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Landscape review of international assessments of the economic impacts of climate change

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Executive Summary

The Scottish Government is considering introducing a new Climate Change Bill, which will amend the existing Climate Change Act (Scotland) 2009 to strengthen the emissions reduction target for 2050 in line with the 2015 Paris Agreement objectives to pursue efforts to limit warming to 1.5°C. The Government has commissioned via ClimateXChange (CXC) this Rapid Evidence Assessment (REA) and synthesis of key global assessments of the costs and benefits of climate change action in order to give context to the Scottish Government's decisions and as a basis for continuing policy development. Detailed pathways to 2050, including costs and policy options, are not in the scope of this report.

The study focuses on literature that has emerged since the Stern Review of the Economics of Climate Change (Stern 2007), and seeks to build upon previous review exercises. The REA, a constrained form of systematic review, was carried out using a recognised approach developed by the UK Energy Research Centre (UKERC).

A key message arising from this review is that estimates of climate impacts are inherently uncertain, so that climate policy needs to be assessed in terms of risk management, rather than straight-forward cost-benefit analysis. Uncertainties arise on many fronts.

The biophysical impacts of climate change include changes to atmospheric temperatures, ocean temperatures, sea levels, ocean acidity, water cycles, carbon cycles, and other earth systems. The rate at which these systems will change is uncertain, with the possibility that tipping points might be exceeded above which some processes start to further accelerate warming rates. These physical impacts in turn cause human and economic impacts through multiple channels such as crop yields, storm damages, flood and drought impacts, health impacts and reduced productivity. Estimating these economic impacts is also inherently uncertain. Some indirect impacts are harder to measure because their effects are diffused across the economy, or relate to non-market impacts. This means that not all analyses include the same set of impacts, leading to considerable variation in estimates of climate damages, even when the same degree of warming is assumed.

Global impact estimates can mask deep differences between regions of the world; developing countries, particularly those in the global South, are far more vulnerable, because they already operate at elevated temperatures, and their economic structures are more exposed to the external environment, and poorer populations generally have lower adaptive capacity.

The literature unambiguously concludes that abatement of emissions can reduce the level and risk of such damages. However, these economic gains from reduced climate damages are traded off against economic losses from increased abatement costs. Several studies attempt to find a socially optimal balance between the costs and benefits of different emissions targets. Such attempts face several difficulties, including incompleteness in the set of impacts covered, difficulty of monetising some of these impacts, the fact that Gross Domestic Product (GDP) impacts tend to become weighted towards rich countries (where impacts are generally lower). Climate damages and abatement costs also face risks that are very different nature, making them hard to trade off against each other. In addition, abatement costs and damage costs are borne by different people geographically, and different generations in time, which raises important issues of intergenerational and international equity that are as much the domain of ethics and politics as they are of economics.

The balance of evidence suggests that although the *mid-point* estimates of abatement cost may be higher than the *mid-point* damage estimates, it is reasonable to conclude that there is a considerable risk of much higher-than-expected damages which would justify the cost of ambitious abatement action.

This is in line with the conclusion arising from climate risk literature suggesting that reducing the risk of exceeding tipping points is a key reason to aim for strong abatement targets globally.

Global cost estimates therefore need to be interpreted with caution, but damage costs still provide a useful (albeit not a very precise) yardstick for assessing how much should reasonably be spent on reducing emissions. The evidence suggests that the probability distribution in the range of climate damage estimates is wider and more skewed to high values than the range of abatement cost estimates. For the most ambitious scenario covered by the studies included in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) in 2014[1], median **abatement costs** were 3.4% of GDP by 2050, with an upper (90th percentile) estimate of 6.2% of GDP by 2050. Studies carried out since the IPCC review have found abatement costs in a similar range[2] to achieve the more ambitious target of limiting warming to 1.5°C. This contrasts with IPCC estimates of **climate damages** which have a median value of 1.5% of GDP, but with a significantly higher upper (90th percentile) estimate of 9.5% of GDP by 2050[3]. Some studies carried out since then have a smaller range of damages, whilst others have considerably higher estimates of damages, particularly at the upper end of the probability range.

