2: Comparison of probabilistic and non-probabilistic methods to represent uncertainty of future socioeconomic changes

	Probabilistic methods	Non-probabilistic methods
Examples	Monte Carlo simulation	Scenario analysis, robust decision making
Combination of input parameters	Large number of combinations	Only a few combinations
Exploring the uncertainty space	Consistently and widely	Only a limited part of it
Assessment of input parameters under deep uncertainty	Ambiguous, not recommended	Combined with robust methods can deal with deep uncertainty
Reporting error bars	Individually for all outcomes	Does not report
Interlinkages over time or between different outcomes	Often lost	Appropriate to create storylines or narratives
Potential biases	Assumptions and simplifications of inputs	Bias when designing scenarios (which uncertainties are combined)

Impacts of adaptation policies and autonomous adaptation

In the context of uncertainty about the impacts of adaptation policies, Chapter 4 ‘Methodologies for appraising adaptation policy packages’ discusses a variety of methods which are suitable for dealing with uncertainty (i.e. they support robust decision-making). Although Chapter 3 focussed specifically on the assessment of adaptation policy packages, its implementation can be broadly applied to general decision-making under uncertainty.

When analysing the impact of policies, the source of the uncertainty is often the poorly understood relationship between the outcome of the policy and its intended objective. Uncertainty about policy impacts can be translated into the weak, or even non-existent estimates of some parameters, such as the magnitude or order of the impact of policy measures (e.g. due to rebound effects or no prior implementation). For instance, in the case of flood protection, building a dam in one part of a river (e.g. upstream) may achieve its objectives in the region where it is built (i.e. settlements and land are protected from flooding). However, it may adversely affect other groups, particularly increasing the vulnerability of those living downstream, as substantially less water is retained in upstream parts of the river. Without further adaptation, the original dam may result in floods in downstream areas. This example illustrates that the link between the policy intervention (building dams to protect settlements and property from flooding) and its outcome (the level of adaptation to flooding) is uncertain (i.e. improved flood protection in one region does not always lead to improved adaptation to flooding at the national or international level).

As introduced in Chapter 3, there are several methods which can address the problem of decision-making under uncertainty (even under *deep* uncertainty). Methods that have been shown to be robust include **robust decision making, dynamic adaptation policy pathways, and the info-gap method**. These approaches are designed to deal with the uncertainty around the parameters.

Another widely used tool to improve robustness and reduce uncertainty around the impact of policies is the use of **sensitivity analysis** (for example, in the case of agent-based social simulation or, more generally, in the case of scenario design). Sensitivity analysis demonstrates how changing some parameters affects the main outcomes (how sensitive the modelling results are to changing the parameters), which is particularly useful if the modelling involves uncertain assumptions. This approach may be appropriate in situations where uncertainty is not particularly high (the range of possible parameters is not large).

Interdependencies

The interdependencies of climate risks with other non-climate risks are discussed in detail in Chapter 3.

Interdependencies, such as risks arising from the international impacts of climate change or the cascading effects of different risks (see the earlier example of the combination of socioeconomic and climate risks), can add up in a non-linear way. As a result, aggregating different risks individually does not capture the real impact of their combination. In other words, they have a network effect. In order to address international and cascading risks, **Q and Deliberative Q-methodology, Deliberative Valuation Method, Deliberative Value Formation Model, Qualitative Network Analysis, and Dependency Modelling** can be used. Section 2.6 ‘Deep dive evaluation into a shortlist of alternative valuation methodologies’ provides a detailed description of these methodologies and suggests when they are appropriate to use.

Another potential solution for dealing with uncertainties arising from different types of risk is **combined scenario analysis**. For example, the creation of a matrix with SSPs and emissions pathways such as Representative Concentration Pathways (RCPs) in its columns and rows, respectively, is an efficient tool to capture the impact of SSP scenarios on the emission pathways and to consider further consequences, such as the cost of adaptation and mitigation (Berkhout et al., 2013; van Vuuren et al., 2014) . In this way, the OpenClim model combines the UK-SSPs and UKCP18 climate projections together with different economic and natural dimensions such as social vulnerability, agricultural risks, or biodiversity and floor risks. It quantifies the risks to natural capital and economy at the same time (UK Climate Resilience Programme, 2020).

Valuation method choice

The choice of an appropriate valuation method is challenging in situations where (1) there is a disagreement on the valuation of different parameters, (e.g. discount factors, the value of life, the evolution of the baseline) or (2) the quantification of different values is difficult or impossible (e.g. the current level of adaptation compared to no adaptation or because of intangible or non-market characteristics).

In some cases, disagreement is caused by the fact that different stakeholders face different types and magnitudes of challenges (e.g. comparing those who depend on agriculture for their livelihoods with those who do not). When the valuations of different societal groups differ, multi-criteria decision analysis (MCDA) can be a powerful approach. As described in Chapter 4, MCDA can consider several different aspects simultaneously, both quantitative and qualitative. As a result, different stakeholder views can be incorporated (e.g. different assessments of the benefits of the strategy can be considered) and the value of non-monetisable assets can be assessed.

Other methods introduced in this report incorporate similar features to MCDA, but their focus may be different. For example, DAPP often involves a 'scorecard' where different aspects are evaluated, often qualitatively (e.g. side-effects, acceptability). Stakeholder approaches (e.g. horizontal evaluation or willingness to pay) build on the involvement of different stakeholders and their evaluation of assets which can indicate the value of some non-monetisable assets and services or that of discount factors.

4.4 Key takeaways

- In addition to uncertainties related to climate scenarios and climate modelling, there are several types of uncertainties associated with the assessment of climate change risks and the appraisal of adaptation policy packages. Various methods exist to address these uncertainties within risk assessments, decision-making and policy appraisal.
- The **unknown level of socioeconomic, technological, institutional and other changes** are key drivers of the future and in the long-term (i.e. at the end of the century), these are the most substantial sources of uncertainty. However, current decisions can greatly influence these uncertainties. *Scenario analysis, for example shared socioeconomic pathways,* can be an efficient tool to address the uncertainties arising from different physical and socioeconomic pathways, even under deep uncertainty. *Probabilistic approaches,* such as *Monte Carlo simulation*, can guide policy-makers on the distribution of different impacts and explore different combinations of different uncertainties.
- **The uncertainty arising from the unknown impacts of policy packages** is driven by the lack of evidence on how to design and implement an appropriate set of policies. *Robust methods,* for example *robust decision making*, are designed to achieve policy objectives with a high degree of certainty, even under deep uncertainty. *Sensitivity analysis* can also reduce the uncertainty around outcomes, particularly in the case of scenario-based planning (e.g. agent-based social simulation).
- **The interdependencies of climatic risks with non-climatic risks** often lead to a cascading effect, i.e. different risks add up in a non-linear way. International and cascading risks can be addressed using *Q and Deliberative Q-methodology, Deliberative Valuation Method, Deliberative Value Formation Model, Qualitative Network Analysis, and*

Dependency Modelling. *Combined scenario analysis* can also consider the joint effects of different risks (e.g. the evolution of climatic and socioeconomic pathways).

- **The uncertainty around the choice of appropriate valuation techniques** is driven by a disagreement on the valuation of different parameters, or by the difficulty or impossibility of quantifying different values. In such cases, MCDA, DAPP and stakeholder approaches may be appropriate to support the decision-making process.

5 Options for estimating the macroeconomic impact of climate change on the UK economy

Climate change and the decarbonisation policies implemented by different governments and institutions will affect economic and financial systems, producing considerable impacts some of which will be irreversible (NGFS, 2020). Most studies which analyse the impact of climate change on the economy show the considerable downside risks of climate change, and the possible welfare losses it can create, both globally and in the UK.

The increase in global temperatures is expected to increase the risk of floods, food insecurity and natural catastrophes and have negative impacts on ecosystems, biodiversity and other natural and economic systems like agriculture or tourism (IPCC, 2022). In the UK, even if net zero greenhouse gas emissions are achieved by 2050, sea levels will keep rising after 2100, increasing the flooding risk of several areas and directly affecting multiple sectors such as farming or tourism (Met Office, 2018).

The quantification of the macroeconomic impacts of climate change is generally regarded a difficult and complex task. This chapter explores existing tools for quantifying these impacts, with a focus on the UK economy.

5.1 Challenges in quantifying the economic impacts of climate change

There are multiple sources of uncertainty

While most of the literature agrees on the negative economic impact of climate change, there is wide variability in the estimates of these impacts. This is in part because of the uncertain and multidimensional nature of climate change, which makes the task of modelling climate impacts complex. The impact of climate change can occur gradually (chronic) and/or through extreme (acute) climatic events, and it can trigger both demand and supply impacts (Canevari, 2019). These impacts can also generate cascading effects across different sectors, deriving from dynamics which are difficult to incorporate into economic models.

Another consideration is the existence of feedback loops (UCAR, 2023) which characterise the interactions across different climate variables which produce reinforcing effects, both positive and negative, such as increasing/decreasing the temperature level. The parameters determining the strength of such feedback loops are largely unknown (Pindyck, 2013), which results in inaccurate estimates of economic impacts.

Finally, many economic models are used for scenario analysis, in which different policies (e.g. decarbonisation policies) are assumed to be implemented across the scenarios. However, even when scenarios attempt to account for different sources of uncertainty (see Chapter 5 for a more in-depth discussion), it is possible that some policies are eventually delayed, or do not happen at all in the expected or considered way, which adds another layer of uncertainty to modelling analyses. Shared Socioeconomic Pathways (for example, the UK-SSPs) also suffer from the same kind of drawbacks since assumptions on the evolution of population, GDP, and other dynamics underlie the scenarios but the final evolution of these variables could differ from the evolution projected in the scenario. While the UK-SSPs (and global equivalents) seek to address uncertainty by setting out five materially different pathways for future socioeconomic development in the UK, it is clear that five pathways cannot cover all potential future outcomes (see Chapter 5 for a more in-depth discussion of SSPs). Additionally, SSPs explicitly avoid building in climate change impacts (by design). Therefore in order to understand the full risk and resilience implications of climate change, the SSPs need to be combined with climate pathways such as the Representative Concentration Pathways (RCPs) or the UKCP18, produced by the Met Office.

There are multiple quantification methodologies, leading to different macroeconomic impacts

Depending on the quantitative methodology applied, estimated economic impacts of climate change differ, making the quantification of climate change impacts more difficult and hindering policymakers' task of analysing adaptation and mitigation benefits and selecting appropriate measures (Piontek et al., 2021). Different results can be explained by the following factors:

- The distinct structure and assumptions underlying the different modelling approaches producing macroeconomic estimates. For instance, some models (e.g. general equilibrium models) assume economic rationality of individuals and firms while others assume individuals and firms are not fully rational or do not perfectly understand market mechanisms (e.g. macro-econometric approaches).
- The definition of 'macroeconomic impacts' – while many structural models limit these effects to specific individual variables (e.g. the impact on GDP), others combine multiple impacts (often using different monetarisation methods) into a single 'costs of climate change' impact, which is then expressed as a percentage of GDP.

Even while using similar approaches, results can still differ in terms of the economic or social cost of climate change, (Hope, 2013). This can be due to a range of factors, such as:

- The specific data sets used and the level of disaggregation of the variables, or the particularities of the scenarios assumed in a given exercise.
- New adjustments applied to an existing model specification may produce different results compared to previous/older specifications of the same model.

Recent estimates of the macroeconomic impacts of climate change

As a consequence of this heterogeneity, multiple and varying estimates of the impact of climate change on different economic variables can be found. For example, at a global level, Burke et al., (2018) finds that an increase in temperatures between 2.5ºC and 3ºC compared to preindustrial levels could lead to a reduction in global GDP of 10% by the middle of the century, and 15-25% by 2100; all compared to a baseline case in which an increase in temperature does not occur (Burke et al., 2018). However, there are more conservative estimates, for example produced by the FUND model, in which the same increase in global temperature could lead to GDP losses of less than 2.5% (Diaz & Moore, 2017).

The same variability in outcomes occurs when estimating the impact of climate change on the UK economy specifically. A recent study found that the macroeconomic costs of climate change are projected to reach 7.4% of the UK's GDP by 2100 with the policies currently enforced and an increase in temperature of 2.9ºC with respect to pre-industrial levels. Furthermore, reductions in international trade (due to both national and international impacts of climate change) could imply a further 1.1% loss of GDP, while agriculture could halve its direct contribution to the economy (LSE et al., 2022). Other macroeconomic estimates of similar temperature changes suggest UK GDP losses of more than 30% by 2100, (Cambridge Econometrics calculation, based on (Burke & Tanutama, 2019) in a 2.8°C scenario). This specific value is excluding acute risks (i.e. extreme natural disasters such as floodings or droughts) so it could be a conservative estimate.

Table 5.1: Summary of recent estimates of the macroeconomic impacts of climate change

Approach / Study	Physical risk	Impact	Geographical scope
Burke et al. (2018).	Increase in temperature between 2.5ºC and 3ºC compared to preindustrial levels.	Reduction in global GDP of 10% by the middle of the century, and 15-25% by the end of the century.	Global.
FUND model	Increase in temperature between 2.5ºC and 3ºC compared to preindustrial levels.	GDP losses of less than 2.5%.	Global.
LSE (2022)	Increase in temperature of 2.9ºC compared to preindustrial levels, under policies currently enforced.	7.4% of UK's GDP loss by 2100.	UK.
Cambridge Econometrics based on Burke-Tanutama (2019)	Increase in temperature by 2.8ºC compared to preindustrial levels.	More than 30% GDP loss by 2100.	UK.

The following table structures and summarises the different modelling approaches which are covered in further detail throughout the chapter:

Table 5.2: Summary of the existing approaches to estimate macroeconomic impacts of climate change

Broad category of model	Model type	Description	Assumptions	Models	Example application of model or model manual	Indicators produced
Integrated Assessment Models (IAMs) integrate inter-disciplinary information and describe the human (economy, energy) and earth (climate) systems to provide a quantitative description of them such that environmental assessments can be conducted (UNCC).	**Cost-benefit IAMs.**	Cost-benefit IAMs produce aggregated results through welfare optimization, determining emissions abatement at different steps.	Assumptions include an inelastic labour supply, or certain functional shapes for particular variables (for example, a linear specification for consumption).	DICE, DSICE.	(Cai et al., 2012)	Level of emissions or temperature in the atmosphere, capital, consumption or income.
	IAMS with detailed energy system and land use; general equilibrium (GE) models.	These models offer climate-economy results for multiple markets, not allowing for market unbalances and assuming perfect rationality of the economic agents.	Perfect rationality of economic agents. General equilibrium across markets is reached.	IMAGE, GCAM.	(PBL Netherlands Environmental Assessment Agency, 2020) (Joint Global Change Research Institute, 2022)	Indicators for energy, land, water and other natural resources.
	IAMS with detailed representations of energy systems and land use; partial equilibrium (PE) models.	These models offer climate-economy results, considering a particular market, which reaches perfect equilibrium, and assuming perfect rationality of the economic agents.	Similar assumptions related to the optimisation of economic agents' behaviour as in GE models apply.	DIVA.	(Hinkel & Klein, 2009)	Flooding, total erosion, indirect erosion, sea-level rise, wetland change, tourism, climate damage and adaptation measures cost.

	Computable general equilibrium (CGE).	These models offer multi-sector and multi-regional analysis but rely on strong assumptions based on optimal behaviour of economic agents.	Assumptions underlying agents' behaviour may slightly differ from GE or PE approaches, for instance with different consumption and investment patterns for individuals.	G-CUBED, GEM-E3.	(Ciscar et al., 2011)	Effect of climate change on GDP and welfare. Disaggregation by different sectors: mining, agriculture or manufacturing. GEM-E3 can also report distributional effects across the economy.
	Stock-flow consistent IAMs.	Stock-flow consistent IAMs are aggregated models of climate change and the monetary economy. The model introduces monetary aspects as the interaction across the systems (climate/environment and economy) is represented by transactions (flows) of the specific assets (stocks).	Assumptions include full utilisation of capital, or no inflation in the theoretical derivations.	Stock-flow consistent IAMs.	(Bovari et al., 2018)	Labour market indicators, environmental damage, production, wages, temperature change.

Other models accounting for climate-economy relationships.	**Macro-econometric climate-economy models.**	Produces multi-sectoral and regional results as the CGE models described above, however, these models are econometrically calibrated, contrary to the theoretical and strong assumptions behind CGE models such as optimal behaviour or perfect equilibrium across markets.	Optimising behaviour and full utilisation of resources are not part of the requirements of the model. Endogenous money.	E3ME.	(Cambridge Econometrics, 2021a)	GDP, GVA, international trade by sector origin and destination, consumer prices and expenditures, sectoral employment, unemployment, energy demand, CO_2 emissions by sector and fuel, material demands.
	Growth models.	Models usually used for estimating economic growth but accounting for climate extensions.	The models rely on different assumptions such as inelastic labour supply or persistent climate change impacts (the impact of a particular year depends on previous year impact).	FUND, PAGE.	(Waldhoff et al., 2012)	Damage potential and social cost of different gases such as sulphur hexafluoride, methane or nitrous oxide.

	Agent-based models.	These models account for heterogeneous agents and reduce the number of underlying assumptions underlying CGE models. They represent climate and economic relationships through relationships between individual agents' (a bottom up approach) allowing for this behavioural heterogeneity.	High complexity of the model, which hinders the explanation and understanding of the results.	Agent-based models.	(Lamperti et al., 2018)	Output, energy demand, level of emissions, atmospheric concentration of CO_2.
	Input-output (IO) models.	These models are generally more simple representations of economic reality through interdependencies across sectors.	One of the shortcomings of these models is the short-run focus characterising them. Inter-sectoral dependencies are assumed to be fixed, weakening the long-run estimations.	Input-output (IO) models.	(Koks & Thissen, 2016)	Loss of welfare caused by a natural disaster.
	Econometric studies.	These studies focus on assessing the physical risks and climate impacts on macroeconomic outcomes such as GDP or consumption based on past relationships.	Underlying assumptions relevant to the baseline (e.g., population forecasts) and the assumptions underlying the OLS estimator such as a	ClimatePREDICT, Burke et al. (2015).	Ortec Finance and Cambridge Econometrics (2023).	Impact of natural disasters on economic indicators.

			linear relationship of the specification.			
	Natural catastrophe models and micro-empirical studies.	These models assess bottom-up damages from climate change applying spatially and probabilistic estimators.	Assumptions accounting for the spatial relations/climate impact.	Natural catastrophe models and micro-empirical studies.	(Burke et al., 2018)	GDP, avoided damages.
Modified standard macro-economic models constitute more complex versions of CGE models or macro-econometric models with specific applications	**DSGE models.**	These models are similar to CGE models, but they include dynamic relationships instead of static the approach of the former. They also rely on optimal behaviour assumptions.	Optimal behaviour of economic agents.	DSGE models.	(Cantelmo et al., 2023)	Output, private investment, public investment, tax rate, consumption, public debt.
	E-DSGE.	Similar framework to the DSGE models presented above, but also accounting for negative externalities from production as these factors are introduced in the model relationships through costs onto consumers.	Similar to DSGE models.	E-DSGE.	(Heutel, 2012)	Optimal environmental policy response to business cycles.

	Large-scale econometric models.	Similar to macro-econometric or econometric studies described above. However, large-scale econometric approaches often have higher levels of aggregation than macro-econometric models, while requiring higher amounts of data than econometric studies.	Scenario assumptions (for instance population projections or climate policy remains unchanged).	NiGEM.	(Vermeulen et al., 2021)	Supervisory ratios (banking supervision ratios), assets per sector, bond prices, equity prices.

Source (s): Cambridge Econometrics own elaboration. Based on NGFS (2020) and Piontek (2021).

5.2 Existing approaches for estimating and quantifying macroeconomic effects of climate change

As the wide range of estimates shows, quantifying climate change impacts remains a challenging task, as it involves a number of uncertainties and a broad set of interdependent and complex variables. The different economic models reviewed in the following sections attempt to tackle these complexities, and reduce the underlying uncertainty around the macroeconomic impacts of climate change. The latest research from academia, thinktanks and consultancies is analysed. The review focuses on the different approaches widely applied by policy-makers internationally and in the UK, to assess the quantitative macroeconomic impacts of climate change. Specifically, the caveats and weaknesses of the different approaches are set out, paying attention to the different assumptions and drivers of the models which ultimately determine the results of modelling analyses. Similarly, the inputs or data required, and economic indicators (outputs) produced by the approaches are addressed.

The literature review is structured mostly following the Network for Greening the Financial System (NGFS, 2020) classification for economic models to assess climate risks:

1 Integrated-climate-economy models

2 Other climate-economy models

3 Modified standard macroeconomic models

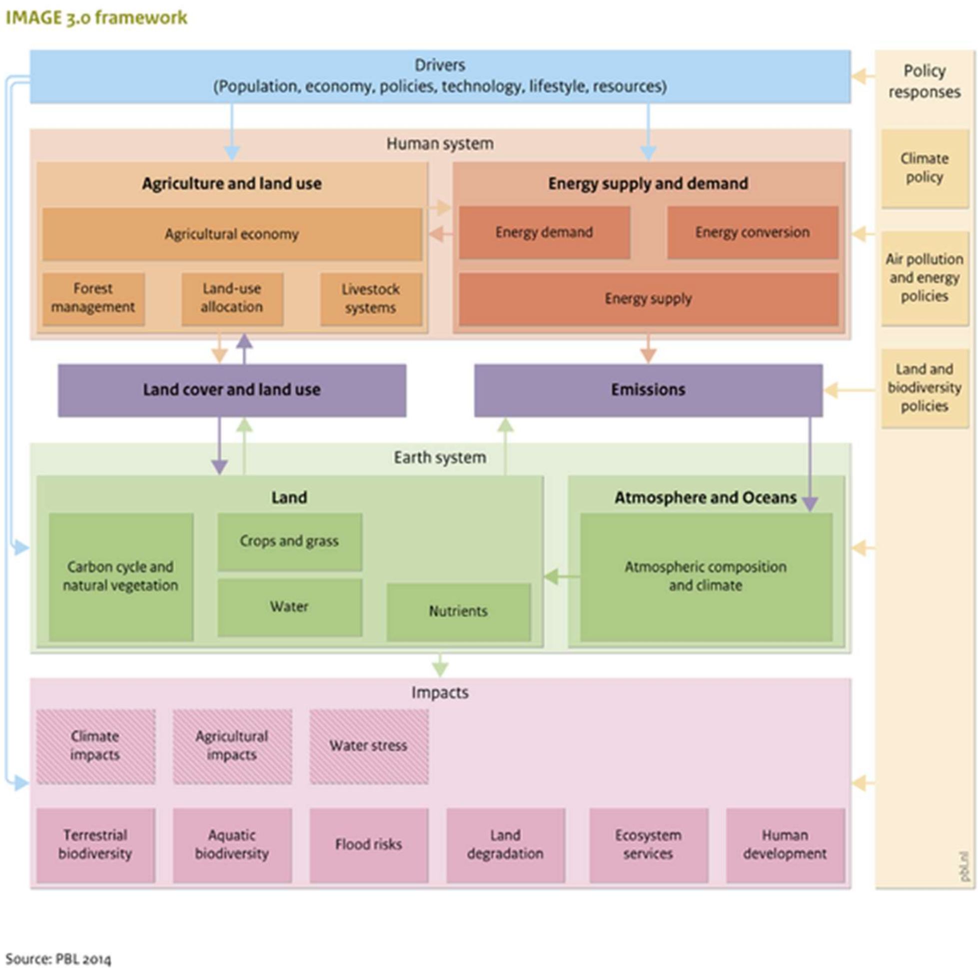
UK organisations such as the Bank of England, and The Prudential Regulation Authority work collaboratively with the NGFS, and participated in the elaboration of the classification here used (Bank of England, 2021).

5.3 Integrated climate-economy models

Integrated Assessment Models (IAMs) integrate inter-disciplinary information and describe the human (economy and energy) and earth (climate) systems to provide a quantitative description of them such that environmental assessments can be conducted (United Nations, 2023). Such models have been used by the Prudential Regulation Authority to assess the impact of climate change on the UK insurance sector. Economy, energy, and earth (climate) systems are described by multiple relationships expressed by mathematical equations, constituting the core of the model. Different assumptions underlying the model, and a given set of inputs (usually empirical data of main economic, energy and climate variables), allow the user to obtain estimated outputs. The outputs are usually projected evolutions of economic variables such as GDP or consumption, together with climate related outputs such as temperature levels or emissions.

In Figure 5.1Figure 5.4, a graphical explanation of an example IAM (IMAGE model) is shown. The model describes the economy, energy, and climate through multiple relationships, shown through arrows in the figure. Under a set of assumptions (see later in the report), this allows for the estimation of environmental, energy-related and economic variables.

Figure 5.1: Example of an IAM; IMAGE model



Source (s): Netherlands Environmental Assessment Agency

There are various forms of IAMs, which are described in the following sub-section. Depending on the underlying assumptions within IAMs, these models can be categorised as cost-benefit models, IAMs with detailed energy system and land use (general equilibrium models and partial equilibrium models), computable general equilibrium (CGE) models, and stock-flow consistent IAMs. The underlying assumptions may be related to income and transport demand for example, or related to the model estimation/calibration. These points are covered in more detail under the different model categories described below.

Cost-benefit IAMs

Cost–benefit IAMs are simple economic models that use assumptions to estimate climate mitigation costs and future climate damages. More concretely, this type of IAM typically offers aggregated results for climate and economic variables obtained through welfare optimization. Cost-benefit IAMs can evaluate possible costs, for instance of emissions abatement, and compare them with benefits associated with this emissions reduction.

One example of a cost-benefit IAM is the **DSICE model**, (Cai et al., 2012).

Modelling approach and underlying assumptions

The DSICE model maximises welfare in a cost-benefit framework as set out above. It includes random variables which represent economic and climate shocks to account for uncertainty. This offers an improvement above other cost-benefit models (e.g. DICE2007 or DICE-CJL), and also allows the model to account for annual time periods, contrary to other frameworks which work with longer time periods. In more technical terms, the DSICE model is a dynamic stochastic integrated approach together with a dynamic programming algorithm used for the model solution.

Some key assumptions of the model are an inelastic supply of labour, and certain functional shapes assumed for particular variables (for example, a linear specification for consumption). These assumptions ease the model calculations and derivations as they are simpler specifications. However, these simplifications may reduce the reliability of the final estimates. For instance, the real economic labour supply is elastic (i.e. changes to prevailing wage rates lead to more or fewer people actively participating in the labour market). Removing the inelastic labour supply assumption would generate cascading effects across other variables, and therefore lead to different estimates of economic activity as a result of any policy which changes demand for labour (and therefore wage rates).

Scope

The DSICE model estimates outcomes over the period 2020-2200. As per the geographical scope, Cai et al., (2012) estimates results for the UK economy specifically, and at higher levels of aggregation as well, e.g., global results.

Required inputs and outputs produced

The model produces outputs for the level of emissions and temperature in the atmosphere, and capital, consumption or income within the economy. In terms of model inputs, it requires time-series data for the different variables used (past values of the outputs mentioned before).

How climate change impacts are modelled

Direct climate change impacts can be modelled through tipping point shocks. In other words, exogenous shocks to model these impacts can be added. Additionally, temperature changes in the atmosphere could be also modelled in a similar way.

Application

Cai et al., (2012) developed the DSICE model and solve an example with a time scope of 600 years and considering annual time periods. They evaluate the impact of tipping points (modelled as stochastic states), for example occurring during the initial year, on variables such as capital, temperature in the atmosphere or the emission control rate.

IAMs with detailed energy system and land use; general equilibrium models

General equilibrium models (GE) assume that all markets clear (i.e. perfect equilibrium whereby supply equals demand across all the sectors), accounting for a description of the different markets in the economy. These models do not allow for unbalances between supply and demand, and perfect rationality of the economic agents is one of the main assumptions.

The **Global Change Assessment Model or GCAM**, is an example of an IAM in this category (Joint Global Change Research Institute, 2022).

Modelling approach and underlying assumptions

GCAM is a general equilibrium model integrating energy and climate systems, together with economic relationships. It also includes agriculture and land use as a specific feature of the model. Technically, it is a dynamic recursive model (results are computed one-period-at-a-time) offering results for the level of emissions, energy or trade for example.

The underlying assumptions of the model are present in terms of the socioeconomic pathways followed by the economy, for instance in terms of GDP future evolution. If the economic growth projections are not satisfied or altered (i.e. the economy experiences different growth rates than the rates assumed), the impacts of the model could be over/underestimated. Another important assumption builds on the economic rationality of economic agents. The actual behaviour of economic agents usually contradicts this assumption, and this can also alter the results of the model. For example, the behaviour of non-rational individuals could lead to the existence of business cycles or even economic bubbles, altering the evolution of GDP compared to the evolution it would follow with perfectly rational agents.

Scope

The GCAM model has a global scope, and it also produces country-level results, including for the UK, for the years between 1990-2100 at 5 year intervals.

Required inputs and outputs produced

GCAM uses time-series data for different economic variables such as income or consumption, together with energy consumption or population. It produces outputs such as future energy supply and demand, together with greenhouse gas emissions and climate effects of 16 greenhouse gases.

How climate change impacts are modelled

The physical impacts of climate change, such as increases in temperatures, could be incorporated as part of the model, for instance through an exogenous shock affecting different sectors or technologies.

Application

Calvin et al., (2019) perform several simulations using the GCAM model, obtaining results for the period 2010-2100. They estimate climate and economic evolutions under 11 different scenarios considering various socioeconomic and climate policy pathways. Some of the variables for which they project future evolutions are global water consumption and withdrawals, CO_2 concentration, income, and energy use by sector (Calvin et al., 2019).

The **IMAGE** model is another IAM, integrating a modelling framework for both human (socioeconomic) and natural (climate, environment) systems. It represents a simulation of the impact of human activities on the environment. The model follows a long-term approach, focusing on future environmental impacts, and it is built on a general equilibrium framework.

Modelling approach and underlying assumptions

The model identifies socioeconomic pathways and their implications for energy, water and other natural resources.

Some of the key assumptions of IMAGE are related to population growth or technological change under different scenarios; these are specified as part of the scenario design process. The model also assumes perfect rationality of economic agents, similarly to GCAM. These assumptions can affect the precision of the final estimates, as they fail to represent economic reality. If in fact the population projections assumed are a conservative estimate (population experiences higher growth than expected in the model), the model would likely be underestimating climate impacts, as the level of emissions predicted by the model is likely to be underestimated.

Scope

The IMAGE model reports country-specific results up to 2100 including for the UK.

Required inputs and outputs produced

IMAGE offers results for emissions, prices, energy supply and demand, and agricultural production among other variables. Historical time-series data of these indicators are needed as an input for the model.

How climate change impacts are modelled

The model would need further adjustments in terms of the interlinkages between economic and climate variables to quantify the direct impact of climate change on the economy.

Application

Doelman et al., (2018) produce regional scenarios considering the SSPs up to 2100 using the IMAGE model. They analyse the impact of climate change mitigation policies on land-use changes and land pressures. Their estimations offer high variation in the results and the degree of land used, depending on the scenario and policies followed. They offer results aggregated at the OECD countries level; however, the model could be adjusted to provide further disaggregation to obtain UK-specific results (Doelman et al., 2018).

IAMs with detailed energy system and land use; partial equilibrium models

Modelling approach and underlying assumptions

Partial equilibrium models do not account for interactions across all markets in the economy. Instead, they focus on a market or markets where a specific policy or shock occurs. Even though this approach depicts an incomplete picture of the entire economy, it also reduces the data requirements, allowing for a more straightforward modelling framework, which produces results which are typically easier to explain.

Similarly to CGE models, assumptions related to the optimization of economic agents' behaviour apply. However, the main drawback here is the partial representation of the economy, which may negatively impact the precision of the final estimates. By not considering dynamic interactions between markets, these models have the potential to miss important feedback loops related to the impacts of climate change. For instance, the relationships between the economy and climate are typically represented, but the energy components are often missing. This implies that the possible connections of the latter with the two former areas are not accounted for in the model, likely resulting in an underestimation of the impacts of climate change.

An example of the partial equilibrium approach is the **DIVA model** (Global Climate Forum, 2023). DIVA is an IAM with specific detail for coastal systems. It assesses biophysical and socioeconomic impacts of sea-level rise, focusing on adaptation costs. Coastal erosion, flooding and wetland change or salinity are also integrated into the model framework. Figure 5.2 shows a graphical representation of the different interrelationships integrated into the model framework. In this figure, the degree of complexity usually achieved by IAMs in general can be observed.

Figure 5.2: DIVA model diagram.

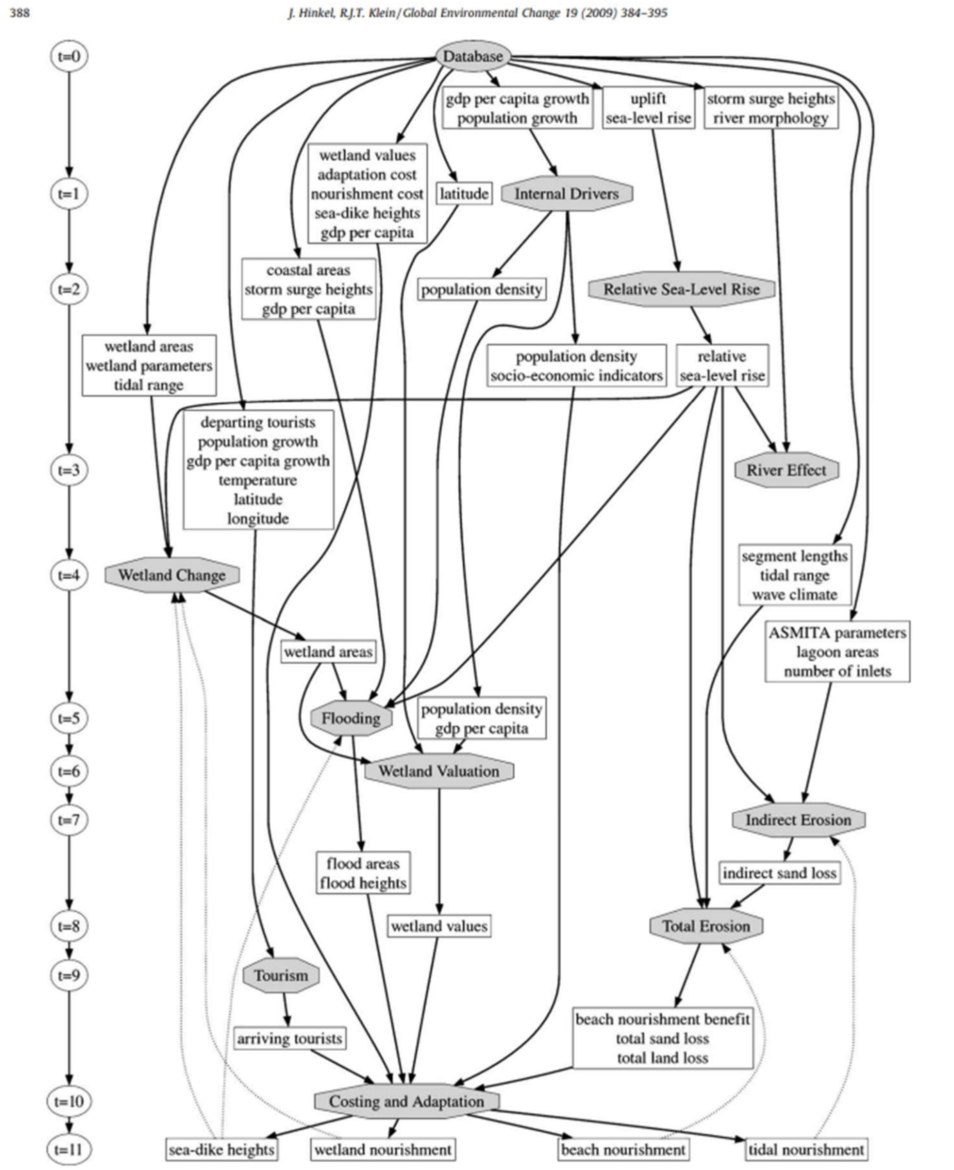


Fig. 2. Module linkages in DIVA 2.0.3. Octagons represent the modules, rectangles represent data, the solid arrows represent the flow of data during one time step, and the dotted arrows represent the data fed into the next time step.

Source(s): Hinkel and Klein (2009)

Scope The DIVA model produces results for the timeframe 2000-2100, and the geographical scope includes both global and national results, producing both aggregated results and also country-specific results, including for the UK.

Required inputs and outputs produced The model requires global biophysical and socioeconomic coastal data, regionally disaggregated data for sea-level, and socioeconomic scenarios with a time scope till 2100. It produces outputs such as number of people subject to annual flooding, erosion, wetland change and salinity intrusion.

How climate change impacts are modelled Climate change impacts are modelled through interrelationships between sea-levels and flooding risk, river effects and erosion, for example. This is then translated into economic costs and indirect effects such effects on tourism.

Application

An example application of the DIVA model is provided by Hinkel and Klein (2009); in which the DIVA model is used to assess coastal vulnerabilities to climate risks such as sea-level rise (the input of the model). The model estimates the impacts on tourism or wetland and erosion changes (Hinkel & Klein, 2009).

Bosello et al., (2012) provides another example application of the DIVA model, in which the economic costs and physical impacts derived from sea-level rise scenarios between 2020 and 2080 are estimated. The research finds that the UK could face a 1.2% land loss by 2085, and a small (i.e. less and 0.01%) loss of GDP compared to the baseline scenario (Bosello et al., 2012).

Computable general equilibrium (CGE) models

CGE approaches are large-scale (compared to lower scale GE models) numerical models which integrate various economic and climate relationships. Specifically, CGE models offer multi-sector and multi-regional analysis but rely on strong assumptions based on optimal economic agent behaviour.

G-CUBED (McKibbin & Wilcoxen, 1999) and the **GEM-E3 Model** (Capros et al., 2013) are two examples of CGE models.

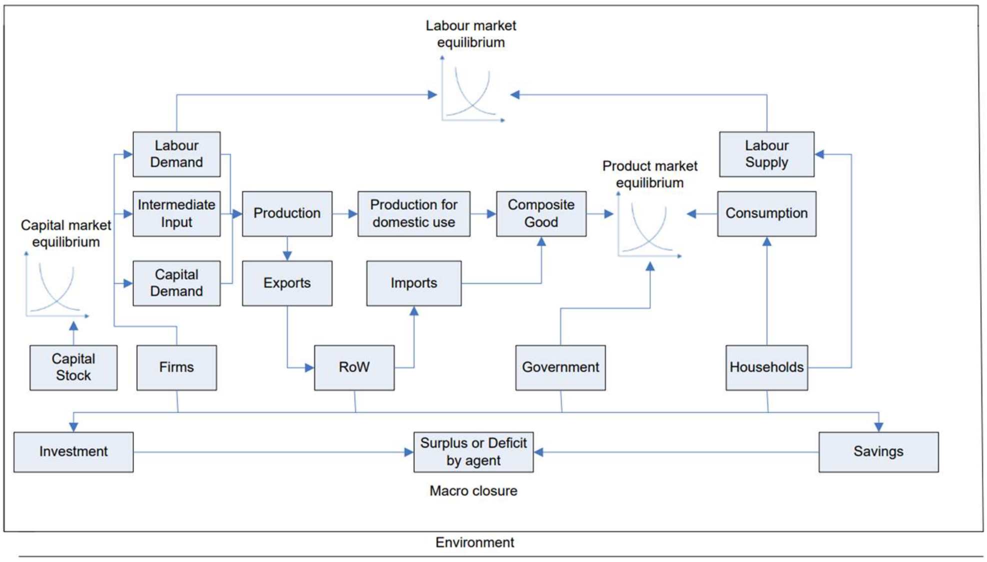
Modelling approach and underlying assumptions

Both models are specially designed to contribute to climate policy strategies and evaluations. G-CUBED integrates economic and climate variables focusing on environmental policy questions and international trade, and it also incorporates some macroeconomic aspects allowing for both long and short-term analysis. GEM-E3 is an empirical large-scale model following a GE approach, which includes some micro-economic features allowing the model to report distributional impacts as part of the results.

The assumptions behind economic agents' optimal behaviour differs slightly across both models, for instance by different consumption and investment patterns assumed. As already addressed, these assumptions of perfect rationality ease the derivation of the model. CGE models are designed to map an optimal trajectory to a pre-determined target. But these assumptions are arguably very restrictive for capturing the range of possible responses to policy changes or climate events, characterised by high uncertainty. Additionally, static general equilibrium models solve for an optimal pathway, treating each time period as independent of past or future periods. However, in reality, the energy-economy system constantly evolves, and past decisions do affect the future. This is usually the case faced by economic agents as well, as decisions like investment clearly take into account past and expected future trends.

In Figure 5.3 a graphical representation of the economic part of the GEM-E3 model is shown. The figure shows that different (perfect) equilibriums exist across all the economic markets represented (labour, capital and products). The underlying assumptions previously explained allow the represented variables to reach an equilibrium. Then, the different economic variables are integrated together with the environmental side of the model, allowing for the estimation of climate variables.

Figure 5.3: GEM-E3 Model.



Source(s): GEM-E3 Model Documentation

Scope The timescale of both GCUBED and GEM-E3 is annual, solving up to 2050. As per the geographical scope, both models produce disaggregated results for multiple regions in the world, including the UK.

Required inputs and outputs produced The input data used by the models can differ, as no specific dataset is required to calibrate the parameters of the G-CUBED model. This affects the parameters estimated within the model, and therefore the model outcomes. For GEM-E3 the GTAP database (Corong et al., 2017) is specified to be used with the model. Some of the required inputs (present in the GTAP database) include data on bilateral trade, production, consumption of commodities. The models produce results for different sectors and economic variables such as mining, agriculture or manufacturing, but the models differ in the level of disaggregation of results. GEM-E3 can also report distributional effects across the economy.

How climate change impacts are modelled Physical impacts of climate change, such as increase in temperatures or the level of emissions, can be incorporated as part of the model, for instance through an exogenous shock affecting different sectors or technologies.

Application Fragkos et al., (2021) find that the transition to climate neutrality can increase inequality across income deciles, with low-income households facing considerable negative effects. They use a multi-sectoral CGE model, GEM-E3-FIT, with income deciles incorporated to the GEM-E3 model discussed above (Fragkos et al., 2021). The results are obtained for the EU on aggregate. While the estimates for the UK alone are not offered, the model could be extended to produce results for the UK alone. Even though direct climate impacts are not assessed, these could be incorporated through different scenarios.

To estimate economic damages caused by climate change, and particularly to calculate overall welfare losses, GEM-E3 can be used. Ciscar et al., (2011) estimate that if the climate evolves following current projections, by 2080 the annual loss of household welfare in the EU would be between 0.2 and 1%. The study produces results for the UK, where the welfare loss would lie in a similar range as the EU but with higher sensitivity to the different scenarios (Ciscar et al., 2011).

The impacts of climate change on international trade have also been addressed by CGE models. The ENV-Linkages model, a dynamic CGE, offers estimates of trade impacts at the regional and sectoral level, indicating a general reduction for all economic sectors (Dellink et al., 2017). The study does not offer UK specific results, but the analysis could be extended such that estimates are produced for the UK.

Stock-flow consistent IAMs

Stock-flow consistent IAMs are aggregated models of climate change and the monetary economy. They introduce monetary aspects as the interaction across the systems (climate/environment and economy) is represented by transactions (flows) of the specific assets (stocks). Such models are consistent as the assets involved in the transactions can never exceed the stocks, which behaves as a budget constraint and enforces consistency. (Bovari et al., 2018) provides an example of a stock-flow consistent IAM.

Modelling approach and underlying assumptions

In contrast to CGE models, this stock-flow consistent IAM does not assume optimal behaviour of economic agents. Some strong assumptions are made however, such as full utilisation of capital for each period, or zero percent inflation. Similarly, these assumptions may create some biases in the outputs (for instance, it is easy to observe that the no inflation assumption is quite restrictive and could change some estimates such as investment, given the change in the real interest rate).

Required inputs and outputs produced

This specific stock-flow consistent model reads time-series data from four databases: World Bank, Penn World Tables, BIS (Bank for International Settlements) and FRED (Federal Reserve Economic Data). The model produces results for production, environmental damage, and temperature change.

Scope

The geographical scope of the model covers most developed countries, including the UK, and some emerging economies. The results produced by Bovari et al., (2018) are aggregated at a global level, however with further model development it is possible results could be further disaggregated at national levels such that UK specific estimates are obtained.

How climate change impacts are modelled

Economic damages from climate change are modelled following the environmental damage function produced by Nordhaus (2014), together with the abatement costs associated with mitigating climate change (Nordhaus, 2014).