In addition to summarising these quantitative estimates in the literature, this report also covers other research efforts which avoid the difficulties of aggregation by focusing on understanding each type of impact more completely. Separating out different cost elements allows policy-makers to engage more directly with the ethical and political dimensions of climate decisions, but makes it imperative that policy-makers are conscious of the complexities of comparing these different types of cost.

Limiting warming to below 1.5°C by 2100 generally requires similar deep transformations in the energy system as holding warming to below 2°C during the 21st century, but the decarbonisation of the energy system needs to be faster and more pronounced. Like most 2°C scenarios, 1.5°C scenarios depend on the availability of negative emissions technologies (such as biomass energy plus carbon capture and storage (BECCS)) with controversial implications for land-use change.

Further research is helping to understand the range of these risks, and information will emerge over the coming years and decades. While taking a long-term outlook and managing the energy transition, policy will need to maintain flexibility to adapt the new circumstances and emerging evidence.

[1] Limiting atmospheric concentrations of GHGs to 450 parts per million CO_2, consistent with about 50% chance of limiting warming to below 2°C

[2] A range 0.6%-5% of GDP

[3] Damages estimated at warming of between 2.5-3°C

Contents

Glossary

Abatement costs	The cost of reducing emissions of greenhouse gases
Adaptation costs	The cost of reducing exposure and vulnerability to climate change impacts
AMOS CGE model	A macro-micro Model Of Scotland based on computable general equilibrium modelling techniques
Anthropogenic emissions	Emissions of greenhouse gases caused by human activity (including emissions from farmed animals and crops etc.)
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy and Industrial Strategy
Biophysical	Describes how biological systems interact with their physical environment (including temperature, chemical composition etc.).
CCRA	Climate Change Risk Assessment

CCS	Carbon Capture and Storage
Climate impacts	Includes impacts on biophysical earth systems (e.g. atmospheric and ocean temperatures, sea level rise, ocean acidity etc.) and impacts on human systems (e.g. crop yields, flooding, drought etc.).
Climate damages	The economic consequences of climate impacts (including indirect and non-market impacts such as loss of species and natural habitats)
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CGE	Computable General Equilibrium
CXC	ClimateXChange – Scotland's Centre of Expertise on Climate Change
Discount rate	The rate at which future costs are reduced to bring them into present value terms
Emissions trajectory	The pathway of future emissions
EPRI	Electric Power Research Institute
Fat-tail	A probability distribution which has elevated probabilities at one or both edges of the distribution compared to a normal distribution
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IAM	Integrated assessment model
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IRENA	The International Renewable Energy Agency
IWG	Interagency Working Group
Maladaptation	Development that increases exposure or vulnerability to climate impacts
MARKAL	An energy systems model using least-cost optimisation
Mean	Average
Median	Mid-point of a distribution (50^{th} percentile)
Mitigation costs	Cost of reducing emissions of greenhouse gases
Nordhaus DICE model	The Dynamic Integrated Climate-Economy model developed by William Nordhaus of Yale University
OECD	Organisation for Economic Cooperation and Development
Partial equilibrium model	A model which finds an optimal solution but only for part of the economy
ppm	parts per million
REA	Rapid Evidence Assessment
RCP	Representative Concentration Pathways
Social Cost of Carbon	SCC – measures both the value of damages incurred for each tonne emitted, and the value of saving a tonne of CO_2
Skew	An asymmetrical probability distribution
TIMES	An energy systems model using least-cost optimisation
UKERC	UK Energy Research Centre
UNFCCC	United Nations Framework Convention on Climate Change
UEA	University of East Anglia
US DOE	U.S. Department of Energy
WB	World Bank

1. Introduction

The Scottish Government is considering introducing a new Climate Change Bill, which will amend the existing Climate Change Act (Scotland), 2009 to strengthen the emissions reduction target for 2050 in line with the 2015 Paris Agreement objectives to pursue efforts to limit warming to 1.5°C. To support continuing policy development in this area, and the forthcoming Bill process, the Scottish Government commissioned via CXC a meta-review and synthesis of key international assessments of the costs and benefits of climate change action. The scope for the work includes: projected costs and benefits at varying scales; the timescales over which these economic impacts may emerge; and the degree of uncertainty reflected in estimates. The aim is also to consider the applicability of the literature to the specific circumstances of European countries, and where possible Scotland.

The principal objective is thus to review and synthesise the global literature on the economic impacts of climate change and climate mitigation, including, but not limited to, the economic impacts of the 1.5°C target. This is a large global literature, with meta-analysis and review undertaken by bodies such as the IPCC. The study focuses on literature that has emerged since the Stern Review of the Economics of Climate Change (Stern 2007).

The report is based upon a REA, a constrained form of systematic review described in Part 2. The report provides a concise review of the literature on the economics of climate change impacts and mitigation with the aim of providing context and information that can be used as a basis for continuing policy development and to support the development of the Climate Change Bill.

The study includes the direct and indirect costs and benefits associated with mitigation (e.g. reallocation of resources in the energy sector and other key sectors), as well as the benefits associated with avoided climate change impacts. Economic damages of climate impacts are therefore within the scope of the study. To the extent that some models assume a level of adaptation to the effects of climate change, this is also within scope, but the study does not focus on the costs or wider impacts of climate adaptation measures.

The costs of achieving particular levels of mitigation are dependent on many factors, such as the choice of economic development pathway, the types of policies enacted, and the technologies and behaviours that are deployed in response to these policies. Whilst there is a deep literature on these issues, they are beyond the scope of this review, and we do not attempt to assess the relative advantages of different policy or technology approaches.

The remainder of the report is structured as follows: Part 2 describes the research method – our approach to REA and to review and synthesis; Part 3 discusses the biophysical and social impacts of climate change; Part 4 considers key issues in climate economics; Part 5 is focused on global estimates of climate change damage costs; Part 6 on global estimates of climate change mitigation costs; Part 7 considers the implications for national / sub-national decision making. Part 8 concludes.

2. Research method – REA and approach to review and synthesis

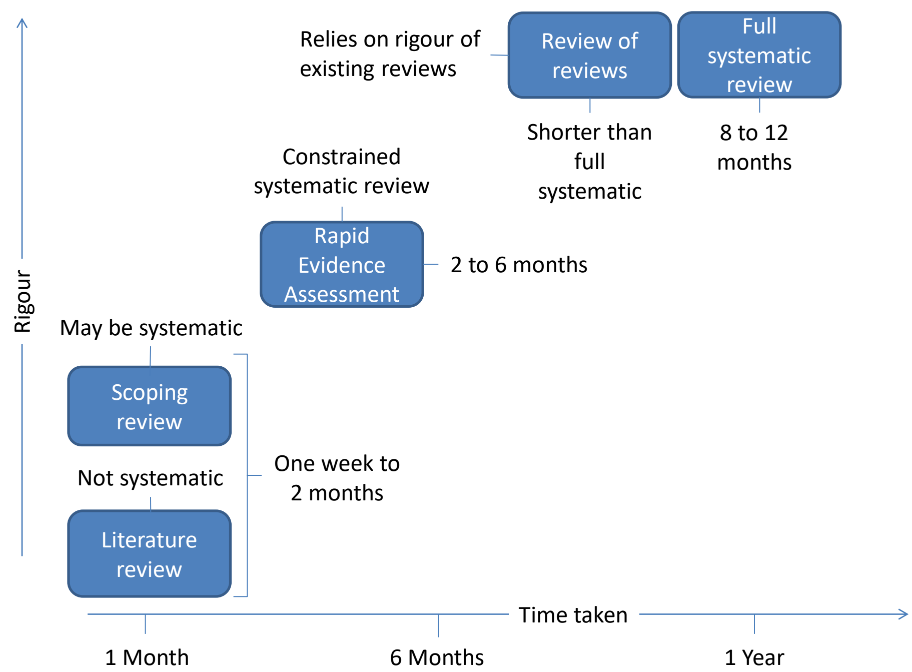
A REA was conducted during August and September 2017. The REA was undertaken using a generic approach to REA developed by UKERC and overseen by Dr Gross, who leads UKERC's evidence review research. The specific review protocol used for this report was undertaken at the University of Strathclyde by Oluwafisayo Alabi.