Application

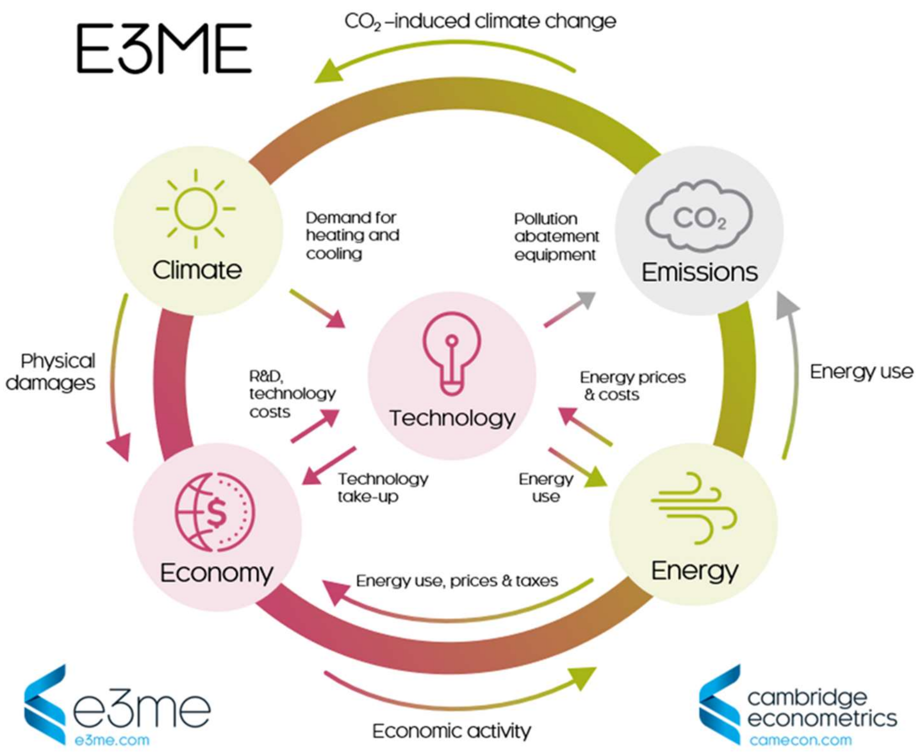
This stock-flow consistent model has been calibrated at a global level and can estimate environmental and financial risks associated with climate change. According to the model, limiting global warming to 2ºC above preindustrial levels is unachievable, and that the long-term effects of climate change can be severe. Reducing private debt levels as well as implementing optimal carbon prices are key for achieving climate and growth targets (Bovari et al., 2018).

5.4 Other climate-economy models

Macro-econometric models

Macro-econometric models incorporate various relationships existing between human (economic) systems, climate and the environment. These models usually provide high disaggregation levels, offering multi-sectoral and regional results. Compared to the GE or CGE models described above, the estimations produced by macro-econometric are based more heavily on empirical data, without relying on the strong assumptions underpinning the former approaches.

Figure 5.4: E3ME Macro-econometric model.



Source (s): Cambridge Econometrics

The **E3ME** model is an example of a macro-econometric model. It contains a regionally disaggregated representation of energy, environmental and economic systems, with a two-way linkage (interaction) between each of these systems (Cambridge Econometrics, 2021a). Figure 5.4 provides an intuitive visualisation of the model, where each arrow shows the relationship (linkage) existing between the different systems.

Modelling approach and underlying assumptions

In contrast to CGE models, optimising behaviour and full utilisation of resources are not part of the underlying assumptions of E3ME. The model also accounts for more realistic representation of the financial sector (e.g. it does not assume a fixed money supply that is fully utilised in all future time periods) and treatment of technology through the incorporation of technology diffusion models (the Future Technology Transformation sub-models) (Cambridge Econometrics, 2023). On the other hand, macro-econometric models rely on relationships and trends empirically observed in past data, implying that future trends would continue to follow these historical trends (Lucas, 1976).

The model is widely used by British, European and global institutions to assess climate change mitigation policies.

Required inputs and outputs produced

The model requires empirical data as inputs for key economic and climate variables such as income or employment or historical levels of GHG emissions. It produces highly disaggregated outputs for GDP, government expenditure, GVA or international trade, sectoral employment, wages, together with CO_2 emissions by sector and fuel, energy demand, energy prices and material demands among others. Distributional impacts can be implicitly calculated within the model.

Scope

E3ME produces very detailed results, disaggregated to a high level of granularity. The main dimensions of E3ME are 71 global regions, including all G20 economies treated individually (including the UK) and EU Member States explicitly, plus a set of regions to meet global totals, 43 economic sectors in each region, with additional detail in European countries, and a timeframe covering 1970-2070 on an annual basis.

How climate change impacts are modelled

GDP damages due to climate change (gradual physical risks) are estimated in an off-model approach that combines environmental outcomes from E3ME and the literature on the relationship between global temperature change and GDP impacts. Other physical impacts of climate change can also be incorporated as part of the model to assess specific risks, for instance through an exogenous shock affecting different sectors or technologies. E3ME, being a demand-driven model, does not currently include feedback loops between climate impacts (implying major structural supply-side constraints) and economic growth.

Application

E3ME has been used to analyse the impact of the net-zero transition in the UK (Cambridge Econometrics, 2020). This project analysed the economic impacts in the UK of moving towards a net-zero carbon economy by 2050. It produced estimates over different variables such as GDP, inflation or trade. The model also projected the evolution for multiple sectors such as agriculture, manufacturing, transport or services.

For other examples see the E3ME blog of Cambridge Econometrics (Cambridge Econometrics, 2021b, 2021c).

Growth models

The **FUND**, (Waldhoff et al., 2012), and **PAGE** models (Hope, 2013), are two additional approaches which can be considered as **growth models**. Economic **growth models** are typically used to analyse the underlying factors behind the growth of a particular economy. For instance, they can be used to quantify the impact on economic growth of a particular technology or change in employment level. These models can also be extended such that they also integrate climate (earth) and energy systems together with the economy.

Modelling approach and underlying assumptions

Growth models rely on different assumptions such as inelastic labour supply or persistent impacts of climate change (the impact of a particular year depends on the impacts in the previous year). In the case of persistent impacts from climate change, the uncertainty following acute risks, together with potential adaptation policy measures enforced, could cast doubt on this persistency assumed, and affect the precision of the final estimates. For instance, a low presence of acute risks could imply that the model overestimates climate change impacts.

Scope

The timescale of the model covers 1950-2300, and the geographical scope covers 16 aggregated major world regions, for instance “Western Europe”, in which the UK is included. While individual results for the UK are not specifically produced, the approach could be further adapted or expanded to disaggregate results to such a level.

Required inputs and outputs produced

The inputs used by FUND and PAGE are CO_2 and different greenhouse gases (GHG) levels, respectively. The outputs of the two models are, in the case of the FUND model, the damages associated with different GHG emissions levels, and in the case of the PAGE model, an estimate of the social cost of CO_2.

How climate change impacts are modelled

The models do not directly estimate the impact of climate change on the economy, but the level of emissions produced by an economy and economic growth. However, climate change impacts could be incorporated into the models through interrelationships between physical risks and the economic variables included in the models.

Application

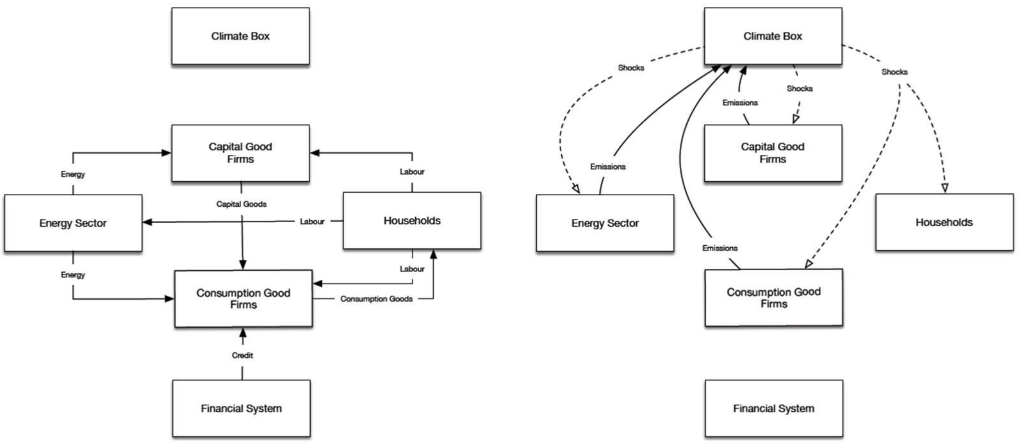
Waldhoff et al, (2012) apply the FUND model to estimate the social cost of different GHGs. The social cost for CO_2 is estimated to be $6.60 per tonne of CO_2. Given the number of underlying assumptions required to produce such estimates, different sensitivity tests are performed. These results are calculated at the global level, but the methodology could be applied to the UK in isolation.

Agent-based models

Agent-based models (ABM) account for heterogenous agents and reduce some of the underlying assumptions given by CGE models (homogeneous agents, within others). They represent climate and economic relationships through individual agents’ relationships (a bottom up approach) allowing for this behavioural heterogeneity.

An instance can be found in Lamperti et al., (2018), using a DSK (Dystopian Schumpeter Keynes) model to assess different macroeconomic options together with climate variables. The DSK approach is an agent-based IAM which integrates the economy with climate elements such as carbon and temperature dynamics. This integration can be graphically observed in Figure 5.5, with the economic flows on the left-hand side, and the climate flows on the right-hand side. Even though the flows are separated, both are interrelated, as it can be seen with the economic variables also interconnected with the climate aspect.

Figure 5.5: Agent Based Model diagram.



(a) economic flows

(b) climate flows

Source(s): Lamperti et al., (2017)

Modelling approach and underlying assumptions

These models offer a stochastic approach produced by computer simulations. The shortcomings of these models rely on their complexity, which hinders the implementation of the model for large systems and makes the explanation and comprehension of results more difficult, especially compared to more simplistic representations such as the CGE or PE models.

Application and Required inputs and outputs produced

The model used by Lamperti et al., (2018) uses time-series data for consumption, GDP or investment together with I-O data, and historical data from emissions and energy consumption. Input output data are usually produced by national governments or international organisations such as the OECD[16]. This research offers indicators for GDP, energy demand and emissions within others (Lamperti et al., 2018).

How climate change impacts are modelled

Climate impacts are modelled through exogenous shocks on labour productivity or energy efficiency, and economic agents are assumed to be rational.

Scope

The model covers a timescale up to 2100. As per the geographical scope, the model produces globally aggregated results, while country-specific results are not available. However, with further development it is possible the model could be extended so that UK specific results are produced.

How climate change impacts are modelled

Even though physical impacts of climate change are not directly accounted for by the model, they could be incorporated in the approach. For instance, through exogenous climate shocks affecting different sectors or variables such as physical capital.

Input-output models

Modelling approach and underlying assumptions

An input-output (IO) model measures the (historical) purchases of goods and services from each industry within the economy, capturing supply chain links. An initial investment or expenditure creates output in specific sectors, and the IO table is used to quantify the increase in purchases of goods and services

[16] Input-Output Tables (IOTs) 2021 ed. (oecd.org)

required to deliver that output, and consequently additional impacts further up the supply chain. One of the shortcomings of IO models is their static nature. They therefore fail to capture the dynamic impacts of climate change. The structure of inter-sectoral dependencies is assumed to be fixed, while in reality the structure will vary substantially over time, weakening the robustness of future estimations.

Required inputs and outputs produced

An IO model uses IO table data, together with additional climate variables such as emissions levels. The outputs of the models cover levels of emissions by sector, decarbonisation policies costs or welfare loss.

How climate change impacts are modelled

The climate is not directly integrated in these models as in the case of IAMs. They can however account for climate impacts by establishing additional relationships into the model.

Application & Scope

Some examples of IO modelling approaches include Liping & Bin (2010) or Koks & Thissen (2016), in which indicators of emissions by sector and loss of welfare for a Chinese city and Europe are produced respectively. The studies focus on a particular city and Europe respectively across the two examples, not offering UK-specific results. However the approaches could be feasibly replicated to obtain UK-specific results (Koks & Thissen, 2016; Liping & Bin, 2010).

Another instance of IO modelling can be found in a study carried by Greenpeace and Cambridge Econometrics, 2022, analysing the economic impacts of decarbonising household heating in the UK (Dicks & Dellaccio, 2022).

Econometric studies

Modelling approach and underlying assumptions

Econometric studies focus on assessing the physical risks and climate impacts on macroeconomic outcomes such as GDP or consumption based on past relationships. These studies differ from macro-econometric approaches as they represent simpler analysis, without trying to fully represent economic and climate systems, as in the case of the former. For instance, considering the systems described in Figure 5.4, an econometric study would focus on an specific linkage or relationship between two of the systems, whereas a macro-econometric approach models all systems.

Burke et al., (2015) use econometric approaches to estimate economic impacts of temperature raises on indicators such as GDP per capita and economic growth. They also reports distributional impacts across the different regions analysed. In this case, some of the underlying assumptions include the baselines assumed and the assumptions underlying OLS (Ordinary Least Squares) estimator such as the linear relationship of the specification (Burke et al., 2015). This could result in a biased estimator if, for example, the relationship were in fact following a non-linear shape or they failed to account for all relevant variables determining GDP.

Relying on historic data to predict future impacts of climate change also has limitations. These studies will fail to capture the non-linear impacts of temperature on economic outcomes, and will not consider potential autonomous adaptation action that may occur in an economy as the impacts of climate change worsen.

Scope

The econometric models addressed do not offer UK-specific results, but they could be feasibly replicated to produce UK-specific estimates. As per the time scale, these models offer results for the 2020-2100 time range.

Required inputs and outputs produced

Econometric studies often produce outputs for different economic variables such as GDP per capita or energy consumption, requiring the past values of these variables together with the temperature changes as inputs to the model.

Climate change impacts

Climate change impacts are modelled thorough various interrelationships between climate and economic variables incorporated in the model.

Applications

Kalkuhl and Wenz (2020) study the effects of historic climate impacts on different variables such as economic growth or productivity, using annual panel models with long-difference and cross-section regressions. The geographical scope of the study is wide, with global and regional coverage, including the UK. They find that productivity levels are negatively affected by increases in temperature, and that an increase of mean surface temperature by 3.5ºC would shrink global economic output by 7-14% by 2100 (Kalkuhl & Wenz, 2020).

Dell et al, (2012) apply another econometric model to assess the impact of temperature shocks on economic growth. The analysis follows the methodology derived in Bond et al., (2010). Using historical temperature data across different countries the study finds that the effect of temperature shocks is higher in poor countries and that shocks can also negatively affect growth together with output levels (Bond et al., 2010; Dell et al., 2012). Finally, climate shocks may have indirect effects across sectors and political stability. The approach is global, however disaggregated results could be feasibly replicated for the UK.

The **ClimatePREDICT** model is another approach which can be used for estimating acute physical risks, producing estimates of climate-adjusted GDP after acute physical events. The model is specifically focused on financial losses, incorporating the relationships between weather risks, physical assets and different financial elements such as mortgages, real-state or capital market returns. See for instance Ortec Finance and Cambridge Econometrics (2023). The model uses specific data for estimated acute climate risks, for instance temperature anomalies or sea level data (Ortec Finance, 2023).

It covers 154 countries worldwide producing estimates up to 2100. Different assumptions apply for the relationships between climate and economic variables, for instance the parameters describing impact of temperature levels on different economic sectors (such as real estate). In reality, the parameters are unknown, so certain assumptions about the size of these parameters need to be made. The ClimatePREDICT produces outputs for variables such as mortgages risks, real-estate evaluation or capital market returns.

Natural catastrophe models and micro-empirical studies

Modelling approach and underlying assumptions

Natural catastrophe models and micro-empirical studies assess bottom-up damages from climate change. They have higher levels of spatial granularity (geographic disaggregation) than the models previously outlined, so they can produce estimates for highly disaggregated variables, while also allowing for the aggregation of results to higher levels afterwards. Technically, these models apply spatial and probabilistic estimators to account for possible geographic correlations.

Application

Hsiang et al. (2017) is an example of this approach, where the effect on different sectors and production associated with an increase in temperatures is analysed. The research also reports distributional impacts across the population. In this case, further assumptions accounting for the spatial relations between the variables and climate impacts exist. These result in higher data requirements which may constrain the application of the model (Hsiang et al., 2017).

Scope

The model produces indicators for US economy between the years 2020 and 2099. The UK is not covered in the example above, however it is possible that the approach could be replicated for the UK.

Required inputs and outputs produced

This natural catastrophe model uses data country-level GDP per capita data of 165 countries (1960-2010) from the World Bank's Development Indicators, and temperature and precipitation data from the University of Delaware (Matsuura & Willmott, 2012; World Bank, 2023). The outputs produced include economic variables such as GDP or consumption, together with economic damages avoided following the emission mitigation targets of the UN.

How climate change impacts are modelled

The model uses a probabilistic framework to incorporate climate change, and estimates the impacts through different panel regressions using empirical time-series data.

5.5 Modified standard macro-economic models

Dynamic Stochastic General Equilibrium (DSGE) models

Modelling approach and underlying assumptions

DSGE models are similar to CGE models, but they include dynamic relationships instead of the static (i.e. a particular/given period) approach followed by CGE models. This means they try to incorporate economic agents' expectations in the model to account for the influence of current trends in the future. The approach also tries to incorporate climate shocks through the inclusion of a stochastic (random) variable. While DSGE models are an improvement to CGE models in their treatment of temporal relationships, DSGE approaches still make restrictive assumptions about the optimal behaviour of economic agents' and equilibrium across all markets.

Application

Golosov et al., (2014) and Cantelmo et al., (2023) are two instances of the application of DSGE models, calculating the optimal Pigouvian tax and the relationship between climate change and economic development respectively. Both rely on standard, often restrictive, microeconomic assumptions such as optimal decision rules taken by economic agents or capital depreciation.

Scope

The first of these DSGE models has a global geographical scope, producing results at global aggregation levels. Even though UK-specific results are not provided, it is possible the approach could feasibly be replicated or extended for the UK, producing UK-specific results (Golosov et al., 2014). The model solves for the time period 2010-2120. The latter DSGE model can offer results for 100 years intervals (e.g., 2020-2120) and similarly has a global geographical scope. Again, it is possible that the model could be feasibly replicated or extended to produce UK-specific results (Cantelmo et al., 2023).

Required inputs and outputs produced

Both are theoretical papers involving these approaches, however they would both need time-series data from economic variables such as GDP, consumption or taxes as inputs. The models could produce different outputs such as projections for economic variables and levels of emissions or temperature in the atmosphere.

How climate change impacts are modelled

The two DSGE models integrate climate change impacts through exogenous shocks affecting various economic variables, and apply a micro-econometric framework to estimate these impacts.

Environmental-Dynamic Stochastic General Equilibrium (E-DSGE)

Modelling approach and underlying assumptions

The approach and assumptions underlying E-DSGE models constitute a similar framework to the DSGE models presented above, however, E-DSGE models also account for negative externalities from production. These negative externalities are introduced in the model through costs incurred by consumers.

Application

Heutel (2012) provides an example of this approach, studying the relationship between environmental policy and business cycles in the US, with similar assumptions to DSGE applied.

Scope

US economy data is used within the calibration of the model. Economic parameters are obtained from the real business cycle (RBC) literature (Tallarini, 2000) and the climate parameters are obtained from climate literature (reference) in a similar way (Fischer & Springborn, 2011). Heutel (2012) offers results for a 100-year time range (e.g., 2020-2120). The model does not produce UK results specifically, however it is possible the approach could be extended and applied to the UK (Heutel, 2012).

Required inputs and outputs produced

Economic time-series data such for indications such as output, capital and consumption are required, together with CO_2 emissions data as inputs. The model also builds on Nordhaus (2008) for an abatement cost function and a pollution damages function. The outputs produced by the model focus on the effect of business cycles on GDP and carbon emissions. Based on the results offered by the model, Heutel (2012) concludes that optimal policies should allow carbon emissions to follow a procyclical evolution (i.e. allowing higher levels of emissions with higher economic growth), and a similar reasoning to climate-related tax rates applies (i.e. higher taxes on emissions with higher economic growth).

How climate change impacts are modelled

The model does not specifically assess economic impacts of climate change but instead assesses the optimal responses of environmental policy to business cycles. However, the approach could be extended to incorporate climate change shocks and link them to business cycles (Heutel, 2012).

Large-scale econometric models

Modelling approach and underlying assumptions

Similar to macro-econometric or the econometric studies described above, large-scale econometric models include dynamic demand and supply equations with coefficients calibrated using historical data and econometric methods. However, large-scale econometric approaches often have higher levels of aggregation than macro-econometric models, while requiring higher amounts of data than econometric studies.

Application

The National Institute of Economic and Social Research in the UK are using and developing large-scale econometrics models, for instance the NiGEM model (National Institute Global Econometric Model (National Institute of Economic and Social Research, 2023).

An example of the application of the NiGEM model is provided by Vermeulen et al., (2021). The paper assesses the climate risks and impacts from a financial perspective, producing economic indicators for assets, the supervisory ratios (ratios used in banking supervision to assess the sustainability of different financial institutions) equity prices, bonds or corporate loans. This research relies on assumptions for the expected evolution of certain variables such as carbon prices or future consumption patterns (Vermeulen et al., 2021).

Scope

The NiGEM model has been applied to the Netherlands, however it is possible it could be extended to the UK, to provide UK-specific results. The timescale offered can vary, but it usually covers short-term periods of time.

Required inputs and outputs produced

This particular application uses bond and equity holdings together with cross-sectoral data and climate scenarios as inputs. The outputs produced cover supervisory ratios, assets per sector, bond prices and equity prices within other financial data.

How climate change impacts are modelled

The NiGEM econometric model is used by Vermeulen et al, (2021) to estimate the financial and economic effects of climate risks in the Netherlands. The authors produce scenarios for the effects of energy transition policies, however the direct physical risks and economic effects could be integrated into the model in a similar way. They find negative impacts for all financial sectors, and a reduction in the global stock market of up to 12% under the worst case scenario. Such analysis could be replicated for the UK's economy.

5.6 Solutions for addressing major uncertainties in macroeconomic modelling of climate change

As previously outlined, there are multiple sources of uncertainty around both the extent of, and impact of climate change, making economic modelling of climate change a challenging exercise.

Climate change risks

Following the taxonomy employed by the Bank of England, climate change can present physical and transition risks (Batten, 2018). The former risks can also be divided into gradual global warming and extreme weather events (or chronic and acute physical risks in the current discourse). Even though gradual global warming can be more predictable to some extent, the problem lies with the rise in average temperature levels beyond what has been observed in historical data, as well as with extreme weather events. Extreme weather events are natural catastrophes with relatively low likelihood (although expected to become more frequent in the future) but high localised economic impacts. Given the unpredictable nature of this type of risks, most of the models do not, or cannot, account for them. There is a remaining weak bridge between natural sciences research and economic analysis. This is common across most of the models presented in the literature, and it remains a gap to be filled by further research.[17]

Discount rates

Discount rates constitute a key component of the uncertainty underlying climate and economic modelling (Batten, 2018). Discount rates are particularly important in the assessment of climate change impacts due to the nature of climate change. The economic impacts of climate change become catastrophic in the second half of this century and persist for centuries into the future. The use of specific discount rates has been subject to intense debate given the complexity these rates involve, and the substantial impact they have on model results and the conclusions drawn. Discount rates are subject to both normative (value judgement) and positive (quantification/measurement) economic questions.

Discount rates commonly enter in the form of model assumptions. They can be disaggregated in two different components: time preference, and economic growth or marginal utility (Heal & Millner, 2013). Subject to modelling needs, these the time and the economic growth component may be considered separately (Goulder Roberton C Williams III et al., 2012).

The temporal preference component of the discount rate is subject to ethical considerations, such as intergenerational equity (Batten, 2018; Stern et al., 2022). First, a value judgement (normative consideration) is needed for an agreement whether to include this subjective component or not. Second, if included, this component would need to be measured (positive consideration). This component is sometimes referred to as 'social discount rate'. Macroeconomic models do not generally use these rates. These tools are specifically designed to assess economy-wide conditions and not account for individual preferences or values.

The economic growth or marginal utility component of the discount rate often covers all the aspects affecting investors, such as financial risks or interest rates. This finance-equivalent discount rate offers an empirical-based approach which attempts to account for pure market considerations (e.g. the cost of capital). Macroeconomic models often rely on this treatment of the discount rates, as this measurement approach can offer a more objective and accurate representation of the reality according to the goal of these models - trying to capture the full picture of the economy.

Including dynamics

Finally, different pitfalls across the models exist when including dynamics in the relationships represented. Economic relationships can often be path dependent, and past choices have an influence on the present or future trajectories of the economic variables (Grubb et al., 2021). However, general equilibrium or partial equilibrium models assume temporal independence

[17] Acute physical risks tend to have a large local economic impact, but their aggregate, macroeconomic impacts appear to be relatively small. Highly granular, asset level physical risk indicators lead to small macroeconomic impacts when aggregated. One possible factor which could aggrevate the macroeconomic impact of acute physical risks are cases when multiple perils take place in a short period of time, compounding their individual damages (eg. when floods and droughts, as well as wildfires hit an economy within a season or a year). However, since historical weather observations suggest that the likelihood of such co-incidense of multiple events is very low, such compounding affects are typically not modelled in most publicly available scenarios.

across the different variables. This results in representations of the economy which might fail to capture the underlying uncertainties of both climate and economy, and this temporal independence also constitutes an assumption which has been proven to be false. This can be specifically seen while accounting for capital formation or the evolution of innovation. For instance, even though most of the models treat technological change as an exogenous variable, to better reflect reality models should treat innovations endogenously. Failing to do this may lead to an inaccurate level of innovation which has consequences for productivity and other variables. The same applies to capital inertia (the evolution of capital), which many models have failed to adequately represent. In reality, unlike in the models, technology adoption typically follows a non-linear path, with non-stationary elasticities of demand.

The Lucas Critique argues that macro-econometric models misrepresent economic reality, as they place too much weight on past observations in projecting future trends, and ignore the endogeneity of responses to the policy environment (e.g. agents adjust expectations based on what they observe or predict) (Lucas, 1976). However, these points can also constitute one of the strengths of macro-econometric models, given the path-dependency structure of many economic variables and relationships. Macro-econometric models take into account past relationships (path dependencies) across time, and some have a more realistic representation of many economic variables such as innovation or capital formation. Additionally, as they do not build in pure microeconomic assumptions, macro-econometric approaches can indirectly account for heterogeneous preferences, and different returns to scale. Similarly, in relation to the innovation and capital inertia previously mentioned, the dynamic relationships represented by these models can offer a more reliable representation of economic reality than approaches like CGE or PE models do.

5.7 Concluding remarks

Modelling climate impacts on the economy is a difficult task. The parameters describing climate-economic relationships are largely unknown, so addressing effects such as feedback loop impacts constitutes an intricate exercise. On the other hand, the uncertainty of climate change, and its different degrees of impact (chronic or acute) impose a challenge while trying to model the aggregated impact on the economy. Nevertheless, a wide range of economic models trying to tackle this challenge exist. Depending on the specific contexts, some models may be more suitable, and different assumptions underlying the models apply. This eventually leads to the existence of multiple estimates for the macroeconomic impact of climate change, both globally and in the UK. **There is no perfect model, but depending on the specific situations, and policy exercises, these tools can positively contribute in terms of policy-making and understanding climate-economic systems.**

In this brief summary, the three groups of models previously addressed are discussed, offering some key points and aspects covering their assumptions and economic indicators studied.

Integrated climate-economy models

This group consists of a wide range of models, differing in the approach and assumptions made. Firstly, *IAMs with detailed energy system and land use (GE and PE models) and CGE models*, rely on perfect optimisation of economic agents' behaviour, together with perfect equilibrium across markets. These assumptions usually simplify these models, but they can generate biased estimates, as the assumptions might be too restrictive. Some applications of such IAMs range from analysing the effect of climate change on GDP and welfare, to the effect climate change on water and other natural resources. *Stock-flow consistent IAMs* rely on assumptions such as full utilisation of capital, while producing estimates for environmental damage or temperature change given the economic activity.

There is a wide spectrum of approaches within the category of integrated climate-economy models**. Depending on the specific requirements of an analysis, and the existing constraints, some models may be more appropriate than others.** In the case of data availability constraints, GE or PE and CGE models may be valid candidates for modelling the macroeconomic impacts of climate change. **When the required data is available, approaches with empirical macro-econometric foundations may constitute a better choice**, as they usually offer a more accurate representation of economic reality, and the different relationships of the model are empirically tested. Additionally, these approaches can account for path dependencies and dynamics within economic variables, overcoming one of the limitations of static approaches such as GE and PE.

One of the drawbacks present in all these approaches, however, is that direct climate impacts, and acute risks specifically, are not usually directly accounted for. These can be integrated into them through additional specifications of climate variables (e.g. temperatures, or CO_2 emissions), and their impact on economic variables (e.g. income, investment). Afterwards, exogenous shocks can be a way to represent either gradual (chronic) impacts, or extreme (acute) impacts.

Other climate-economy models

Macro-econometric models attempt to overcome the drawbacks of the previous models by econometrically calibrating the different parameters using large panel databases for GDP, investment and other economic variables. This results in higher data and computing needs, but more realistic representations of the systems modelled. Climate change impacts can be incorporated into macro-econometric approaches through integrating physical risks at a sectoral level for instance. Macro-econometric models also allow for a more granular sectoral and regional breakdown, as well as more explicit modelling of policies at a detailed level, as opposed to models which proxy the decarbonisation effort with a shadow price for carbon. **These levels of high granularity can be reached in macro-econometrics models, whereas they are more difficult to model in closed-form equilibrium models**, such as the models discussed under the category of integrated climate-economy models.

Growth models can account for climate change impacts and climate variables while using a well-known or standard theoretical economic background. They rely on assumptions such as inelastic labour supply or persistency of climate change across time. These models can be a good option if a comparison with other growth models is needed, both at the climate or economic level. *Agent-based models* account for heterogeneous agents compared to the homogeneity assumed by CGE or PE models. This assumption can be less restrictive, however, it may still be insufficient for a realistic representation of economic reality. Agent-based models have been applied to measure energy demand, or the atmospheric concentration of CO_2. These models can be an optimal option to look at individual heterogeneity, while assuming higher levels of complexity at the same time.

Input-output (IO) models offer a simple representation of economic reality, while relying on the strong assumption that intersectoral dependencies remain constant across time. This can lead to inaccurate estimates if these dependencies are in fact time-variant. I-O models can be applied to calculate the loss of welfare caused by a natural disaster. I-O models can serve as a straightforward modelling option, in which exogenous shocks representing climate change impacts, (either gradual or extreme), can be added.

The *econometric studies models* rely on functional assumptions (such as linear specifications for the different variables). They can also be used to estimate the impact of natural disasters on economic indicators while accounting for lower amounts of data and levels of granularity than macro-econometric approaches.

Natural catastrophe models and micro-empirical studies can compute GDP and damages after natural catastrophes. As they usually include spatial (geographical) characteristics of the observations, the model specification accounts for possible spatial interlinkages (correlations) across the variables. If the model fails to properly account for these relationships, it could be mis specified. This approach offers an alternative to specifically account for extreme (acute) climate change impacts on the economy. However, as these models are usually event and time specific (they are applied to a particular catastrophic event, at a particular time and place), the models may lack external validity (i.e. the results cannot be extrapolated to other events or geographical places).

Modified standard macro-economic models

Modified standard macro-economic models usually constitute more complex versions of CGE models or macro-econometric models with specific applications. For instance, the *DSGE or E-DSGE models* rely on assumptions about optimal behaviour of economic agent's while including dynamic relationships and negative externalities respectively. Major economic indicators such as public debt or investment can be analysed, as well as specific aspects such as environmental policy and business cycles.

Large-scale econometric models such as the NiGEM model can be used to assess climate impacts on financial stability (e.g. supervisory ratios or bond prices), relying on similar assumptions to those of macro-econometric models.

DSGE or E-DSGE models constitute good alternatives to CGE models since they account for more realistic representations of the economic relationships as a larger time-horizon is considered. E-DSGE has an added advantage over the DSGE model in that it can specifically accounting for the measurement of externalities. However, the drawbacks of assumptions about rational behaviour and perfect equilibrium across markets remain.

5.8 Key takeaways

- There are multiple and different models producing results for the macroeconomic impacts of climate change across different indicators and sectors, and with a wide geographical scope (including the UK).
- The existence of these different approaches and their respective assumptions, results in widely varying estimates of the macroeconomic impact of climate change. Furthermore, the complex nature of climate change and (sometimes too restrictive) assumptions underlying the approaches add another layer of difficulty for interpreting and relying on the results of modelling exercises. These challenges lead to uncertainty and difficulty for policy- and decision-makers.
- Overall, the evidence shows that the macroeconomic impacts of climate change are expected to be negative for most of countries worldwide, including the UK.
- The literature and modelling approaches covering acute risks is scarce compared to approaches addressing gradual or chronic impacts of climate change. Quantifying these extreme impacts remains a gap to be filled with further research.
- The discount rate assumed by the models is subject to discussion as it is a key component affecting the results of the model. The time preference component of the discount rate relies on ethical assessments and a normative (subjective) judgement. However, for climate-economy policy exercises, the use of empirical, market-based discount rates is recommended.
- **No perfect method for estimating the macroeconomic impacts of climate change exists given the underlying uncertainties of both climate and economic variables. Furthermore, different models may constitute a good choice under different circumstances and policy exercises. This will ultimately depend on the resources available (e.g. data or skillset of analysts), or the specific points of interest (economic/climate variables, specific impacts, country studied).**
- **Ideally, the most robust model would be an enhanced IAM which has empirical properties of macro-econometric models, detailed treatment of climate from climate specific models, and micro-foundations (depicting individual preferences and behaviours) from agent-based models. Such a combination currently does not exist in any single approach, however linking existing models with the relevant properties under a coherent framework could provide an imminent solution.**

References

Admiraal, J. (2015). *Discourses about economic valuation of biodiversity in Europe: An application of Q-Methodology*.

Ahrens, P. (2015). *Qualitative Network Analysis: A Useful Tool for Investigating Policy Networks in Transnational Settings?* https://ecpr.eu/Events/Event/PaperDetails/22818

Alam, S. J., & Geller, A. (2012). Networks in agent-based social simulation. *Agent-Based Models of Geographical Systems*, 199–216. https://doi.org/10.1007/978-90-481-8927-4_11/COVER

Armatas, C. A., Venn, T. J., & Watson, A. E. (2014). Applying Q-methodology to select and define attributes for non-market valuation: A case study from Northwest Wyoming, United States. *Ecological Economics*, *107*, 447–456. https://doi.org/10.1016/J.ECOLECON.2014.09.010

Bank of England. (2021). *Climate-related financial risk management and the role of capital requirements: Prudential Regulation Authority Climate Change Adaptation Report*.

Bank of England. (2023). *Results of the 2021 Climate Biennial Exploratory Scenario (CBES)*. https://www.bankofengland.co.uk/stress-testing/2022/results-of-the-2021-climate-biennial-exploratory-scenario

Bastin, L., & Longden, D. M. (2009). Comparing transport emissions and impacts for energy recovery from domestic waste (EfW): Centralised and distributed disposal options for two UK Counties. *Computers, Environment and Urban Systems*, *33*(6), 492–503. https://doi.org/10.1016/J.COMPENVURBSYS.2009.05.003

Batten, S. (2018). *Climate change and the macro-economy: a critical review*. https://www.bankofengland.co.uk/working-paper/2018/climate-change-and-the-macro-economy-a-critical-review

Baudry, G., Macharis, C., & Vallée, T. (2018). Range-based Multi-Actor Multi-Criteria Analysis: A combined method of Multi-Actor Multi-Criteria Analysis and Monte Carlo simulation to support participatory decision making under uncertainty. *European Journal of Operational Research*, *264*(1), 257–269. https://doi.org/10.1016/J.EJOR.2017.06.036

Ben-Haim, Y. (2006). *Info-Gap Decision Theory: Decisions Under Severe Uncertainty - - Google Könyvek*. https://books.google.hu/books?hl=hu&lr=&id=yR9H_WbkIHkC&oi=fnd&pg=PP1&dq=Ben-Haim,+Y.+(2006).+Info-gap+decision+theory:+Decisions+under+severe+uncertainty+(2nd+ed.).+London:+Academic+Press.&ots=9jiSHNxh_Y&sig=vPEmxTXfFIynXnQAKxnrgUBrpuo&redir_esc=y#v=onepage&q&f=false

Ben-Haim, Y. (2010). Info-Gap economics: An operational introduction. *Info-Gap Economics: An Operational Introduction*, 1–245. https://doi.org/10.1057/9780230277328/COVER

Berkhout, F., van den Hurk, B., Bessembinder, J., de Boer, J., Bregman, B., & van Drunen, M. (2013). Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments. *Regional Environmental Change 2013 14:3*, *14*(3), 879–893. https://doi.org/10.1007/S10113-013-0519-2

Better Evaluation. (n.d.). *Key informant interviews | Better Evaluation*. Retrieved June 19, 2023, from https://www.betterevaluation.org/methods-approaches/methods/key-informant-interviews

Better Evaluation. (2022). *Qualitative impact assessment protocol | Better Evaluation*. https://www.betterevaluation.org/methods-approaches/approaches/qualitative-impact-assessment-protocol

Bhave, A. G., Conway, D., Dessai, S., & Stainforth, D. A. (2016). Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world. *Climate Risk Management*, *14*, 1–10. https://doi.org/10.1016/J.CRM.2016.09.004

Bond, S., Leblebicio-Lu, A., & Schiantarelli, F. (2010). Capital accumulation and growth: a new look at the empirical evidence. *Journal of Applied Econometrics*, *25*(7), 1073–1099. https://doi.org/10.1002/JAE.1163

Borsuk, M. E., Mavrommati, G., Samal, N. R., Zuidema, S., Wollheim, W., Rogers, S. H., Thorn, A. M., Lutz, D., Mineau, M., Grimm, C., Wake, C. P., Howarth, R., & Gardner, K. (2019). *Deliberative multiattribute valuation of ecosystem services across a range of regional land-use, socioeconomic, and climate scenarios for the upper Merrimack River watershed, New Hampshire, USA*. *24*(2). https://doi.org/10.5751/ES-10806-240211

Bosello, F., Eboli, F., & Pierfederici, R. (2012). Assessing the Economic Impacts of Climate Change - An Updated CGE Point of View. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.2004966

Bovari, E., Giraud, G., & Mc Isaac, F. (2018). Coping With Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, *147*, 383–398. https://doi.org/10.1016/J.ECOLECON.2018.01.034

Brander, L. (2013). *Guidance Manual on Value Transfer Methods for Ecosystem Services*

Brown, I., & Berry, P. (2022). National Climate Change Risk Assessments to inform adaptation policy priorities and environmental sustainability outcomes: a knowledge systems perspective. *Climatic Change*, *175*(3–4). https://doi.org/10.1007/S10584-022-03464-2

Burke, M., Davis, W. M., & Diffenbaugh, N. S. (2018). *Large potential reduction in economic damages under UN mitigation targets*. https://doi.org/10.1038/s41586-018-0071-9

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature 2015 527:7577*, *527*(7577), 235–239. https://doi.org/10.1038/nature15725

Burke, M., & Tanutama, V. (2019). *Climatic Constraints on Aggregate Economic Output*. https://doi.org/10.3386/W25779

Cai, Y., Judd, K. L., & Lontzek, T. S. (2012). DSICE: A Dynamic Stochastic Integrated Model of Climate and Economy. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.1992674

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Yiyun Cui, R., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., Mcjeon, H., Smith, S. J., Snyder, A., … Wise, M. (2019). GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, *12*(2), 677–698. https://doi.org/10.5194/GMD-12-677-2019

Cambridge Econometrics. (2020). *Economic impact of the Sixth Carbon Budget*. www.camecon.com

Cambridge Econometrics. (2021a). *E3ME*. https://www.e3me.com/

Cambridge Econometrics. (2021b). *Modelling the regional impacts of low-carbon transition - E3ME*. https://www.e3me.com/2021/10/11/regional-impacts-just-transition/

Cambridge Econometrics. (2021c). *Switzerland's energy system: How E3ME worked with STEM, the Swiss energy system model - E3ME*. https://www.e3me.com/2021/06/16/e3me-stem-linkage-swiss-industry/
Cambridge Econometrics. (2023). *FTT - Future Technology Transformations*. https://www.e3me.com/what/ftt/
Canevari, L. (2019). *UK: Climate change and the macro-economy | PreventionWeb*. https://www.preventionweb.net/news/uk-climate-change-and-macro-economy
Cantelmo, A., Melina, G., & Papageorgiou, C. (2023). Macroeconomic outcomes in disaster-prone countries. *Journal of Development Economics*, *161*, 103037. https://doi.org/10.1016/J.JDEVECO.2022.103037
Capros, P., van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S., Charalampidis, I., & Revesz, T. (2013). GEM-E3 Model Documentation. *JRC Technical Reports*, 1–154. https://doi.org/10.2788/47872
Chilton, S., Jones-Lee, M., Metcalf, H., Nielsen, J. S., Baker, R., Donaldson, C., Mason, H., Mchugh, N., Mcdonald, R., Spackman, M., Moore, M., & Bateman, C. (2020). *A scoping study on the valuation of risks to life and health: the monetary value of a life year (VOLY)*.
Ciscar, J. C., Iglesias, A., Feyen, L., Szabó, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O. B., Dankers, R., Garrote, L., Goodess, C. M., Hunt, A., Moreno, A., Richards, J., & Soria, A. (2011). Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 2678–2683. https://doi.org/10.1073/PNAS.1011612108/-/DCSUPPLEMENTAL
Corong, E. L., Hertel, T. W., McDougall, R. A., Tsigas, M. E., & van der Mensbrugghe, D. (2017). The Standard GTAP Model, Version 7. *Journal of Global Economic Analysis*, *2*(1), 1–119. https://doi.org/10.21642/JGEA.020101AF
Crowder, George. (2021). *Problem of value Pluralism: Isaiah Berlin and beyond.* ROUTLEDGE. https://www.routledge.com/The-Problem-of-Value-Pluralism-Isaiah-Berlin-and-Beyond/Crowder/p/book/9781032085227
Daron, J. (2015). Challenges in using a Robust Decision Making approach to guide climate change adaptation in South Africa. *Climatic Change*, *132*(3), 459–473. https://doi.org/10.1007/S10584-014-1242-9/METRICS
Decuypere, M. (2020). Visual Network Analysis: a qualitative method for researching sociomaterial practice. *Qualitative Research*, *20*(1), 73–90. https://doi.org/10.1177/1468794118816613/ASSET/IMAGES/LARGE/10.1177_1468794118816613-FIG2.JPEG
Defra. (2020). *Accounting for the Effects of Climate Change Supplementary Green Book Guidance*.
Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, *4*(3), 66–95. https://doi.org/10.1257/MAC.4.3.66
Dellink, R., Hwang, H., Lanzi, E., & Chateau, J. (2017). *International trade consequences of climate change*. https://doi.org/10.1787/9f446180-en
Department for Communities and Local Government. (2009). *Multi-criteria analysis: a manual*. www.communities.gov.ukcommunity,opportunity,prosperity
Dessai, S., & Hulme, M. (2007). Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change*, *17*(1), 59–72. https://doi.org/10.1016/J.GLOENVCHA.2006.11.005
Diaz, D., & Moore, F. (2017). *Quantifying the economic risks of climate change*. https://doi.org/10.1038/NCLIMATE3411
Dicks, J., & Dellaccio, O. (2022). *The economic impact of decarbonising household heating in the UK in an era of high fossil fuel prices Economic impacts of decarbonising heating in residential buildings 2*. www.camecon.com

Doelman, J. C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D. E. H. J., Neumann-Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., & van Vuuren, D. P. (2018). Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change*, *48*, 119–135. https://doi.org/10.1016/J.GLOENVCHA.2017.11.014

Downing, T. E., Moss, S., & Pahl-Wostl, C. (2000). *Understanding Climate Policy Using Participatory Agent-Based Social Simulation*. 198–213. https://doi.org/10.1007/3-540-44561-7_15

Durbach, I. N., & Stewart, T. J. (2012). Modeling uncertainty in multi-criteria decision analysis. *European Journal of Operational Research*, *223*(1), 1–14. https://doi.org/10.1016/J.EJOR.2012.04.038

Fischer, C., & Springborn, M. (2011). Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *Journal of Environmental Economics and Management*, *62*(3), 352–366. https://doi.org/10.1016/J.JEEM.2011.04.005

Flum, M. R., Siqueira, C. E., DeCaro, A., & Redway, S. (2010). Photovoice in the workplace: A participatory method to give voice to workers to identify health and safety hazards and promote workplace change-a study of university custodians. *American Journal of Industrial Medicine*, *53*(11), 1150–1158. https://doi.org/10.1002/AJIM.20873/ABSTRACT

Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., & Charalampidis, I. (2021). Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. *Energy*, *237*, 121591. https://doi.org/10.1016/J.ENERGY.2021.121591

Gersonius, B., Nasruddin, F., Ashley, R., Jeuken, A., Pathirana, A., & Zevenbergen, C. (2012). Developing the evidence base for mainstreaming adaptation of stormwater systems to climate change. *Water Research*, *46*(20), 6824–6835. https://doi.org/10.1016/J.WATRES.2012.03.060

Gigerenzer, G., & Brighton, H. (2009). Homo Heuristicus: Why Biased Minds Make Better Inferences. *Topics in Cognitive Science*, *1*(1), 107–143. https://doi.org/10.1111/J.1756-8765.2008.01006.X

Gigerenzer, G., & Gaissmaier, W. (2010). Heuristic Decision Making. *Https://Doi.Org/10.1146/Annurev-Psych-120709-145346*, *62*, 451–482. https://doi.org/10.1146/ANNUREV-PSYCH-120709-145346

Gilbert, N. (2004). *Agent-based social simulation: dealing with complexity*.