REA is a form of constrained systematic review which aims to maintain as much as possible of the rigour of full systematic review within the time and resources available. REA reviews require a trade-off between rigour and rapidity, as Figure 1 below shows. A particular challenge for REA in the context of this report is the large and diverse literature associated with the economics of climate change. In discussion with the Project Steering Group it was agreed that the review needed to provide wide, but not exhaustive, coverage of the literature and could derive more detailed findings from particularly important sources: Parts 5 and 6 show the range of findings from key quantitative sources.

The study seeks to build upon previous review exercises and therefore included search terms designed to find existing reviews. To make the search manageable, the initial review phase focused on Google and Google Scholar[4], and document review was constrained to the first 100 hits for each search term and a relatively constrained set of individual search terms were deployed (see Table 2). A more limited search was then undertaken of the websites of the specialist organisations listed below, with the specific objective of seeking any documents from those organisations not already revealed through Google or Google Scholar. The search was constrained to English language documents and to reports and papers published since the Stern Review (2007). Because of the short timeline for the report, following an initial trawl which revealed around 30 relevant documents, review and synthesis was undertaken concurrently with ongoing document searching. The REA also benefitted from discussion with and input from the Project Steering Group.

[4] The UKERC team led by Dr Gross have experimented with different search engines as part of their work to develop rapid evidence assessment for energy policy. This experience suggests that whilst dedicated academic search engines such as Science Direct, Web of Science or Scopus will reveal a few documents not found on Google Scholar the hit rate on Google Scholar is generally very high. Given the constrained timescale the search used Google to search for general literature and Google Scholar to search for academic papers. Follow up searches of institutional websites revealed a small number of additional documents in the grey literature.

Figure 1. Mapping the different types of literature and evidence review methodologies[5]



The initial search rapidly reviewed titles and abstracts to include or exclude based upon relevance. A large number of documents were excluded at this stage (see Figure 2). A more detailed review of full text was used to provide a fuller relevance rating. Only documents rated relevance 1 or 2 were included for further consideration. The key stages of the REA process for this project are described in Table 1 below, with the document screening outcomes at each stage summarised in Figure 2.

Table 1. Key stages of the REA

Stage	Description
1	**Identify search sources and inclusion/exclusion criteria** The sources to be searched were discussed with the Project Steering Group, together with the evidence inclusion/exclusion criteria and the format of the evidence capture spreadsheet. To constrain the searches it was agreed that approximately 100 items (the first 10 webpages) from each of these searches were taken forward to the first screening stage described below.
2	**Identify search terms and conduct searches** Initial searches were undertaken in Google and Google Scholar. Combinations of search terms were trialled and 21 search terms applied to Google/Google Scholar. A more limited set of search terms were applied to specialist organisations such as the IPCC, BEIS and IEA. Citation trails, recommendations from the Project Steering Group, and advice from stakeholders were used to directly identify additional documents.

[5] Figure derived by UKERC from the Government Social Research Service and described in more detail at http://www.ukerc.ac.uk/programmes/technology-and-policy-assessment.html