Global Climate Forum. (2023). *DIVA Model – Global Climate Forum*. https://globalclimateforum.org/portfolio-item/diva-model/

Global Evaluation Initiative. (2021). *Horizontal evaluation | Better Evaluation*. https://www.betterevaluation.org/methods-approaches/approaches/horizontal-evaluation

Global Evaluation Initiative. (2022). *Mixed methods in evaluation part 2: exploring the case of a mixed-method outcome evaluation - Blog post on Better Evaluation*. https://www.betterevaluation.org/blog/mixed-methods-evaluation-part-2-exploring-case-mixed-method-outcome-evaluation

Golosov, M., Hassler, J., Krusell, P., & Tsyvinski, A. (2014). Optimal Taxes on Fossil Fuel in General Equilibrium. *Econometrica*, *82*(1), 41–88. https://doi.org/10.3982/ECTA10217

Goulder Roberton C Williams III, L. H., Goulder, L. H., & Williams III, R. C. (2012). *The Choice of Discount Rate for Climate Change Policy Evaluation*. https://doi.org/10.3386/W18301

Groves, D., Bloom, E., Fischbach, J. R., & Knopman, D. (2013). Adapting to a Changing Colorado River: Making Future Water Deliveries More Reliable Through Robust Management Strategies. *AGUFM*, *2013*, H41K-1407. https://ui.adsabs.harvard.edu/abs/2013AGUFM.H41K1407G/abstract

Groves, D. G., & Lempert, R. J. (2007). A new analytic method for finding policy-relevant scenarios. *Global Environmental Change*, *17*(1), 73–85. https://doi.org/10.1016/J.GLOENVCHA.2006.11.006

Groves, D. G., & Sharon, C. (2013). Planning tool to support planning the future of coastal louisiana. *Journal of Coastal Research*, *67*(SPEC. ISSUE), 147–161. https://doi.org/10.2112/SI_67_10/177813/PLANNING-TOOL-TO-SUPPORT-PLANNING-THE-FUTURE-OF

Grubb, M., Wieners, C., & Yang, P. (2021). Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation. *Wiley Interdisciplinary Reviews: Climate Change*, *12*(3). https://doi.org/10.1002/WCC.698

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Heal, G., & Millner, A. (2013). *Uncertainty and decision in climate change economics*. http://www.cccep.ac.uk.

Heutel, G. (2012). How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Review of Economic Dynamics*, *15*(2), 244–264. https://doi.org/10.1016/J.RED.2011.05.002

Hinkel, J., & Klein, R. J. T. (2009). Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. *Global Environmental Change*, *19*(3), 384–395. https://doi.org/10.1016/J.GLOENVCHA.2009.03.002

HM Treasury. (2020). *Magenta Book Central Government guidance on evaluation*.

HM Treasury. (2021). *The Economics of Biodiversity: The Dasgupta Review*.

HM Treasury. (2022). *The Green Book Central Government Guidance on Appraisal and Evaluation*. www.gov.uk/official-documents

Hope, C. (2013). Critical issues for the calculation of the social cost of CO2: Why the estimates from PAGE09 are higher than those from PAGE2002. *Climatic Change*, *117*(3), 531–543. https://doi.org/10.1007/S10584-012-0633-Z/TABLES/3

Horton, D., Akello, B., Aliguma, L., Bernet, T., Devaux, A., Lemaga, B., Magala, D., Mayanja, S., Sekitto, I., Thiele, G., & Velasco, C. (2010). Developing capacity for agricultural market chain innovation: Experience with the 'PMCA' in Uganda. *Journal of International Development*, *22*(3), 367–389. https://doi.org/10.1002/JID.1694

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D. J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K., & Houser, T. (2017). Estimating economic damage from climate change in the United States. *Science*, *356*(6345), 1362–1369. https://doi.org/10.1126/SCIENCE.AAL4369/SUPPL_FILE/AAL4369_HSIANG_SM.PDF

Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of The Total Environment*, *409*(19), 3578–3594. https://doi.org/10.1016/J.SCITOTENV.2011.06.022

IPBES. (2023). *Deliberative valuation | IPBES secretariat*. https://www.ipbes.net/deliberative-valuation

IPCC. (2001). *Climate Change 2001: Synthesis Report: Q5*. https://archive.ipcc.ch/ipccreports/tar/vol4/011.htm

IPCC. (2021). *CCRA3 Glossary*.

IPCC. (2022). Global Warming of 1.5°C: Summary for Policy Makers. In *Global Warming of 1.5°C*. Cambridge University Press. https://doi.org/10.1017/9781009157940.001

Isacs, L., Kenter, J. O., Wetterstrand, H., & Katzeff, C. (2023). What does value pluralism mean in practice? An empirical demonstration from a deliberative valuation. *People and Nature*, *5*(2), 384–402. https://doi.org/10.1002/PAN3.10324

Jeuken, A., & Reeder, T. (2011). Short-term decision making and long-term strategies: how to adapt to uncertain climate change Examples from the Thames Estuary and the Dutch Rhine-Meuse Delta. *Water Governance*, *1*, 29–35. https://doi.org/10.1002/wcc.64

Joint Global Change Research Institute. (2022). *GCAM v4.2 Documentation: Global Change Assessment Model (GCAM)*. https://jgcri.github.io/gcam-doc/v4.2/

Kalkuhl, M., & Wenz, L. (2020). The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management*, *103*, 102360. https://doi.org/10.1016/J.JEEM.2020.102360

Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., & Shah, A. (2014). *Agreeing on Robust Decisions: New Processes for Decision Making Under Deep Uncertainty by Nidhi Kalra, S. Hallegatte, Robert Lempert, Casey Brown, Adrian Fozzard, Stuart Gill, Ankur Shah :: SSRN*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2446310

Kelemen, E., & Saarikoski, H. (2014). *METHOD FACTSHEET Deliberative valuation*. www.openness-project.eu

Kenter, J. O., Reed, M. S., & Fazey, I. (2016). The Deliberative Value Formation model. *Ecosystem Services*, *21*, 194–207. https://doi.org/10.1016/J.ECOSER.2016.09.015

Khirfan, L., & Peck, M. L. (2021). Deliberative Q-method: A combined method for understanding the ecological value of urban ecosystem services and disservices. *MethodsX*, *8*, 101547. https://doi.org/10.1016/J.MEX.2021.101547

Kiker, G. A., Bridges, T. S., Varghese, A., Seager, P. T. P., & Linkov, I. (2005). Application of multicriteria decision analysis in environmental decision making. *Integrated Environmental Assessment and Management*, *1*(2), 95–108. https://doi.org/10.1897/IEAM_2004A-015.1

Kim, K., Ha, S., & Kim, H. (2017). Using real options for urban infrastructure adaptation under climate change. *Journal of Cleaner Production*, *143*, 40–50. https://doi.org/10.1016/j.jclepro.2016.12.152

Koks, E. E., & Thissen, M. (2016). A Multiregional Impact Assessment Model for disaster analysis. *Economic Systems Research*, *28*(4), 429–449. https://doi.org/10.1080/09535314.2016.1232701/SUPPL_FILE/CESR_A_1232701_SM3178.DOCX

Korteling, B., Dessai, S., & Kapelan, Z. (2013). Using Information-Gap Decision Theory for Water Resources Planning Under Severe Uncertainty. *Water Resources Management*, *27*(4), 1149–1172. https://doi.org/10.1007/S11269-012-0164-4/TABLES/3

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., & Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, *22*(4), 807–822. https://doi.org/10.1016/J.GLOENVCHA.2012.05.005

Kwakkel, J. H. (2020). Is real options analysis fit for purpose in supporting climate adaptation planning and decision-making? *Wiley Interdisciplinary Reviews: Climate Change*, *11*(3). https://doi.org/10.1002/wcc.638

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., & Sapio, A. (2018). Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. *Ecological Economics*, *150*, 315–339. https://doi.org/10.1016/J.ECOLECON.2018.03.023

Lempert, R. J., & Collins, M. T. (2007). Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches. *Risk Analysis*, *27*(4), 1009–1026. https://doi.org/10.1111/J.1539-6924.2007.00940.X

Lempert, R., Kalra, N., Peyraud, S., Mao, Z., Tan, S. B., Cira, D., & Lotsch, A. (2013). *Ensuring Robust Flood Risk Management in Ho Chi Minh City*. World Bank Policy Research Working Paper, (6465). https://papers.ssrn.com/abstract=2271955

Linquiti, P., & Vonortas, N. (2012). THE VALUE OF FLEXIBILITY IN ADAPTING TO CLIMATE CHANGE: A REAL OPTIONS ANALYSIS OF INVESTMENTS IN COASTAL DEFENSE. *Climate Change Economics*, *3*(2). https://doi.org/10.1142/S201000781250008X

Liping, J., & Bin, C. (2010). An Input-output Model to Analyze Sector Linkages and CO2 Emissions. *Procedia Environmental Sciences*, *2*, 1841–1845. https://doi.org/10.1016/J.PROENV.2010.10.195

Lorig, F., Johansson, E., & Davidsson, P. (2021). Agent-based Social Simulation of the Covid-19 Pandemic : A Systematic Review. *JASSS: Journal of Artificial Societies and Social Simulation*, *24*(3). https://doi.org/10.18564/JASSS.4601

LSE, Imperial College London, University of Exeter, University of Leeds, & University of Delaware. (2022). *What will climate change cost the UK? Acknowledgements*. www.lse.ac.uk/grantham

Lucas, R. E. (1976). Econometric policy evaluation: A critique. *Carnegie-Rochester Conference Series on Public Policy*, *1*(C), 19–46. https://doi.org/10.1016/S0167-2231(76)80003-6

Maniatakou, S., Berg, H., Maneas, G., & Daw, T. M. (2020). Unravelling Diverse Values of Ecosystem Services: A Socio-Cultural Valuation Using Q Methodology in Messenia, Greece. *Sustainability 2020, Vol. 12, Page 10320*, *12*(24), 10320. https://doi.org/10.3390/SU122410320

Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M., & Popper, S. W. (2019). Decision Making under Deep Uncertainty. *Decision Making under Deep Uncertainty: From Theory to Practice*, 405. https://doi.org/10.1007/978-3-030-05252-2

Mason, E. (2023). *Value Pluralism (Stanford Encyclopedia of Philosophy)*. https://plato.stanford.edu/entries/value-pluralism/

Matrosov, E. S., Woods, A. M., & Harou, J. J. (2013). Robust Decision Making and Info-Gap Decision Theory for water resource system planning. *Journal of Hydrology*, *494*, 43–58. https://doi.org/10.1016/J.JHYDROL.2013.03.006

Matsuura, K., & Willmott, J. (2012). *Terrestrial Air Temperature: 1900-2010: Gridded Monthly Time Series (version 3.01)*.

McCarthy, M. A., & Lindenmayer, D. B. (2007). Info-Gap Decision Theory for Assessing the Management of Catchments for Timber Production and Urban Water Supply. *Environmental Management 2007 39:4*, *39*(4), 553–562. https://doi.org/10.1007/S00267-006-0022-3

McKibbin, W. J., & Wilcoxen, P. J. (1999). The theoretical and empirical structure of the G-Cubed model. *Economic Modelling*, *16*(1), 123–148. https://doi.org/10.1016/S0264-9993(98)00035-2

MET Office. (2018). *Effects of climate change - Met Office*. https://www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change

Meyer, V. (2018). Decision Support on Flood Management in Complex Urban Settings. Is Risk Assessment the Right Approach or Do We Need Decision Heuristics? *Urban Transformations: Sustainable Urban Development Through Resource Efficiency, Quality of Life and Resilience*, 363–373. https://doi.org/10.1007/978-3-319-59324-1_20

Michailidou, A. V., Vlachokostas, C., & Moussiopoulos, N. (2016). Interactions between climate change and the tourism sector: Multiple-criteria decision analysis to assess mitigation and adaptation options in tourism areas. *Tourism Management*, *55*, 1–12. https://doi.org/10.1016/J.TOURMAN.2016.01.010

Morris, J., Reilly, J., Paltsev, S., Sokolov, A., & Cox, K. (2022). Representing Socio-Economic Uncertainty in Human System Models. *Earth's Future*, *10*(4), e2021EF002239. https://doi.org/10.1029/2021EF002239

Munday, P., Woolgar, M., Rees, C., Foulkes, C., Thorogood, K., Berry, A., & Davidson, C. (2020). *Interacting risks in infrastructure and the built and natural environment: Research in support of the UK's Third Climate Change Risk Assessment Evidence Report*.

National Institute of Economic and Social Research. (2023). *NiGEM Macroeconomic Model - NIESR*. https://www.niesr.ac.uk/nigem-macroeconomic-model

NGFS. (2020). *Guide to climate scenario analysis for central banks and supervisors*.

Nordhaus, W. (2014). Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, *1*(1/2), 273–312. https://doi.org/10.1086/676035

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017a). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/J.GLOENVCHA.2015.01.004

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017b). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/J.GLOENVCHA.2015.01.004

Openness Project. (n.d.). *From concepts to real-world applications: Method Factsheet Deliberative Valuation*. Retrieved June 19, 2023, from www.openness-project.eu

Ortec Finance. (2023). *Ortec Finance releases its 2023 ClimateMAPS standard climate scenario set*. https://www.ortecfinance.com/en/about-ortec-finance/news-and-events/ortec-finance-releases-its-2023-climatemaps-standard-climate-scenario-set

Papageorgiou, K., Singh, P. K., Papageorgiou, E., Chudasama, H., Bochtis, D., & Stamoulis, G. (2019). Fuzzy Cognitive Map-Based Sustainable Socio-Economic Development Planning for Rural Communities. *Sustainability 2020, Vol. 12, Page 305*, *12*(1), 305. https://doi.org/10.3390/SU12010305

Paul Watkiss Associates. (2021). *Monetary Valuation of Risks and Opportunities in CCRA3 Report to the Climate Change Committee as part of the UK Climate Change Risk Assessment 3 FINAL REPORT*.

PBL Netherlands Environmental Assessment Agency. (2020). *Model Documentation - IMAGE - IAMC-Documentation*. https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_IMAGE

Pindyck, R. S. (2013). Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, *51*(3), 860–872. https://doi.org/10.1257/JEL.51.3.860

Piontek, F., Drouet, L., Emmerling, J., Kompas, T., Méjean, A., Otto, C., Rising, J., Soergel, B., Taconet, N., & Tavoni, M. (2021). Integrated perspective on translating biophysical to economic impacts of climate change. *Nature Climate Change 2021 11:7*, *11*(7), 563–572. https://doi.org/10.1038/s41558-021-01065-y

Polasky, S., Carpenter, S. R., Folke, C., & Keeler, B. (2011). Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology & Evolution*, *26*(8), 398–404. https://doi.org/10.1016/J.TREE.2011.04.007

Porthin, M., Rosqvist, T., Perrels, A., & Molarius, R. (2013). Multi-criteria decision analysis in adaptation decision-making: A flood case study in Finland. *Regional Environmental Change*, *13*(6), 1171–1180. https://doi.org/10.1007/S10113-013-0423-9/METRICS

Quiggin, D., De Meyer, K., Hubble-Rose, L., & Froggatt, A. (2021). *Climate change risk assessment 2021 The risks are compounding, and without immediate action the impacts will be devastating*.

Radke, N., Yousefpour, R., von Detten, R., Reifenberg, S., & Hanewinkel, M. (2017). Adopting robust decision-making to forest management under climate change. *Annals of Forest Science*, *74*(2), 1–16. https://doi.org/10.1007/S13595-017-0641-2/FIGURES/5
Refsgaard, J. C., van der Sluijs, J. P., Højberg, A. L., & Vanrolleghem, P. A. (2007). Uncertainty in the environmental modelling process – A framework and guidance. *Environmental Modelling & Software*, *22*(11), 1543–1556. https://doi.org/10.1016/J.ENVSOFT.2007.02.004
Richiardi, M. G., Leombruni, R., Saam, N. J., & Sonnessa, M. (2006). A Common Protocol for Agent-Based Social Simulation by Matteo G. Richiardi, Roberto Leombruni, Nicole J. Saam, Michele Sonnessa :: SSRN. *Journal of Artificial Societies and Social Simulation*, *9*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=931875
Roca, E., Julià-Verdaguer, A., Villares, M., & Rosas-Casals, M. (2018). *Applying network analysis to assess coastal risk planning*. https://doi.org/10.1016/j.ocecoaman.2018.02.001
Roy Haines-Young, by, & Potschin, M. (2018a). *Common International Classification of Ecosystem Services (CICES) V5.1 Guidance on the Application of the Revised Structure*. www.cices.eu
Roy Haines-Young, & Potschin, M. (2018b). *Common International Classification of Ecosystem Services (CICES) V5.1 Guidance on the Application of the Revised Structure*. www.cices.eu
Ryan, L., & Dahinden, J. (2021). Qualitative network analysis for migration studies: Beyond metaphors and epistemological pitfalls. *Global Networks*, *21*(3), 459–469. https://doi.org/10.1111/GLOB.12319
Sanderson, T., Hertzler, G., Capon, T., & Hayman, P. (2016). A real options analysis of Australian wheat production under climate change. *Australian Journal of Agricultural and Resource Economics*, *60*(1), 79–96. https://doi.org/10.1111/1467-8489.12104
Scandizzo, P. L. L. (2011). Climate Change Adaptation and Real Option Evaluation. *CEIS Working Paper*, *232*. https://doi.org/10.2139/SSRN.2046955
Schulte-Rentrop, A., & Rudolph, E. (2013). A Sensitivity Study of Storm Surges Under the Conditions of Climate Change in the Elbe Estuary. *Climate Change Management*, 295–309. https://doi.org/10.1007/978-3-642-31110-9_18/COVER
Siders, A. R., & Pierce, A. L. (2021). Deciding how to make climate change adaptation decisions. *Current Opinion in Environmental Sustainability*, *52*, 1–8. https://doi.org/10.1016/J.COSUST.2021.03.017
Sneegas, G., Beckner, S., Brannstrom, C., Jepson, W., Lee, K., & Seghezzo, L. (2021). Using Q-methodology in environmental sustainability research: A bibliometric analysis and systematic review. *Ecological Economics*, *180*, 106864. https://doi.org/10.1016/J.ECOLECON.2020.106864
Sonawane, P. R., Bhandari, S., Patil, R. B., & Al-Dahidi, S. (2023). Reliability and Criticality Analysis of a Large-Scale Solar Photovoltaic System Using Fault Tree Analysis Approach. *Sustainability 2023, Vol. 15, Page 4609*, *15*(5), 4609. https://doi.org/10.3390/SU15054609
Stern, N., Stiglitz, J., & Taylor, C. (2022). The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change. *Https://Doi.Org/10.1080/1350178X.2022.2040740*, *29*(3), 181–216. https://doi.org/10.1080/1350178X.2022.2040740
Tallarini, T. D. (2000). Risk-sensitive real business cycles. *Journal of Monetary Economics*, *45*(3), 507–532. https://doi.org/10.1016/S0304-3932(00)00012-X
Thiele, G., Devaux, A., Velasco, C., & Horton, D. (2007). Horizontal evaluation: Fostering knowledge sharing and program improvement within a network. *American Journal of Evaluation*, *28*(4), 493–508. https://doi.org/10.1177/1098214007308989

UCAR. (2023). *Climate Feedback Loops and Tipping Points | Center for Science Education*. https://scied.ucar.edu/learning-zone/earth-system/climate-system/feedback-loops-tipping-points

UK Climate Resilience Programme. (2020). *OpenCLIM: Open Climate Impacts Modelling Framework -*. https://www.ukclimateresilience.org/projects/openclim-open-climate-impacts-modelling-framework/

UK Climate Resilience Programme. (2021). *Products of the UK-SSPs project -*. https://www.ukclimateresilience.org/products-of-the-uk-ssps-project/

UNFCC. (2004a). *Agent Based Social Simulation*. https://unfccc.int/files/methods_and_science/impacts_vulnerability_and_adaptation/methods_and_tools_for_assessment/application/pdf/simul.pdf

UNFCC. (2004b). *Expert Judgment*. https://unfccc.int/files/methods_and_science/impacts_vulnerability_and_adaptation/methods_and_tools_for_assessment/application/pdf/expert.pdf

UNFCC. (2004c). *Multistakeholder Processes*. https://unfccc.int/files/methods_and_science/impacts_vulnerability_and_adaptation/methods_and_tools_for_assessment/application/pdf/multi.pdf

UNFCC. (2004d). *Vulnerability Indices*. https://unfccc.int/files/methods_and_science/impacts_vulnerability_and_adaptation/methods_and_tools_for_assessment/application/pdf/vulne.pdfUnited Nations. (2023). *Integrated Assessment Models (IAMs) and Energy-Environment-Economy (E3) models | UNFCCC*. https://unfccc.int/topics/mitigation/workstreams/response-measures/modelling-tools-to-assess-the-impact-of-the-implementation-of-response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., & Winkler, H. (2014). A new scenario framework for Climate Change Research: Scenario matrix architecture. *Climatic Change*, *122*(3), 373–386. https://doi.org/10.1007/S10584-013-0906-1/FIGURES/6

Vander Bilt, L., Shrestha, P., Nowicki, A., Huber, J., Subba, A. :, Chaganti, R., Fraker, M., Godwin, C., Manome, A., & Wang, R. (2022). *Using Fuzzy Cognitive Mapping to Assess the Impacts of Climate Change on Great Lakes Ecosystem Services*

Vermeulen, R., Schets, E., Lohuis, M., Kölbl, B., Jansen, D. J., & Heeringa, W. (2021). The heat is on: A framework for measuring financial stress under disruptive energy transition scenarios. *Ecological Economics*, *190*, 107205. https://doi.org/10.1016/J.ECOLECON.2021.107205

Waldhoff, S. T., Anthoff, D., Rose, S., & Tol, R. S. J. (2012). The Marginal Damage Costs of Different Greenhouse Gases: An Application of Fund. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.1974111

Walker, W. E., Haasnoot, M., & Kwakkel, J. H. (2013). Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. *Sustainability 2013, Vol. 5, Pages 955-979*, *5*(3), 955–979. https://doi.org/10.3390/SU5030955

Watkiss, P., & Betts, R. A. (2021). *Third UK Climate Change Risk Assessment Technical Report UK Climate Risk Independent Assessment (CCRA3) Chapter 2: Method*.

Watkiss, P., Hunt, A., Blyth, W., & Dyszynski, J. (2015). The use of new economic decision support tools for adaptation assessment: A review of methods and applications, towards guidance on applicability. *Climatic Change*, *132*(3), 401–416. https://doi.org/10.1007/S10584-014-1250-9/METRICSWerners, S. E., van Slobbe, E., Bölscher, T., Oost, A., Pfenninger, S., Trombi, G., Bindi, M., & Moriondo, M. (2015). Turning points in climate change adaptation on JSTOR. *Ecology and Society*, *20*(4). https://www.jstor.org/stable/26270274

Woodward, M., Kapelan, Z., & Gouldby, B. (2014). Adaptive flood risk management under climate change uncertainty using real options and optimization. *Risk Analysis*, *34*(1), 75–92. https://doi.org/10.1111/risa.12088

World Bank. (2023). *World Development Indicators*.

6 Annex

6.1 Annex A. Long list of methods for the valuation of risks/opportunities induced by climate change

Full name	Key sources	Detailed description (based on cited source)
Qualitative Impact Assessment Protocol	Better Evaluation, 2022; Key Informant Interviews | Better Evaluation, n.d.	The Qualitative Impact Assessment Protocol collects evidence on a project's impact based on narrative causal statements, which are collected directly from individuals affected by an intervention or an event (e.g. climate change risk). Respondents are requested to reflect on the principal changes they experience in their lives. To safeguard against bias, respondents are asked to limit responses to a pre-defined recall period. Respondents are also encouraged to share what they perceive to be the main drivers of change, and to whom or what they attribute perceived changes - the method allows for the selection of multiple sources. The method does not require the identification of a control group. Evidence of attribution is identified through respondents' own accounts of causal mechanisms linking cause and effect subject to a certain set of prevalent structural circumstances. No statistical inference analysis is required to attribute causality. As is often with narrative data, findings need to be triangulated with other data - complementing qualitative or quantitative evidence relating to cause and effect. This approach can be particularly well-suited to the development of an independent reality check relating to a predetermined theory of change. This can help policy-makers to assess, learn and demonstrate the perceived impact of climate change risks. USAID (1996) highlights a number of situations in which key informant interviews can be particularly useful: "when decision-making can be achieved through qualitative and descriptive information; when it is important to gain an understanding of the perspectives, behaviour and motivations of customers and partners of an activity or project in order to explain the shortcomings and successes of an activity; when generating recommendations is the key purpose; in order to interpret quantitative data by interviewing key informants about the how and why of the quantitative findings; to help frame the issues that are relevant before designing a quantitative study."
Deliberative Valuation Method	From Concepts to Real-World Applications METHOD FACTSHEET Deliberative	Deliberative Valuation Method (DVM) offers a framework to combine several tools and techniques that have the potential to bridge citizens with academia, and overlay different science disciplines. Key assumption in DVM is that the process of valuation is a social process, during which values are discovered, constructed and reflected in dialogue. Based on this, DVM relies on a process of deliberation with different stakeholders - encourages discussion and learning - for data collection. DVM is commonly used as a method to elicit the willingness to pay for a certain change with respect to an activity of interest.

Full name	Key sources	Detailed description (based on cited source)
	Valuation, n.d.	
Deliberative Value Formation model	Kenter et al., 2016	DVF presents an extended form of a Deliberative Valuation Method. DVF offers a theoretical and methodological framework for more rigorous monetary and non-monetary deliberative valuation, enabling extensive integration of social learning and plural knowledges and values in valuation and decision-making. It focuses on how values are formed though ‘translating’ transcendental values, our principles and life goals, into more specific contextual values. Its principal contribution involves the identification of a range of potential positive (e.g. learning) and negative (e.g. social desirability bias) outcomes of deliberation and key factors that influence outcomes (e.g. ability to deliberate, institutional factors, power dynamics).
Q-methodology	Mixed Methods in Evaluation Part 2: Exploring the Case of a Mixed-Method Outcome Evaluation - Blog Post on Better Evaluation, n.d.	Q-methodology is used to investigate the perspectives of participants who represent different stances on an issue, by having participants rank and sort a series of statements. It uses the qualitative judgements of the researcher in defining the problem, developing statements to investigate the perspectives of participants (some of the statements may be developed after interviewing key informants), and selecting participants. For instance, Q-methodology can be used to examine experts'/stakeholders perspectives on the type/magnitude of the impact on the UK of climate-induced reduction in access to wheat imports from a key importing country. Q-method can provide a useful complement to a range of other evaluation metrics, such as macro and micro assessment of the expected impact of climate-induced reduction in access to wheat imports from a key importing country.

Full name	Key sources	Detailed description (based on cited source)
Deliberative Q-method	Khirfan & Peck, 2021	The deliberative Q-method combines deliberative focus groups and Q method to develop a holistic understanding of shared(group) values. The statistical anlysis of Q-method weighs competing values to better understand polarized and consensus views. Deliberative features enhance value plurality, promoting mutual learning through results that are informed by socially robust knowledge. At its core, Q-method is a flexible approach that can be used alongside other techniques, such as semi-structured interviews. In this case, Q-method can be used as a coding tool for interview data. Q-method's purpose is to understand varying attitudes with respect to a given topic (e.g. value of a given climate impact or types of expected climate impacts). It leverages on quantitative analysis techniques to identify variation in subjective perspectives. Q-method utilises a type of factor analysis to systematically identify groups that share common attitude features (factors). It identifies what individuals consider significant by prompting individuals to rank a set of subjective statements. The end result is a distribution of columns that shows what individuals consider as significant (considering frequency and relative ranking). For example, Q-methodology can be used to examine experts'/stakeholders perspectives on the type/magnitude of the impact on the UK of climate-induced reduction in access to wheat imports from a key importing country. Q-method can be a useful complement to a range of other evaluation metrics, such as macro and micro assessment of the expected impact of climate-induced reduction in access to wheat imports from a key importing country. The use of focus groups leverages on group interaction and deliberation to explore human knowledge and experiences. Deliberation helps to identify shared values and value plurality, as well as control for different forms of human communication. Q-method is a reductionist method. Rather than leveraging on representative sampling with the objective of extrapolation, it uses purposefully selected sample groups to identify key trends and opinions - e.g. climate impact experts or sector stakeholders. This leads to relatively smaller number of participants: 12-40 individuals split in focus groups. Participants are invited to perform a rank order exercise in small groups (4-8 individuals), with the help of a facilitator. Finally, the collectively performed sortings are aggregated to deduce commonalities in valuation perspectives.

Full name	Key sources	Detailed description (based on cited source)
Deliberative multiattribute valuation	Borsuk et al., 2019	Deliberative Multiattribute Valuation rests on two analytical steps: a non-monetary multiattribute value function for quantifying the relative desirability of a particular state of the world, as described by a multidimensional space of attributes that characterise the degree to which various outcomes are realised or objectives met. On this basis, this method may be a particularly useful tool for the valuation of alternative adaptation policies. With respect to risks/opportunities, it could be implemented within broader risks - direct risks if it were not for the statistical requirements of this method. The additive form of the value function suggests that there are no interactions between preferences (variables). This means that the preferences/dimensions included are compensatory - low score by one can be offset by high score in another. In practical terms, within a setting that this method is used to describe interaction among preferences for ecosystem services, the assumption would be equivalent to adoption of compensatory preferences - low provision of one ecosystem service can be offset by high provision of another - and weak sustainability - substitution between various forms of (natural) capital. In this setting, attributes need to be mutually independent and collectively exhaustive. Discursive process is used to aggregate preferences of individuals, instead of a mathematical process. Subject matter experts and stakeholders are invited to reach a collective judgment, which is then used instead of the individual preferences.

Full name	Key sources	Detailed description (based on cited source)
Qualitative Network Analysis	Ahrens, 2015	This approach is specifically designed to investigate phenomena that can be represented as a complex system of interactions - network. Qualitative Network Analysis (QNA) approaches the study and representation of networks through a qualitative perspective, this often involves the use of interviews, focus groups or literature review. The development of network maps is an essential part of QNA. Unstructured maps are free-style drawings, developed by interviewees. Thus, they reflect the individual's view on the structure of the interactions, based on own-narrative. An alternative to unstructured maps is standardised or non-standardised structured maps. Here, interviewees are presented with a fixed definition of circles or sector of circles that they are invited to populate with information. In this setting, resulting network maps of different persons are highly comparable. For instance, participants could be presented with a map of broader risk categories and the key conceptual areas and asked to introduce information relating to affected broader categories, including info relating to the value of the impact at key conceptual area level. Information could also be added with respect to the type of impact, direct, of international origin or cascade effect.

Full name	Key sources	Detailed description (based on cited source)
Dependency modelling mixed with systems mapping (framework developed for the CCRA3 report)	Munday et al., 2020	This method presents the proposed framework for the investigation of interacting risks as part of the CCRA3. It relies on two key parts. Part I, involves the use of an iterative process, which leveraged on workshop-style engagement and literature review, to develop and validate systems maps. Part II, involves the employment of Bayesian Belief Networks - here presented as Dependency models. Systems maps visually communicate the process through which a top level cause (climate variable) has a direct associated biophysical impact (effect). At the next level, the previously identified effects were treated as causes investigating whether a second degree impact (effect) can be identifeid, and so on. Dependency models provide a quantitative description of nodes and the relationship that exists between them. The nodes can take the form of climate drivers, hazardous events, or impacts. Relationships between nodes (on various states) are described using conditional probability tables that are based on event frequencies or expert judgment. In this way, dependency models can also handle uncertainty. For each node an indication of relative impact was attached, with impact values expressed in different units. The expression of overall risk was based on a weighting factor to represent equivalents between differently dimensioned parameters. For the interacting risks report, the level of detail that was deemed appropriate was between the system and assets. This was decided to allow the identification of key interdependencies between sectors and safeguard the identification of most CCRA3 descriptors. Quantitative estimates were derived using OpenMarkov, a probabilistic graphical modelling software. A reduced form of this framework could involve application between the system and broader risk categories or the conceptual areas of each broader risk category. Subject to needs, the dependency model could be used in its full form - probability table - or in a reduced form involving a mapping of interconnections and indication of relative impacts.
Fault/Event tree analysis	Sonawane et al., 2023	Fault tree analysis (FTA) present an analysis method that relies on logic diagrams for finding deductive failures. It can be used for tracing all possible key factors and branches of a given event. Event tree analysis (ETA) is another logical model for the investigation of failure and success responses. The model has a number of pathways for analysing probabilities of results and the analysis of the whole structure. Event tree analysis can be used for reviewing the effects of functions, or any error systems.

Full name	Key sources	Detailed description (based on cited source)
Fuzzy cognitive mapping	Papageorgiou et al., 2019; Vander Bilt et al., n.d.	Fuzzy cognitive maps (FCM) can be used to encode expert knowledge relating to interactions among components of a given theme. For instance, FCM can be used for the study of ecosystem components with the aim to leverage on subjective and qualitative data to draw predictions relating to the effects of an intervention on an ecosystem. FCMs are soft computing techniques that combine fuzzy logic and neural networks. They provide a relatively flexible framework for knowledge representation and reasoning. An FCM is comprised by a set of nodes (concepts), used to represent the key elements of the given system, and directed arcs (links), record the causal relationships between the nodes. A weight adjacency matrix is then used to describe the type of relationship. The matrix can be populated with numeric or ordinal values. Both the matrix and the map can be developed through literature review, or stakeholder engagement. In the event of stakeholder engagement, an aggregation techniques needs to be developed.
Visual Network Analysis	Decuypere, 2020	Visual Network Analysis (VNA) adopts the notion of 'network' as a method to trace the complex entanglements by means of which specific practices are constituted. VNA implementation requires: collection and coding of relational data; visualisation of network diagrams (through software); analysis of the form of network diagrams; and, interpretation of results based on narrative readings of the forms of the network diagrams. Results are expected to effectively communicate the effects that the different diagram forms generate for the system.
Multi-Criteria Decision Analysis	Siders & Pierce, 2021	Multi-Criteria Decision Analysis (MCDA) is a method that is similar to Cost-Benefit Analysis. They key difference between the two is that MCDA presents an explicit framework for the consideration of ordinal and nominal criteria. MCDA is best applied to assessment where value plurality needs to be considered and a single optimal solution can be expressed. For instance, MCDA can be used in cases where assessment goes beyond the monetisation of costs and benefits, with explicit accounting of non-monetary factors. MCDA attributes scores to alternative outcomes/scenarios or options on multiple criteria. This then leads to an aggregate score that is meant to inform or even identify an optimal solution. Aggregation can rely on different methods, such as Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), and Simple Additive Weighting.
Expert Judgment	UNFCC, 2004b	Expert judgment aims at the solicitation of informed opinions on a given topic from individuals with particular expertise. This approach is used to obtain a rapid assessment of the state of knowledge about a particular aspect of a given topic. It is can be used in panel or individual format.

Full name	Key sources	Detailed description (based on cited source)
Vulnerability indices	UNFCC, 2004c	Vulnerability Indices can be used to compare and incorporate social values. Within the thematic of climate change, vulnerability refers to the combination of sensitivity to climatic variations and the probability of adverse climate change, and adaptive capacity. For each of these components of vulnerability, formal indices can be constructed and combined. Methods of aggregating across sectors and scales have been developed in other contexts (e.g., the Human Development Index) and are beginning to be applied to climate change. However, substantial methodological challenges remain — in particular estimating the risk of adverse climate change impacts and interpreting relative vulnerability across diverse situations.
Multistakeholder Processes	UNFCC, 2004b	The aim of multistakeholder processes are to promote better decision making by ensuring that the views of the main actors concerned about a particular decision are heard and integrated at all stages through dialogue and consensus building. The approach supports that everyone involved in the assessment has a valid view and relevant knowledge and experience to bring to the decision-making. The approach aims to foster trust between the actors and identify solutions that provide mutual benefits.

6.2 Annex B: Detailed description of the short-listed methods which appraise adaptation policy packages and measures

Real options analysis

Description

Real options analysis (ROA) is an extension of cost-benefit analysis (CBA), which allows uncertainty to be incorporated to some extent by assessing the timing, the flexibility and future opportunities of some measures. While CBA supports decision-making deciding on which alternative to choose or whether to invest or not, ROA can answer the question of whether to invest now, later or not at all, or just a little while keeping open future opportunities for a larger investment (Kwakkel, 2020). In other words, ROA evaluate the delay of an investment and its flexible implementation, in contrast to CBA (Kalra et al., 2014).

The term 'options' refers to the ability, but not the obligation, to undertake a project with uncertain future benefits at known costs (Kalra et al., 2014). The 'real' parts refer to the fact that the value of future options is expressed in real terms (present value), which allows the comparison but requires an agreement on the value of the discount factor.

This method is suitable for situations where (1) the decisions are irreversible (e.g. infrastructural changes), (2) there is some flexibility in when the decision is implemented (e.g. in single or multiple steps), and when (3) postponing the decision allows new information to reduce the level of uncertainty, which might also affect policy implementation (Watkiss et al., 2015).

As ROA is an extension of the CBA approach, it cannot overcome some of its weaknesses. Both methods require the estimation of future probabilities, which is particularly difficult if climate change impacts need to be incorporated. Similarly, the agreement on which discount factors to apply can vary widely, taking into account the different stakeholders affected by climate adaptation measures, their preferences and risk assessments. Furthermore, the assessment of some non-monetary values is also challenging (Kwakkel, 2020). In contrast to that, ROA performs better than CBA as it is able to incorporate the value of future options, such as changing the timing of investments, changing plans at different decision-points in the future, or enabling further opportunities which could not otherwise be realised (Watkiss et al., 2015).

Although the origin of the method is the finance, it has been widely used to appraise climate adaptation measures. This is due to the fact that adaptation measures often require high-value investments, i.e. the construction of new infrastructure, such as dams against flooding, the creation of water reservoirs, or redesign of urban areas.

ROA is often not the most efficient approach to achieving policy objectives for adaptation to climate change, as it is mainly intended to be used in situations where impacts are realised only in the long term, but the method is not robust. Conversely, ROA cannot overcome the weaknesses of CBA, such as being highly sensitive to the assessment of discount factors and probabilities of future events. Adaptation to climate change requires the engagement of multiple stakeholders with widely differing preferences, and future impacts are deeply uncertain. Although ROA is designed to evaluate the value of delay and flexibility, due to poor parameter estimates, it is not well suited to achieve policy objectives with high certainty.

Implementation framework

The implementation framework of ROA is very similar to that of CBA. As such, it includes:

1. Data collection

- the identification of alternative policy measures, and their possible stages, extensions (decision points), etc.
- the assessment of different parameters, such as the probability of different future scenarios and events, or the agreement on the discount factor
- exploring of realistic future scenarios

2. The analysis

- Calculating the net present value, or the extended net present value of different alternatives and compare them[18]. The use of decision trees can be an efficient tool for understanding decision-points through visualisation and for improving the communicability of the method.

Resource requirements, time needed and inputs

To apply the ROA approach, the following inputs are required:

- different decision points for alternative policy measures
- the assumption of future scenarios (e.g. the magnitude of climate damages)
- the estimation of parameters (probabilities, discount factors, time dimension)
- the monetised costs and benefits of different measures, including the monetised assessment of non-market sectors
- in addition, an accurate evaluation method is needed to value options; there are three major families of these, such as (1) continuous time models, (2) tree- and lattice-based approaches, and (3) Monte Carlo simulation-based analyses (Kwakkel, 2020).

The resource requirements of the method are relatively high due to the need to assess probabilities and discount factors, and to identify decision – this may require (1) the involvement of experts, (2) stakeholder engagement (to agree on a balanced discount factor), and/or (3) a deep understanding of the existing literature to use realistic assumptions.

The time required to apply ROA is highly dependent on data availability, particularly for assessing of parameters and decision points. The calculation of the method can be long if a more formalised method is chosen (e.g. Monte Carlo simulation), whereas the use of decision trees is relatively simple.

Accuracy, robustness

As the essence of the method is to estimate the costs and benefits of alternative adaptation policies, the method is very accurate.

[18] Kalra et al. (2014) describes the extended NPV (ENPV) as the following (p. 11):

ENVP = Expected Net Present Value + (Value of options created – Value of options destroyed)

Conversely, the method cannot be considered to be robust as its results depend heavily on the assessment of various parameters and the outcome (when to invest, whether investment is beneficial at all) is sensitive to changes in these parameters. Even though the method assesses flexibility, this does not improve its robustness.

Usability, communication

Although the method might require some expertise to estimate different parameters, in general, its implementation is not very complicated, particularly if decision trees are applied. Moreover, it is easy to communicate its outcomes since most of the stakeholders can easily understand and compare monetised costs and benefits, while the use of decision trees is also highly communicable.

Distributional impacts, UK applicability

The method is not designed to consider different socioeconomic impacts. Monetised costs and benefits are often generalised to society as a whole; therefore, different alternatives do not take distributional impacts into account.

ROA is widely used to appraise different adaptation policy measures. It would be long to list all areas where the method has been used, therefore only a few examples are given below. Scandizzo (2011) applied ROA to assess the value of building a sea wall or to restoring mangrove forests in Mexico and found the second to be more valuable because it kept a future option open (delaying the construction of a sea wall which might not be necessary). Linquiti and Vonortas (2012) also applied ROA to appraise different adaptation strategies to sea level rise in developing countries; they found that ROA can capture the benefits of proactive adaptation and can efficiently incorporate future information, but the results were highly location-specific. Woodward et al. (2014) discussed the potential application of ROA for flood risk reduction in the Thames estuary to capture the value of future opportunities and mitigate the adverse impacts of climate change uncertainties. Other applications include urban infrastructure adaptation in Seoul, Korea (Kim et al., 2017), urban drainage adaptation in West Garforth, England (Gersonius et al., 2012), and agricultural (wheat) production adaptation in Australia (Sanderson et al., 2016).

As the above examples show, the method is widely used in different geographical areas, including the UK, and in different sectors, and therefore its applicability in the UK is not problematic.

Compatibility with the UK Green Book guidance

ROA is cross-referenced with the UK Green Book (HM Treasury, 2022, pp. 106-108) and is particularly recommended in combination with decision trees. In general, the Green Book refers to the method as an efficient way of assessing flexibility, and dealing with uncertainty which might arise from the poorly understood future impacts of climate change (p. 48).

Conclusion

Real options analysis has been designed to improve CBA approach by extending it with the evaluation of delayed decisions and the assessment of future possibilities. As a result, the method is very accurate to estimate the costs and benefits of adaptation measures compared to other methods. Additionally, the methods' outcome is easy to be communicated as most of the stakeholders can compare monetised values without deep understanding of the methodology. If the method is combined with decision tree, the use of ROA is relatively easy (however, other, more formalised options are also available, such as Monte Carlo simulation). The method has been widely applied in the literature, the adaptation of several sectors in different countries and regions, including the UK, is often evaluated by ROA. The UK Green Book recommends the use of the method explicitly.

On the other hand, the method cannot overcome the weaknesses of the CBA approach. Primarily, it is sensitive to the estimation of different parameters, such as the discount factors and probabilities of future events – this reduces robustness significantly. Furthermore, the method has relatively high resource and time requirements, as experts and different stakeholders may be involved to estimate the mentioned parameters. Considering that the method is intended to be used to appraise adaptation policy measures which have long term impacts and are often irreversible, the lack of robustness is identified as a serious drawback to achieve policy objectives.

Robust Decision Making (RDM)

Description

Robust Decision Making refers to a group of approaches which aim to support decision-making under deep uncertainty[19]. RDM helps the user to (1) identify robust strategies and (2) characterise the few deep uncertainties that are the most relevant to the choice between alternatives (D. G. Groves & Lempert, 2007). Rather than optimizing the outcome under different future scenarios, this method focusses on the robustness of different alternatives relative to each other. In other words, RDM can identify those strategies which are insensitive to all or most of the key uncertainties. However, this strategy may not be optimal in the future, but the required policy objectives will be met in (almost) all future states. RDM is also suitable for non-linearities and other threshold responses that may occur. It is also able to capture trade-offs (unlike, for instance, the precautionary principle approach) (R. J. Lempert & Collins, 2007). Other methods listed and evaluated in this report fall under the definition of this method, such as information-gap decision theory or dynamic adaptation pathways (Bhave et al., 2016).

RDM can be particularly useful for designing or appraising different adaptation policy packages, as not only is the path of global warming unknown, but the magnitude of its impacts is poorly understood. Additionally, the global warming involves tipping points and non-linearities, such as the impact of melting ice caps and glaciers on the sea level rise, the increase in the severity and frequency of extreme weather events, and so on. Adaptation measures need to perform well under these uncertain conditions, while policy-makers face with other constraints, such as budget constraints, changing socioeconomic factors, etc.

Implementation framework

This method can be implemented in five main steps (Walker et al., 2013; Kalra et al., 2014):

1. Scoping/decision structuring – in this step, exogenous uncertainties, policy options, key relationships and performance metrics are identified by stakeholders and analysts.

[19] Deep uncertainty refers to the situation where decision-makers are unable to know or agree on the system model that relates actions to consequences.