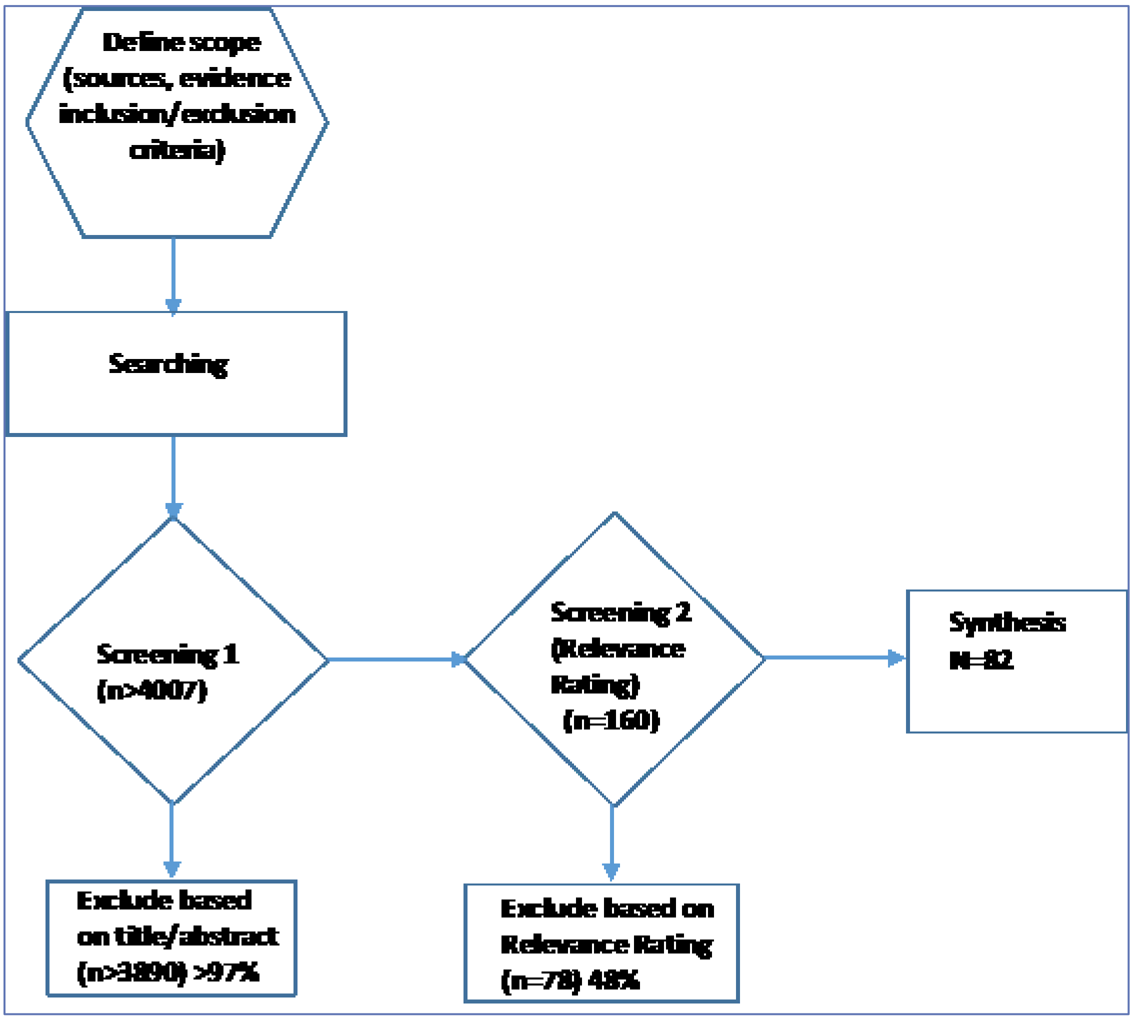
Stage	Description
3	**Screening 1** Documents were initially included or excluded based on basic relevance assessed by review of their titles and abstracts. Bibliographic details for all the documents that passed this stage were recorded in an evidence spreadsheet. Around 4000 studies were considered. 160 studies were selected for further analysis.
4	**Screening 2** Documents were then given a Relevance Rating (RR), established by examination of the full document text. The relevance rating was applied to the 160 studies passing the initial search: The relevance rating is assigned as follows: • RR 1: Title and/or abstract includes one or more of the CXC objectives in clear and detailed manner (i.e. it clearly outlines the what, how and why of the article) • RR 2: Title and/or abstract includes one or more of the CXC objectives, but not very detailed (i.e. does not clearly state the what and how of the article) • RR 3: Does not cover 1 or 2, but mentions other climate change issues (outside objective or research question) • RR 4: Not relevant or duplicate Only studies that meet RR1 and RR2 are included in the main report. A total of 82 studies were included.
5	**Evidence gathering and synthesis** A four-stage approach was followed to allow reports to be categorised and compared. The approach to review and synthesis is shown in Figure 3.

Table 2. Keywords used in Google and Google Scholar

Keywords			
General	Modelling	1.5 Degrees	Reviews
1. Damages OR cost OR assessment of climate change 2. Costs and benefits of climate change mitigation 3. Economic impact OR economic growth AND climate change 4. Cost and benefits of climate change global study 5. Least cost AND climate change global 6. Climate change policy OR targets AND reduction policy 7. Risk assessment OR Vulnerability AND climate change 8. CO_2 impact on economic growth AND climate change	9. Top-down AND Bottom up approaches in climate change 10. MARKAL AND climate change 11. Decarbonisation climate change AND input-output global 12. Carbon abatement and climate change global 13. General equilibrium and climate change global	14. Cost and benefits of 1.5 degree vs 2 degree 15. 1.5 degree or 2 degree limits and climate change	16. Systematic review on the cost and benefits of climate change 17. Systematic literature review on the climate change AND low carbon economy in 'global economy' 18. Systematic literature review on climate change mitigation OR adaptation policies 19. Systematic literature review on the climate change mitigation policies 'global economy' 20. Systematic review OR literature review on the damage AND direct cost and benefits of climate change global context 21. Global impact engineering assessment AND climate change

Simplified searches were undertaken of specific organisational websites (Organisation for Economic Co-operation and Development (OECD), UK Department for Business, Energy and Industrial Strategy (BEIS) International Energy Agency (IEA), International Renewable Energy Agency (IRENA), IPCC, Europa, Electric Power Research Institute (EPRI), US Department of Energy (US DOE) and these were cross-checked with Google/Google Scholar search findings. The manual searches revealed 10 potentially relevant documents of which 2 passed relevance rating.

Figure 2. Rapid review document screening flowchart



Note: for screening 1 and 2 includes 10 documents revealed through manual searches of organisational websites OECD BEIS IEA IRENA IPCC Europa EPRI US DOE. Total excluded documents at screening 1 for these manual searches not recorded.

The review and synthesis followed the four steps illustrated in Figure 3, below.

Figure 3. Review and synthesis approach

1. Categorise

- Each publication identified in the reviwe will be categorised in terms of the types of costs and benefits that are included (direct, indirect etc.). the scope of the study (georgraphical, sectoral, temporal etc.), and the type of model or analytical framework used. If the publication is a review of multiple sources, the range will be noted.
- The main assumptions made in each study will be recorded in order to inform an analysis of the comparability of different results achieved across different studies.
- This categorisation process will be used to identify the main distinct 'strands' of literature that exist in the field.

2. Quantify

- Each of the reports and publications identified by the literature review will be analysed in detail to extract the quantified results in terms of the economic impacts and costs of climate change and climate change mitigation.
- To the extent possible, the results of each of the publications will be normalised to a set of common indicators that can be compared across studies. For example, where possible, costs and benefits will be converted to common financial units, reported for the same year, and adjusted for whether results are reported in absolute terms or per unit of GDP.

3. Compare and explain

- Steps 1 and 2 will provide a quantified summary of the output of studies, as far as possible normalised so that like-for-like comparisons can be made. Step 3 will collate these results, presenting them graphically, so that the ranges of results (both within and across literature strands) can be easily identified.
- Where possible, analysis of assumptions and approaches will be undertaken to provide an explanation of the main causal factors.
- Where literature cannot be put on to a common footing these cases will be identified and explored separately.

4. Synthesise

- The analysis will be synthesised to identify areas where there is common ground between different strands in the literature, and areas where significant deviations and uncertainties still remain.
- The synthesis provides a summary of the causes of variations in estimates, the strength and maturity of research in different strands of the literature and an overall view of the state and quality of evidence as characterised by the literature reviewed.

3. Biophysical and social impacts of climate change

Anthropogenic emissions of greenhouse gases (GHGs) accumulate in the atmosphere, partially absorbing infrared radiation returning to space from the earth's surface, warming the atmosphere, and leading to climate change. Globally, CO_2 is the most significant anthropogenic GHG because of the volumes being emitted from combustion of fossil-fuels. CO_2 is removed from the atmosphere slowly; a third-to-half of emissions are absorbed over a period of several decades by land and oceans, whilst the remaining fraction stays in the atmosphere for periods of several centuries (Ciais *et al.*, 2013). This long lifetime means that our annual flow of emissions contributes to a cumulative stock of GHGs in the atmosphere, effectively locking in the effects for decades or centuries to come.