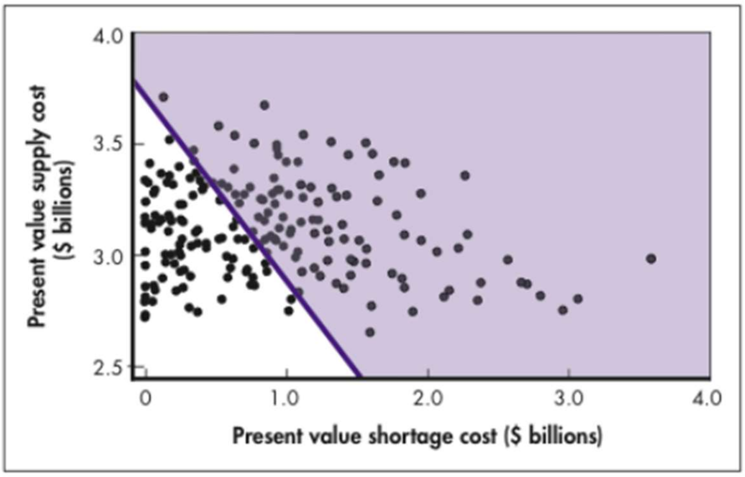
2. Simulation/case generation – in this step, analysts create and use simulation models to assess performance under multiple future states or scenarios (even under hundreds or thousands of combinations of uncertainties). It is also necessary to choose (at least) one rigorous method of evaluation: for instance, there are methods which define a robust strategy as one that (a) trades a small amount of optimal performance for less sensitivity to violated assumptions; (b) performs the best (or reasonably well) under several states of the future; (c) prioritise to have future options open (R. J. Lempert & Collins, 2007).

3. Scenario discovery – this step identifies the vulnerabilities of the strategy/policy (such as under which scenarios or combination of uncertainties would the method fail). This can be done, for instance, by visualisation or analysis.

4. Adaptation – this step explores how the vulnerabilities can be addressed, for example, by modifying existing policies or analysing new policies. Step 2-3 can then be repeated (iterated) several times.

5. Display/Trade-off analysis – finally, the trade-offs of the best alternatives can be analysed and the most robust one selected.

Figure 6.1 Robustness of the water management plan in Southern California under different future scenarios



Source: Kalra et al. (2014), p. 23

Resource requirements, time needed, inputs

This method has relatively high resource and time need compared to, for example, optimum expected utility approaches[20]. This is because it uses several representations of the future rather than a single set of probabilities. To estimate the resource and time requirements, the following aspects need to be considered:

[20] However, there are methods (using more heuristics) which can cut resource and time-need (Kalra et al., 2016)

1. how long it takes to identify exogenous uncertainties, policy options, key relationships, etc., and how easy it is for stakeholders and analysts to agree on different metrics
2. how many stakeholders are involved
3. how many future states (combinations of uncertainties) exist, and therefore, how long it takes to set-up and run the simulation
4. how many iterations are required

The required inputs include the identification of exogenous uncertainties (e.g. the magnitude of climate impacts and their costs and benefits), policy options (e.g. the alternative adaptation policy packages), key relationships, performance metrics (e.g. the increased ability of adaptation and its costs) and the need for an accurate evaluation method.

Accuracy, robustness

RDM is a very robust method in the sense that the policy can achieve one or more objectives with a relatively high degree of certainty: robustness is the essence of the method. The method is appropriate to deal with uncertainties of climate change and appraise adaptation policy packages.

However, it is not designed to estimate the costs and benefits of adaptation policies. Conversely, it does not assign probabilities to future events (it does not optimise the outcome), but rather selects the most robust alternative under deep uncertainty. Although the method is not accurate in estimating the costs of the adaptation policy, it is efficient in mitigating the risks below a certain threshold.

Usability, communication

It is relatively complex to use this method because of the wide range of policy options, uncertainties, etc. that need to be explored and the complexity of the simulation exercise. This makes the communication difficult (the understanding of the process is not easy for many of the stakeholders). However, if the necessary analysts are available, and the outcome is assessed, the method gives policymakers a clear comparison of which policy is the most robust, and it can provide strong support for their decisions. In addition to that, the comparison of different policies is easy to understand for multiple stakeholders as trade-offs can be measured and even visualised.

Distributional impacts, UK applicability

Even though the primary focus of RDM is not to include multiple socioeconomic aspects, it can incorporate one or more aspects among key relationships and performance metrics.

The method is widely used in different geographical locations, including the UK, thus its applicability in the country is high. The paper by Watkiss et al. (2015) provides a good summary of the applications of RDM in a particular sector. Based on this, Groves & Lempert (2007) used RDM to plan an urban water management system in California. Dessai & Hulme (2007) analysed the robustness of a water plan in an English water resource zone against different climate change scenarios (and found it robust). (D. G. Groves & Sharon, 2013) focussed on the coastal resilience in Louisiana, R. Lempert et al. (2013) on the flood risk management in Vietnam (in Ho Chi Minh City), and Groves et al. (2013) on the water management in the Colorado river.

More generally, the paper by Radke et al. (2017) applied the method in forestry management, while Bhave et al. (2016) and Daron (2015) used it to support climate change adaptation in developing countries and in South Africa, respectively.

Compatibility with the UK Green Book guidance

Robust decision making is directly recommended in the supplementary guidance of the UK Green Book (Defra, 2020, pp. 30–31). Furthermore, the Green Book focusses on the robustness of data (e.g. the robustness of revealed preference data), and does recommend the use of sensitivity analysis (Defra, 2020, pp. 52–54), which aims to support more robust decision-making in general.

Conclusion

The robust decision making (RBD) approach has been developed to deal with deep uncertainty and to support decision-making when the probability of future events, the scenarios and the outcomes are hard to assess. It can identify trade-offs and easily compare different alternatives. By design, the method is robust and policy objectives can be achieved with a high degree of certainty compared to other methods. However, the outcome might not be optimal in the future.

The main weaknesses of the method are its relatively high resource and time requirements. It also requires the use of some analysts. As it is a complex method involving simulation, it is not easy to use and to communicate the evolution of the results. Similarly, the method is not suitable for estimating the costs and benefits of adaptation policies, but it can mitigate potential risks below a certain threshold.

Info-Gap Theory

Description

Info-Gap (IG) is a decision theory which was developed by Ben-Haim and aims to prioritise alternatives and support decision-making under deep uncertainty (Ben-Haim, 2006; Ben-Haim, 2010). The theory has two main concepts: the robustness and the opportuneness. The first concept aims to mitigate potential risks arising from uncertainty as much as possible (e.g. due to the unknown change in processes, due to the uncertain impacts of climate change, or when updated data will be released later, but a decision has to be made now), while the second concept seizes opportunities (e.g. which adaptation policy has the greatest chance of achieving some socioeconomic goals, while still increasing the ability of adaptation above a certain extent). More formally, the robustness of an alternative refers to the greatest horizon of uncertainty on which the critical outcome is achieved. The opportuneness refers to the lowest horizon on which a better-than-anticipated outcomes can be achieved. (Marchau et al., 2019, Chapter 5) In this section, mainly robustness will be introduced.

By using the IG approach, short- and long-term decisions and the combination of them (adaptive strategies) can be made. The method can be strongly formalised and give a quantitative appraisal of alternatives, or can be implemented qualitatively, using verbal evaluation.

If a robustness approach is applied, policy objectives can be met with the highest certainty possible. In other words, robustness IG concept supports decision-making by evaluating and selecting different alternatives which are the most insensitive to the change of our current knowledge (to the *information gap*[21]).

Implementation framework

Here, again, the implementation framework of the concept of robustness is described in detail. This can be divided into the set-up of the model and evaluation (based on Marchau et al., 2019, Chapter 5).

a) The model set-up

- *The model*: the understanding and description of the system on which the policy intends to have results.
- The *performance requirement(s):* a well-defined objective or objectives which need to be achieved by the policy. Usually, analysts and decisionmakers agree upon the required or acceptable level of performance.
- The *uncertainty model*: based on IG models, it is not known how wrong (or incomplete) the estimates are, therefore it has an unbounded horizon of uncertainty surrounding the knowledge.

b) The evaluation process

1. *Putative performance*: Checking whether the policy satisfies the given criteria when things happen based on our best knowledge (i.e. the future is exactly that what currently available evidences suggests most likely). If the policy meets these criteria, it will be evaluated in the next step; if not, the policy will be excluded.
2. *Robustness*: This step assesses the robustness to. The question is how much the model could change (what is the greatest horizon of uncertainty) for the policy to still meet its objective and satisfy the initial criteria. The greater the tolerance to all types of error in the model, the higher the horizon of uncertainty within which the policy will perform as expected.

It is important to note that the IG is not an optimisation strategy which means that results might not be optimal in the future (e.g. greater risk mitigation could be achieved), but the pre-defined criteria will be met with the highest certainty possible (e.g. risk will be reduced by *x*%).

Resource requirements, time needed, inputs

The time and resources needed to apply this approach strongly depends on how it is intended to be used. For instance, qualitative, verbal evaluation can be relatively easy and rapid (but not always), while a formalised mathematical representation of the problem requires expertise and deep understanding of the method.

The inputs, which are required to set up the model, are all available and relevant information to understand the system or situation on which the policy intends to have an effect, its temporal dynamics, the evidence, the environment and any other relevant knowledge. There is a need to explore the uncertainties of available knowledge (the info-gap) and agreed criteria when the policy has a satisfactory impact (Marchau et al., 2019, Chapter 5).

[21] Formally, info-gap is is the disparity between what is known and what needs to be known for a responsible decision (Ben-Haim 2019, p. 94)

Accuracy, robustness

The IG method (particularly the robustness concept) was designed to support robust decision-making under deep uncertainty. As a result, this method is very robust and can deal with deep uncertainties arising from the unknown impacts of climate change.

Regarding its accuracy, it does not aim to estimate the costs and benefits of adaptation policy packages, rather suggests policies to mitigate certain risks to an acceptable level (or prioritise policies which can have better-than-average objectives).

Usability, communication

The usability of the method depends on how formalised the implementation is. However, translating the evidence into policy is relatively easy if the model is already set up.

In general, the method suggests a priority list of policies which satisfies the objective of the policy – this can be easily communicated. Moreover, the satisfactory criteria can be easily understood.

Distributional impacts, UK applicability

IG is a relatively flexible method and is used in several disciplines, such as engineering, economics, medicine, homeland security, public policy and biological conservation. Although distributional impacts can be incorporated, the method was not primarily designed to address this.

A few examples, including UK examples, have been identified which use IG method to evaluate adaptation policies. Korteling et al. (2013) applied the IG method for water resource planning in England and Wales, also considering potential impacts of the climate change. Matrosov et al. (2013) both used and compared robust decision making and IG theory to plan the expansion of London's water supply system in the Thames basin. McCarthy & Lindenmayer (2007) used IG approach to evaluate policy options for the revegetation of some areas in Australia.

Compatibility with the UK Green Book guidance

Robust decision making is directly recommended in the supplementary guidance of the UK Green Book (Defra, 2020, p. 30, p. 31). Furthermore, the Green Book focusses on the robustness of data (e.g. the robustness of revealed preference data), and does recommend the use of sensitivity analysis (see the Green Book, pp. 52-54), which aims to support more robust decision-making in general. As the IG approach falls under the definition of robust decision making, it is widely consistent with the Green Book, although it is not cross-referenced.

Conclusion

IG approach has been developed to support decision-making under deep uncertainty by prioritising policies which are robust and insensitive for the change of circumstances. It includes two concepts, which (1) aims to maximise the horizon of uncertainty on which a policy still achieves its objective (robustness) or (2) to prioritise those policies which might have further opportunities (opportuneness). The results of the method can be communicated relatively easily, as minimum performance requirements are easy to be understood and results are often a priority list. Furthermore, it has some easier applications when expertise is less necessary.

Its weaknesses include the relatively wide range of inputs that need to be collected, and the need to understand the system in which the policy is intended to produce results before implementation can be mentioned. If a quantitative, more sophisticated result is expected, the resource and time requirements can be relatively high.

Dynamic Adaptation Policy Pathways

Description

Dynamic Adaptation Policy Pathways (DAPP) is designed to support decision-making under deep uncertainty. It is robust (achieves its objective in most future scenarios), dynamic (includes monitoring and can incorporate new information) and adaptive (can be adjusted based on new information). The method is highly effective in appraising different adaptation policies as it was designed to deal with uncertainties arising from climate change.

It combines the advantages of some other methods, such as Adaptive Policymaking (APM), Adaptation Tipping Point (ATP), Adaptation Pathways (AP) and Robust Decision Making – moreover, the method falls under the definition of the latter one (Bhave et al., 2016). In order to understand the implementation of DAPP, APM, ATP and AP are also introduced shortly.

The DAPP method is designed to meet two main requirements: (1) to produce a robust plan and (2) to enable dynamic planning. For more details on robust planning, see Section 'Robust Decision Making'. Dynamic (robust) planning means that at certain points (at *signposts* and *triggers*) the plan should be reconsidered, and action taken to avoid failure to achieve the original objectives.

DAPP is based on the *Assumption-Based Planning (ABP)* approach. This method includes *signposts* (events or thresholds at which the vulnerable assumptions of the policy are realised and actions need to be taken), *shaping actions* (intended to control the future by mitigating risks and protecting the uncertain assumptions) and *hedging actions* (actions for the case when the assumption fails despite the implementation of the shaping action – insurance is a typical example).

APM (or Dynamic Adaptive Planning, DAP) consists of two main parts: the design phase (in which the dynamic adaptive plan, the monitoring activity and other actions are planned) and the implementation phase (the implementation of the plan and monitoring and taking actions if necessary).

The *ATP* and *AP* approaches focus on timing. ATP is designed to deal with new information (e.g. incorporating the data from new climate scenarios): when this becomes available, the timing of the actions is changed to keep the ability to achieve the original objectives. AP extends ATP by reconsidering actions which should be taken when certain tipping points are reached (rather than just changing the timing), thus creating pathways. As a result, this approach can build in flexibility. The method supports policymaking by exploring opportunities and no-regret actions, revealing lock-ins and suggesting the timing of actions. AP, therefore, contains anticipatory (actions that need to be taken now) and reactive (actions need to be taken in the future when tipping points are reached) elements (Haasnoot et al., 2013; Marchau et al., 2019, Chapter 3&4; Walker et al., 2013).

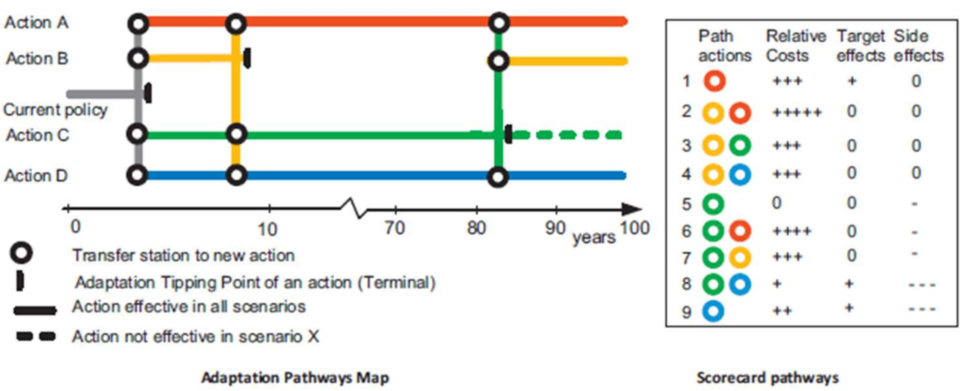
As DAPP combines the merits of the aforementioned methods, policy objectives are likely to be achieved with high certainty, even under deeply uncertain future.

Implementation framework

Based on Haasnoot et al. (2013) and Marchau et al. (2019, Chapter 3&4), the implementation of DAPP consists of 7 steps. These are the following:

1. Stage setting (current situation and problem analysis): exploring the existing conditions and constraints and defining future objectives (what success means)
2. Assessing the vulnerabilities and opportunities of the system and identifying adaptation tipping points
3. Identifying contingent action and assess their ATP conditions and timing: in this step, alternative strategies are explored, and their efficacy are assessed (i.e. whether they can mitigate the risks of failure or can boost the probability of success). Those policy actions which are inefficient are excluded from the further steps.
4. The design and evaluation of pathways: the policy pathways are created in this step (an example can be found in **Error! Reference source not found.**). The scorecard support policymaking by analysing trade-offs, such as opportunities, costs and other factors. This can incorporate qualitative and quantitative aspects.
5. Designing the adaptive strategy: based on the inputs from the previous steps, the adaptive strategy can be designed. This includes initial actions and also long-term flexibilities for different pathways.
6. Implementing the plan
7. Monitoring the strategy: as signpost information raise, actions can be taken based on the plan. Based on the new information, further research and potential modification can be done.

Figure 6.2 The implementation framework of AP



Source: Haasnoot et al. 2013, p. 488

The robustness of the plan is enhanced by different types of actions (Walker et al., 2013), such as:

1. Mitigating actions which mitigate adverse and likely effects of the plan
2. Hedging actions which mitigate adverse and uncertain effects of the plan
3. Seizing actions which exploit opportunities which will likely occur

4. Shaping actions which mitigate the risk of failure or boost the probability of success

To be prepared for trigger points, four types of responses can be given for signposts, such as defensive, corrective, capitalizing and reassessment actions.

Resource requirements, time needed, inputs

DAPP is a complex method as it requires inputs such as the exploration of available future policy options, potential signposts and triggers and the uncertainties against which the plan should be designed robustly. The implementation of it requires expertise and deep understanding of the method.

Similarly, the time required for implementation is relatively high, as the method has a relatively long design phase in which potential trigger points and adaptation pathways are explored. It is also a dynamic approach, used to support decision-making where future flexibility has high value, and includes monitoring. However, this method is appropriate in a situation where the implementation of the policy has high up-front costs and is intended to have long-term effects. As many adaptation policies require long-term planning and the monitoring of the impacts of climate change, the method is appropriate for assessing these policies.

Accuracy and robustness

Since DAPP is a dynamic method, it does not rely on the assumption of static future states and can incorporate information which becomes available in the future. As the magnitude of the impacts of the climate change will become more certain over time, this feature of the method is very valuable. As a result, the costs and benefits of adaptation policies can be estimated relatively accurately. In addition, the method is designed to be robust which is ensured by different types of actions (such as mitigating, hedging, seizing and shaping actions).

Usability and communication

As complex methods in general, DAPP's usability is low due to the high resource need and several pathways which need to be explored. This complexity reduces the communicability significantly, as the interpretation of different pathways and the explanation of tipping points can be difficult. However, these difficulties are eased by the fact that the development of the method can be visualised relatively easily, making a clear representation of options for policymakers and naïve stakeholders.

Distributional impacts, UK applicability

The method was originally designed to support the adaptation planning of flood risk management in the Netherlands (in the Lower Rhine Delta, Haasnoot et al., 2013), but it was already applied in several different situations. Based on Walker et al. (2013), the following applications were identified. In the case of ATP, it was used to evaluate flood risk management in Rotterdam (Gersonius et al., 2012), nature restoration in the Rhine basin and wine production in Italy (Werners et al., 2015) and risk management in the Elba basin (Schulte-Rentrop & Rudolph, 2013). The AP method was applied in the United Kingdom, in the paper of Jeuken & Reeder (2011), to analyse long-term adaptation strategies in the Thames Barrier project.

The method is appropriate for incorporating socioeconomic factors and analysing distributional impacts (Walker et al., 2013). Haasnoot et al. (2013) also considered socioeconomic development in their analysis and case study.

Compatibility with the UK Green Book guidance

Even though this method is not cross-referenced in the UK Green Book (HM Treasury, 2022), it follows several evaluation recommendations (see Section 8)., such as:

- applying monitoring system,
- the use of process evaluation in order to support policy-making about the timing when the current interventions need to be improved, and
- enabling evidence-based future decision-making.

Furthermore, robust decision making is directly recommended in the supplementary guidance of the UK Green Book (p. 30, p. 31) and the DAPP approach falls under the definition of it (Defra, 2020). As a result, DAPP is widely consistent with the recommendations of the Green Book.

Conclusion

DAPP is a method which supports decision-making under deep uncertainty by developing robust policy pathways and assessing the value of future flexibility and opportunities. Its design allows incorporation and the ability to respond to new information (it is dynamic) and therefore to accurately estimate the costs and benefits of the adaptation policies. Available actions are planned in advance and can be implemented when trigger points are reached (monitoring activities are included). As a result, the method can handle non-linear changes, explore opportunities and no-regret actions, and identify potential lock-ins. It is easy to visualise, which makes it easier to communicate. The method has been widely used in several situations, including the planning of climate adaptation policies.

The weaknesses of the method arise from its complexity: it has relatively high resource and time requirements - however, it is generally used in situations where the upfront costs are also high. This complexity also reduces the usability of the method.

Multi-criteria decision analysis (MCDA)

Description

Multi-criteria decision analysis (MCDA) refers to a group of approaches which are able to incorporate several inputs, both quantitative and qualitative, and evaluate them jointly. As a result, this method is useful in situations where it is difficult or impossible to quantify some aspects, such as acceptability, safety, etc., but they are important factors in the evaluation of a policy. These issues come up when analysing climate adaptation measures: policy implementation might fail if, for instance, the local acceptance of new dikes is low, if a new, more resilient type of crop is invasive and affects local biodiversity adversely, etc.

As MCDA is only a collective name for different approaches, there are multiple options available for evaluation, depending on the objectives of the policymakers. Some commonly used methods are the following.

- Multi-attribute utility theory or multi-attribute value theory (MAUT/MAVT) score different options (both quantitative and qualitative) and then aggregate them. The result can be a priority list, the most appropriate approach or a group of acceptable policies can be selected.

- The analytical hierarchy process (AHP) is based on the fact that people are better at making relative judgements than absolute ones, and therefore, one-to-one comparisons are more efficient (e.g. method 1 is better than method 2 and method 2 is better than method 3, etc., rather than stating which is the best method).
- The outranking method does not assume that all criteria are equally important (e.g. cost may be more important) and it compares all criteria at once. (Kiker et al., 2005)

Other advantages of MCDA are that it is suitable for dealing with some degree of uncertainty, for making decisions at group level instead of individual, and for not ignoring available information just to simplify the complexity (Kiker et al., 2005).

By applying this method, policymakers have great flexibility to include any type of criteria to meet their objectives, both quantitative and qualitative inputs. MCDA is widely applied in environmental economics, for instance, to appraise adaptation policies (Huang et al., 2011).

Implementation framework

The implementation framework of MCDA can be divided into three main steps (based on Kiker et al., 2005).

1. Collecting the inputs

In most cases, there are 4 general types of technical inputs:

- results of modelling or monitoring studies (primarily quantitative)
- risk assessment (may be mixed)
- costs or cost-benefit ratio (may be mixed)
- stakeholders' preferences (mainly qualitative)

2. The evaluation of alternatives

Once all the criteria have been defined, the alternative policy packages can be evaluated on the basis of the inputs. This can include expert judgement, monitoring results, stakeholder meetings, etc.