The impacts of climate change are well documented in a number of reviews (Stern, 2007; IPCC, 2013; AVOID2, 2017). Biophysical impacts include largely irreversible changes to atmospheric temperatures, ocean temperatures, sea levels, ocean acidity, water cycles, carbon cycles, and other earth systems. These in turn lead to a wide range of social impacts including on: health, crop yields, risks of water stress drought and flooding, risks of sea level rise for coastal cities, and risks to national and international security (King *et al.*, 2015). Together, these biophysical and social effects are referred to as **climate impacts**, whilst the terms **climate damages** and **economic impacts** are used interchangeably to denote the monetized estimates of the social welfare effects of these climate impacts (National Academies, 2017). Although this report is mainly concerned with economic impacts, it is important to bear in mind the nature of physical and social climate impacts which underpin climate change policy, so we provide a brief overview in this section.

Continuation of current emissions trajectories would lead to temperature increases by the late 21st century of 4-5°C, whilst warming over this period would be limited to 3-4°C under current policies, reducing to just below 3°C with the additional pledges agreed at Paris. Limiting warming to 2°C will require very considerable reductions in emissions and carbon intensity for the global economy relative to current commitments (Rozenberg *et al.*, 2015; Schaeffer *et al.*, 2015), but would reduce the damages from climate change in 2100 by between 20-65% compared to a 4°C pathway (Arnell *et al.*, 2013). Further limiting emissions to 1.5°C requires even steeper emissions reductions, and greater use of negative emissions technologies (Schaeffer *et al.*, 2015). The world is rapidly approaching the threshold at which limiting warming to 1.5°C becomes impossible, although some research adjusting model results to match current temperatures suggests there is a little more headroom, making the 1.5°C target still feasible, though extremely challenging to reach (Millar *et al.*, 2017).

An important rationale for strong action on mitigation is the need to avoid much higher-than-expected damages or 'fat-tail' risks (see Section 5). These become much more likely at higher levels of warming, but cannot be ruled out at low-to-moderate warming levels. One of the key assumptions made in most economic assessment models is that climate damages are a smooth function of temperature[6]. For example in the classic Nordhaus DICE model (Nordhaus, 2014), damages are assumed to be proportional to the square of the temperature change. However, the scientific confidence in such assumptions is not strong, especially at higher temperatures. Evidence from ice core and sediment records shows that in the past, Earth's climate has reached critical thresholds, triggering abrupt change. These can occur due to the existence of positive feedbacks or self-amplification effects (Lenton *et al.*, 2008; Levermann *et al.*, 2012). Evidence from climate models shows that they could be reached again as the planet warms in response to GHGs (AVOID2, 2017). Kriegler *et al.*, (2009) studied the possibility of the following tipping points:

[6] A smooth function implies a predictable relationship between damages and temperature without abrupt changes

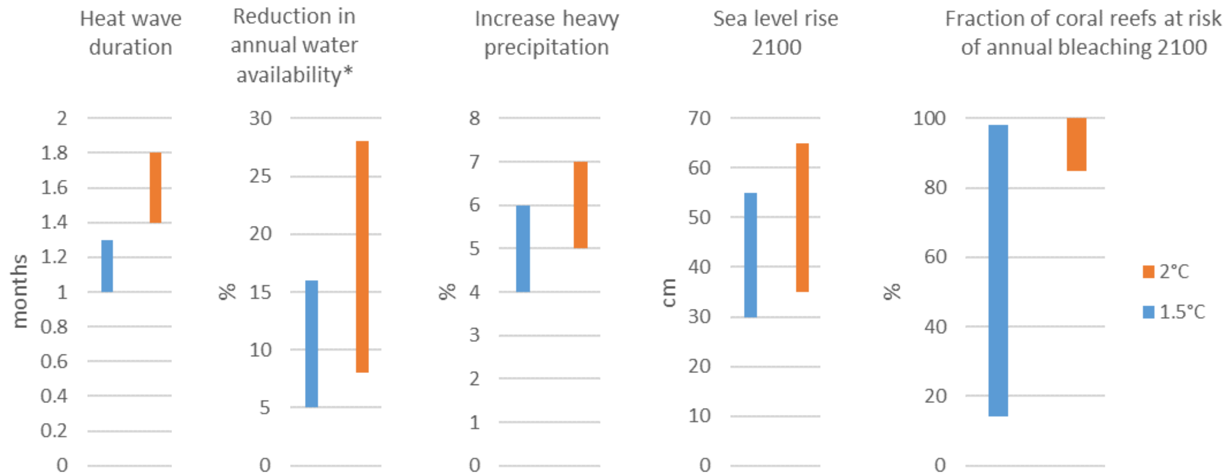
- Ice sheets on Greenland and West Antarctica
- Atlantic meridional overturning circulation
- Dieback of Amazon rainforest
- El Ninõ/Southern Oscillation (ENSO)