3. The use of an aggregation method

Finally, an aggregation method, such as MAUT/MAVT, AHP or outranking, need to be used to select an alternative, to rank alternatives or to group alternatives which are able to achieve certain policy objectives (Durbach & Stewart, 2012).

Resource requirements, time needed, inputs

The input requirements for this method depend very much on the preferences of the policymakers, but in general the results of monitoring studies (or modelling results), risk assessment data, costs or cost-benefit ratios and stakeholder's preferences are required to use this method. An aggregation method needs to be chosen appropriately.

The use of the method is relatively resource-intensive, but, again, it depends on the precise policy objectives and the aggregation method intended to be used. This is because a consistent estimation of both quantitative and qualitative inputs may be required, often involving stakeholder engagement and expert judgement.

Regarding the time required for its use, the following must be taken into account:

1) the availability of monitoring or modelling results and how long it takes to collect them;
2) whether the costs or cost-benefit ratio can be easily calculated;
3) whether experts need to be involved to estimate risks, costs, etc.;
4) whether stakeholder inputs are collected and, if not, how many stakeholders should be involved and how difficult it is to reach them.

Accuracy, robustness

MCDA has a relatively high accuracy in estimating the costs and benefits of adaptation measures. This is because it can incorporate several factors, not only the monetary costs and benefits of the policy, but also, for example, land use needs, ethical issues, social acceptability and the distribution of social costs.

In terms of robustness, the focus of this method is not on dealing with uncertainty, but rather in combining different types of aspects which can be important in the evaluation process. However, there are variations of the MCDA approach that can handle uncertainties to some extent, such as the implementation of non-expected utility or the scenario-based MCDA approaches (Durbach & Stewart, 2012).

Usability, communication

The use of this method requires a consistent evaluation (e.g. to assign qualitative values to some criteria). In addition, the application of the aggregation method is not always straightforward, which diminishes the usability of the method. However, no special software is required to implement this method.

Furthermore, stakeholders can easily interpret and understand the inputs, but the implementation of the aggregation method is more difficult to communicate, especially if it is chosen to be complex (e.g. to incorporate uncertainty to some extent). Final results, such as which policies to exclude, or a priority ranking, can be easily understood by all stakeholders.

Distributional impacts, UK applicability

Distributional impacts can be captured with MCDA, as it is possible to include one or more socioeconomic criteria among the inputs, both qualitative (e.g. the acceptability in different socioeconomic groups) or quantitative (e.g. change in disposable income in different quintiles).

In terms of applicability, Huang et al. (2011) identified 312 studies published between 2000 and 2009 that used different types of MCDA methods for addressing environmental issues and summarised their geographical applications, which were mainly Europe and Asia (120 and 97 studies, respectively). Michailidou et al. (2016) used the method to analyse the adaptation of the tourism sector in Greece, while Porthin et al. (2013) evaluated different adaptation alternatives against river flooding in Finland. However, only one paper was identified which used MCDA in the UK, but its objective was mitigation rather than adaptation (through the use of energy-from-waste (EfW) power plants in two counties) (Bastin & Longden, 2009). Notwithstanding the lack of application in the UK, no specific reason was identified why the method would have limitations in a UK context.

Compatibility with the UK Green Book guidance

MCDA is recommended and cross-referenced with the UK Green Book (HM Treasury, 2022, p. 37). In addition, a supplementary manual was released to support the use of the method (Department for Communities and Local Government, 2009). However, it worth mentioning that its inferior form, called multi criteria analysis (MCA) is not recommended to use as it is rather closer to heuristics.

Conclusion

Multi-criteria decision analysis is an approach which refers to a group of methods that share characteristics of evaluating quantitative and qualitative inputs jointly. As a result, the method is relatively accurate in estimating the costs and benefits of adaptation policies since multiple criteria can be considered (e.g. ethical issues, land and water use, the costs of adaptation, acceptability). Similarly, socioeconomic impacts can be included and assessed. One of its strengths is its flexibility: as several methods are included in the MCDA category, policymakers can apply the most appropriate one, for example, to select the best method, to rank the alternatives or to exclude some policies.

On the other hand, the relatively high resource requirements are one of the method's weaknesses (however, it depends on the policy objectives): a consistent qualitative or quantitative assessment of different factors is necessary which might require the involvement of experts and stakeholders. This also results in a relatively long implementation time. In addition, the use of the aggregation method and the communication of the methodology can be complex (although the results can be easily understood by most of the stakeholders). Generally, the method is not designed to be applied under deep uncertainty, but there are some methods which can improve its robustness.

Agent-based social simulation

Description

Agent-based social simulation (ABSS) is a relatively formal, computer-based modelling approach, which enables its users to realistically model the actions and interactions of different agents under different assumptions (scenarios). In general, agent-based methods are designed to incorporate multiple (realistic) assumptions about the agents, such as environmental values, reactions for economic and regulatory policies, etc. (UNFCC, 2004a).

Agents' actions can be described by 3 main types of features: (1) by the given set of rules which determine their behaviour and interactions; (2) by their ability to incorporate new information through cognitive capabilities; (3) by their ability to consider their environment (Alam & Geller, 2012). It is also important to note that ABSS are mainly built on hypotheses or on the estimation of several parameters (Gilbert, 2004), which need to be verified, tested or realistically assumed.

Social simulations enable the modelling of complex questions, which sometimes cannot be executed (or would not be ethical) under real conditions. Complexity also refers to the fact that the interactions of people include non-linearities, and societies are the results of dynamic processes. (Gilbert, 2004) For example, only implementing adaptation policies in one sector or in one region might affect different groups of people and different economies. Simulations also contribute to the modelling of some problems which cannot be calculated analytically (or would be complicated) (Richiardi et al., 2006).

The method can realistically model agents' decisions under different scenarios which helps to achieve the objectives of policymakers. However, due to its complexity, the method is rather appropriate for appraising a set of adaptation policies instead of individual ones.

Implementation framework

The implementation of the method consists of two major parts:

1. Collection and validation of the hypothesis. In this step, different types of data are collected, and hypotheses are defined, such as the scenario-design, the different constraints, the behaviour norms, the description of different agents, etc. The type of the data can be (1) qualitative data, (2) experimental data or (3) empirically validated theoretical knowledge (Alam & Geller, 2012).
2. The setup of the model based on the pre-defined hypotheses to achieve the objectives of the exercise.

The method can be sensitive for the hypotheses used to model the agents' actions and interactions, which is usually mitigated by applying validated data.

Box 1: Example of applying agent-based social simulation approach

The case of agricultural crop adaptation is a good example of agent-based social simulation. Due to the climate change, the pattern of precipitation will likely change, which increases the number and duration of droughts. This will require the agricultural sector to adapt. Without further data collection, the following example is intended to illustrate a possible implementation of ABSS.

The first step is to validate the hypotheses. This can start by identifying different warming scenarios, such as a 1.5, 2 or 4 C warming by the end of the century. This will allow the assessment of changes in spring and summer precipitation in a particular region – the greater the warming, the more likely a reduction in precipitation. The description of agents should cover the main groups of farmers and consumers. For instance, there is a group of farmers who own smaller fields and have stricter budget constraints, and another group who own larger areas and have more financial options, for example, because they are more creditworthy. In the case of consumers, there are three groups: those who cannot afford to spend more on food products, those who seek quality and are less sensitive to price changes, and those in between. The government can be defined as another agent. The available options for adaptation include introducing new crops, building of new water reservoirs, shifting the focus to different types of agricultural products, while importing more crops.

In the model set-up, the interactions between different agents need to be defined. For example, small farmers have the following options for action:

1. Switch to higher quality, but more expensive crops
2. Switch to lower quality, but cheaper crops
3. Switch to higher value-added products (e.g., vegetables)
4. Do nothing

All the steps lead to interactions with consumers and the government, for instance:

1. In the first case, farmers lose price-sensitive consumers, but can increase their income from other income groups.
2. In the second case, farmers lose quality-sensitive consumers, but can increase their income from lower income groups.
3. The change in production interacts with other farmers already in the vegetable market by increasing competition. This affects farmers' profits and consumers' prices.
4. If there is no change, yields will decrease over time, which is likely to reduce the farmers' revenues, while increasing prices.

Small farmers also interact with the government, as they might need additional subsidies not to increase prices or to invest in water reservoirs.

The results of the ABSS support decision-making, for example, by illustrating different trade-offs (e.g., how small farmers' income will change if they choose different options, how government expenditure and revenue will change).

Resource requirements, time needed, inputs

The inputs of this method are the hypotheses used in the simulation. They can have a very wide range, depending on the use. A few examples are economic and environmental constraints, regulatory, behaviour and financial policies, the behavioural norms, adaptive capacity without adopting policies and the socioeconomic description of different agents.

The relative resource requirements of the method are high: the more realistic the set of hypotheses are used, the more realistic the results can be. Expertise in policy analysis is an essential requirement, while analytical abilities to execute the simulation is also important.

The time needed for implementation strongly depends on the complexity of the task. If policymakers want to have a comprehensive, deep evaluation, both data collection and simulation can be long.

Accuracy, robustness

This method, if hypotheses are correctly assumed, is able to estimate the costs and benefits of adaptation policies (under different scenarios) realistically, even on long-term.

To increase robustness, ABSS can incorporate sensitivity analysis. However, the development of scenarios is often dependent on a few assumptions and parameters (e.g. probabilities), which are usually poorly estimated under deep uncertainty. This diminishes the robustness of the method.

Usability, communication

In general, this method is hard to be used as complex analytical simulation is required to translate the inputs to outputs. However, (agent-based) simulation is not a rarely used modelling exercise, which means that required expertise can be available.

The other drawback of the complexity is that it reduces communicability: it can be hard to communicate all the relevant assumption and design of the method. However, outputs can often be understood easily by the majority of stakeholders.

Distributional impacts, UK applicability

The ABSS is designed to incorporate social aspects, which can be both distributional inputs and outputs.

Furthermore, the method can be used in several parts of the science, for instance for the modelling the spread of Covid-19: Lorig et al. (2021) identified more than 100 article which used this method. It was also applied to model the water demand policies and (demand) response of households in the Thames region (UK) (Downing et al., 2000).

Compatibility with the UK Green Book guidance

Agent-based simulation modelling is mentioned in the Magenta Book, which is the specific guidance for carrying out evaluations, among the theory-based impact evaluation methods (although it is formally not a theory-based method) (HM Treasury, 2020, p. 43).

Conclusion

As ABSS is a computer assisted simulation method, it can realistically model the actions and interactions of different agents. As a result, this approach can estimate the impact of adaptation policies relatively accurately under different scenarios. This also contributes to meet policy objectives and design their implementation. Due to its high resource requirements and complexity, the method is rather recommended to analyse a group of policies and not individual ones. However, even though the communication of the method and assumptions are not always simple, stakeholders are often familiar with understanding the results of simulations, which increases the method's communicability. By design, ABSS is appropriate for model distributional impacts and social interactions.

The main weaknesses of the method are coming from its complexity. In order to model agents realistically, high resource and time requirements emerge: often expertise in policy analysis and analytical abilities are necessary to set up the simulation. These also result relatively low usability, as inputs are hard to be transformed to outputs. Furthermore, the method is not designed to work under deep uncertainty, however, the sensitivity analysis can be incorporated to increase robustness.

Heuristics

Description

Heuristics refer to simplified, generally rule-based decision-making process. It considers only a few inputs (which are usually the most important) and ignores some part of the available information (Meyer, 2018). Different options are available under this framework which includes, for instance, the following:

- 'Tallying', where all the inputs are weighted equally (Meyer, 2018)
- 'Take-the-Best', where different alternatives are compared based on one metric at once and the first outstanding option is chosen based on any metric (ibid.)
- ‘Take-the-first’, where the first option is chosen which can reach a given threshold, without analysing its optimality (e.g. which can reduce risks under a given level) (Siders and Pierce, 2021)

Using heuristics in appraising adaptation policies is a novel approach, however, their use is widely applied in many parts of people’s life. This is due to the fact that people are often unable to handle all the available information or complex situations and, therefore, they use ‘cognitive shortcuts’, such as heuristics (or rule of thumb). The application of heuristics is now widely examined by cognitive sciences, such as psychology (Gigerenzer & Gaissmaier, 2010).

This method is appropriate for the elimination of complex decision-making processes and for choosing strategies which fit the most important policy objective or objectives. However, due to its simplicity, it is hard to evaluate multiple options at the same time. Heuristics are particularly suitable in situations when rapid decision-making is required (e.g. in the case of current disasters, heatwaves) or the cost of rational (or thought-to-be-rational) decision-making outweigh its benefits (e.g. the decision about the re-design of some urban places).

Implementation framework

Heuristics can be both:

a) highly formalised and quantitative, such as in computer programming (for example, to optimise disaster response and recovery, where risks are mitigated under a certain level, but the efficiency is not calculated) or

b) function as a qualitative guideline to support decision-making.

The method requires the choice of an exact evaluation method (such as 'tallying', 'take-the-best', 'take-the-first') and the evaluation of the inputs.

Box 2: Example of applying heuristics in adaptation decision-making

As an example of heuristics, the problem of cities during heat waves can be considered. Urban populations often suffer from higher temperatures in summer due to ’heat islands’ (the infrastructure of cities contributes to higher temperatures, such as the lack of green spaces, the extensive use of concrete, crowded streets, etc.). To mitigate the negative effects of heat waves, cities need to consider adaptation measures when designing public spaces. Important factors include cost, local acceptance, effectiveness of measures, time frame for significant effect (e.g., trees need time to provide shade), space requirements for different vehicles and businesses, etc. Possible alternative measures may include a significant increase in green areas through grass and trees, grass and other plants, the use of lighter coloured concrete, the increased use of water, etc. Alternative plans can be created by combining these methods.
The 'take-the-first' method can then be used. For example, the first alternative which does not cost more than GBP 1 million, which does not reduce the number of parking spaces by more than 20%, which can reduce the average temperature of the whole street by at least 4°C after the first year of implementation compared to the current situation, and which increases the number of available balconies by at least 10% should be chosen.

Resource requirements, time needed, inputs

Compared to the majority of other methods, the resource and requirements for heuristic evaluation are low: the essence of the method is to reduce the complexity of decision-making and, therefore, to enable rapid evaluation. However, this does not mean that data collection is always quick, that the evaluation cannot be formalised, or the appraising process cannot last long, but it is still low compared to other methods.

Even though for this method lower-than-average inputs are need, the method can still incorporate simulation, programming and the collection of a wide range of data, such as alternative strategies, probabilities of different future events and their consequences, costs and benefits of different adaptation methods, etc.

Accuracy, robustness

The method is not designed to accurately estimate all the impacts of adaptation policies, but it can consider risks, costs and benefits of different adaptation strategies. Moreover, even though heuristics are often portrayed as suboptimal decision-making processes, results from cognitive science have pointed out that in some cases, particularly under deep uncertainty, heuristics can outperform rational models (in terms of variance reduction) – this is often referred to as ‘less-is-more effects’ (Gigerenzer & Gaissmaier, 2010; Gigerenzer & Brighton, 2009). As a result, while heuristics are not created to deal with uncertainties, they are often more robust than rational models (ibid.)[22]. This feature of the method is particularly useful in the design and evaluation of adaptation policies, where climate impacts are often highly uncertain.

Usability, communication

The method is relatively easy to be applied and the decision-making process is easy to be understood by any stakeholder. Furthermore, as the method is not complex and intuitive, it can be communicated to a wide range of stakeholders.

Distributional impacts, UK applicability

The method can incorporate a few socioeconomic aspects and outcomes, and it is possible to consider several socioeconomic and different factors (such as environmental, technological, etc.) jointly. However, this depends on the exact method used, and heuristics are not very sophisticated to consider all factors or weight them differently.

The method can be applied in a UK context. However, no article or case study was identified which used the country as an example.

Compatibility with the UK Green Book guidance

Heuristics are not cross-referenced with the Green Book and are poorly compatible with the guidance of it. This is due to its simplifications, which are often not objective, or due to the selection of criteria, which is often not transparent. A simplified form of MCDA, called multi criteria analysis (MCA), which can be interpreted as a heuristic, is particularly not recommended (compared to the MCDA, MCA only uses simple subjective weighting, for instance) (HM Treasury, 2022, p. 37).

Conclusion

The main strength of using heuristics is that it can enable rapid assessment of different alternatives and reduce the complexity of decision-making. As a result, the method works well if decisions have to be made quickly. Moreover, the results in cognitive sciences have shown that the method works efficiently and robustly under deep uncertainty. Further advantages come from its simplicity, such as its easy usability (compared to other methods) and communicability, and (relatively) low resource and time requirements.

Among its weaknesses, the shortage of decision criteria (which can be considered at one time) should be mentioned. As the method cuts complexity, less aspects, such as distributional impacts, can be taken into account. Similarly, its accuracy is also lower as decisions are made based on the most important factors.

Horizontal evaluation

Description

The horizontal evaluation approach was designed to merge the experience of local participants and the knowledge of peer experts. Originally, it was developed to support agricultural innovation in developing countries in the Andes, but it has the potential to be used in other situations (Global Evaluation Initiative, 2021; Thiele et al., 2007).

The method is appropriate for giving an early evaluation of a policy when significant modifications are still possible, but the basic concept has been designed or even initial results are already available. Usually, it consists of 2+1 types of participants and stakeholders: (1) the local participants which

[22] This can partly be explained by the fact that only a few future scenarios' probabilities (if any) are estimated - however, these estimates can be quite poor under deep uncertainty.

refer to the local team who is developing and implementing the policy; (2) experts who owe important knowledge and expertise, but were not involved in the project before; (+1) local stakeholders (beneficiaries) who do not participate in the evaluation process directly, but their view is built in through interviews and field visits.

The essence of the method is a more-day (generally 3) workshop, which also contains a field visit. The responsibility of the local team is to collect and present the context, the outcomes and all available information in a structured way and use autocritique. Peers' responsibility is to assess the strengths and weaknesses they can identify and make constructive suggestions. Local participants (stakeholders) are interviewed and their living and working circumstances are observed on the second day, during the field visit.

Policy objectives can be achieved with a relatively high degree of certainty, as the horizontal evaluation should be applied in a situation where significant changes are still possible, but the initial work has already started. The approach is suitable for evaluating different adaptation policies and incorporating experience from early implementation.

Implementation framework

Based on Thiele et al. (2007, Table 1, p. 500) and betterevaluation.org, the following main steps are necessary to implement the horizontal evaluation method:

Day 1: Introduction of the methodology

- A facilitator, who is an essential part of applying the method, introduce the program and procedure. It should be emphasised that horizontal evaluation only aims to evaluate the methodology (the implementation of the policy), not the project as a whole or the organisation who implements.
- Local team presents their findings of their approach and clarify questions.
- All participants agree on the shortlist of evaluation criteria.
- Preparation for field visits in small groups which consist of local team members and peers.

Day 2: Meeting local stakeholders on the field visit

- The small groups visit different field sites.
- Local team members introduce the intended beneficiaries and peers question and observe local stakeholders.
- A result matrix is constructed to compare the results across small groups.

Day 3: Synthesis, comparative analysis and suggestions

- Peers and local project members work separately, and they phrase for each evaluation criteria no more than six (1) strengths, (2) weaknesses and (3) recommendations.
- The findings are presented on a plenary session. The facilitator helps to identify the similarities and differences and converge points of peers and local members. Those points, which were evaluated to be

strengths (or weaknesses) by both types of participants, are considered aspects to be used further (or to improve). Those points, which are contradictory and diverge, require common exploration and agreement.

- Finally, possible actions and applications are phrased.

Resource requirements, time needed, inputs

Horizontal evaluation requires initial information on how the early implementation of the policy goes (coming from local team members), the selection of appropriate fields to be visited and the right selection of peer experts to involve a wide range of aspects and a long list of evaluation criteria (from which the short list will be created on Day 1).

Even though a lot of information can be collected, and peer experts are also involved, the resource requirements are relatively not high. This is because that local team members, who are actively involved in the implementation of the method, can collect information relatively easily.

Similarly, time needed is relatively low. The method requires initial data collection and the organisation of the 3-day workshop. However, the data collection should be relatively rapid compared to other methods as local team members are already involved in the implementation of the policy.

Accuracy, robustness

This method has a relatively high accuracy to estimate the current and short-term expected costs and benefits of adaptation policies experienced on local level measured through the field visits, which is expanded by the experience of the peers. However, medium- and long-term impacts are hard to be incorporated by this method, as they are not always in the focus. Similarly, this method is not designed to deal with uncertainties. However, robustness, long-term impacts and accuracy can be among the shortlisted criteria.

Usability, communication

The application of the method is not complex. If there are projects and policies which are under implementation, and the progress and initial outcomes are monitored, this method can be relatively easily used, as local team members own most of the relevant information.

Furthermore, it is relatively easy to communicate the results of the evaluation as the participants list the strengths and weaknesses as an output of the workshop and they also phrase suggestions. As intended beneficiaries are involved during the evaluation process (during field visits), they are aware of the concept of the policy.

Distributional impacts, UK applicability

This method was originally designed to foster innovation in developing countries. First, it was used to encourage innovation in the Andes (Peru, Bolivia) in potato production and marketing (Thiele et al., 2007). Later, it was applied in Uganda to develop capacity for agricultural market chain innovation (Horton et al., 2010). However, no article was found which applied the method in the UK or in a developed country. However, no specific reason was identified why it could not be applied in the UK.

Furthermore, through the stakeholders' interviews, field visits and initial data collected, socioeconomic impacts can be, moreover, are usually intended to be considered and incorporated through the evaluation of the policy.

Compatibility with the UK Green Book guidance

Even though this method is not cross-referenced with the UK Green Book (HM Treasury, 2022), it incorporates several suggestions of it, such as to use surveys and interviews to understand the different view of stakeholders (p. 70) and to monitor and evaluate the implementation (when the workshop needs to be held) (p. 69).

Conclusion

Horizontal evaluation is a method which can combine the merits of applying local and peer experts and also incorporate the view of the intended beneficiaries. As a result, a comprehensive evaluation of the policy is possible, while stakeholders are also engaged. The latter mitigates the risk of not accepting the suggested solutions. Moreover, the method's output is a clearly defined list of suggestions (beside the explored strength and weaknesses), which further improve the method's communicability. Even though horizontal evaluation can analyse even complex projects and policies, its time and resource requirements are not as high. This is due to the fact that local project members – if they use monitoring activities – can collect and present inputs relatively easily as they are involved in the implementation of the process. Distributional and socioeconomic impacts can be easily included, for instance, through integrating the view of intended beneficiaries who were interviewed and whose problems and activities were observed during the field visits.

Among the method's weaknesses its low robustness should be mentioned first: horizontal evaluation is not designed to handle uncertainties; however, robustness can be included among the shortlisted criteria. Furthermore, long-term impacts of the adaptation policy are also not supposed to be estimated accurately, as the method rather focusses on current and short-term problems and stakeholders' engagement.