They found a lower bound probability of triggering at least one of these events of 16% for medium (2-4°C), and 56% for high global mean temperature change (above 4 °C) relative to year 2000 levels. Other potential tipping points include melting of Arctic sea ice and mountain glaciers, and climate feedback with stratospheric ozone (Levermann *et al.*, 2012). However, the risks of any of these cannot yet be assessed precisely, neither can the full impacts of any resulting large-scale climate changes. Whilst it is difficult to account for their likelihood in models and associated costs in policy, it is clear that the chance of triggering any such events would be reduced through GHG reductions (AVOID2, 2017), and **avoiding such events is a key reason to aim for lower warming targets**.

Although the worst impacts of climate change are expected to occur at temperatures of 3-4°C or above, there are still expected to be significant impacts at 2°C or below. Impacts are not only associated with increases in mean temperatures, but also with greater climate variability (e.g. swings between wet and dry periods in a particular region). Impacts are already being felt, with the highest economic losses as a proportion of GDP being experienced in developing countries (IPCC, 2012). The IMPACT2C project (IMPACT2C, 2015) has assessed that with the exception of the deep mitigation scenario, we are likely to exceed 2°C warming before the middle of the century. The analysis shows that even if the goal of remaining within 2°C is achieved, Europe will experience physical and economic impacts that are unevenly distributed geographically and between sectors of society: a 2°C world is therefore not benign. Many of the changes will exacerbate existing weather-related impacts including higher relative warming and heat extremes in southern Europe in summertime, and increased heavy precipitation events in Eastern Europe along existing flood risk corridors. Even in areas where there will be benefits (e.g. higher winter warming in the north, which will have the benefit of reduced winter mortality and reduced winter heating demand), there will also be negative impacts, such as on winter tourism and natural ecosystems. Global impacts such as sea level rise will also affect Europe, creating risks particularly for coastal cities, with rises of 0.35m (median) up to 0.52m (95^{th} percentile) by 2100 under a 2°C scenario, and considerably higher rises expected with greater warming.

Assessments of 1.5°C warming scenarios show that for most indicators, impacts are (as expected) less than for 2°C, but are still substantial (Figure 4). However, for some indicators there is little difference in impact between 1.5°C and 2°C for the areas exposed to a decline in crop suitability, and exposure to extreme heat stress is already eliminated at 2°C. Sea dyke costs are similar in 2100 under the 1.5°C and 2°C pathways, but are considerably lower under 1.5°C in earlier years (Arnell *et al.*, 2016).

Figure 4: Summary of differences in climate impacts between 1.5^{0}C and 2^{0}C warming scenarios over the 21st century for selected indicators



Source: (Schleussner et al., 2016). Bars represent likely (66%) confidence ranges.
* Values are global, except for reduction in annual water availability which is for Mediterranean regions

4. Key issues in climate economics

Why look at global costs?

Whilst there is some analysis in the literature of impacts specifically relevant to Scotland (See Section 7), most of the analyses reviewed in this report are global estimates. This is relevant because the physical impacts and economic damages arising from Scotland's GHG emissions are global in nature, and this shared responsibility for global climate change is in the spirit of United Nations Framework Convention on Climate Change (UNFCCC) agreements to which the UK is signatory and from which Scottish Climate Change policy derived. Current Scottish climate change targets are based on an assessment by the Committee on Climate Change regarding Scotland's 'share' of global emissions in a 'below 2 degrees world' (on the same basis as the UK Carbon Budgets) (Committee on Climate Change, 2015). In this important respect assessment of physical impacts and damage costs is essentially 'top down', i.e. determined mainly by external normative factors.

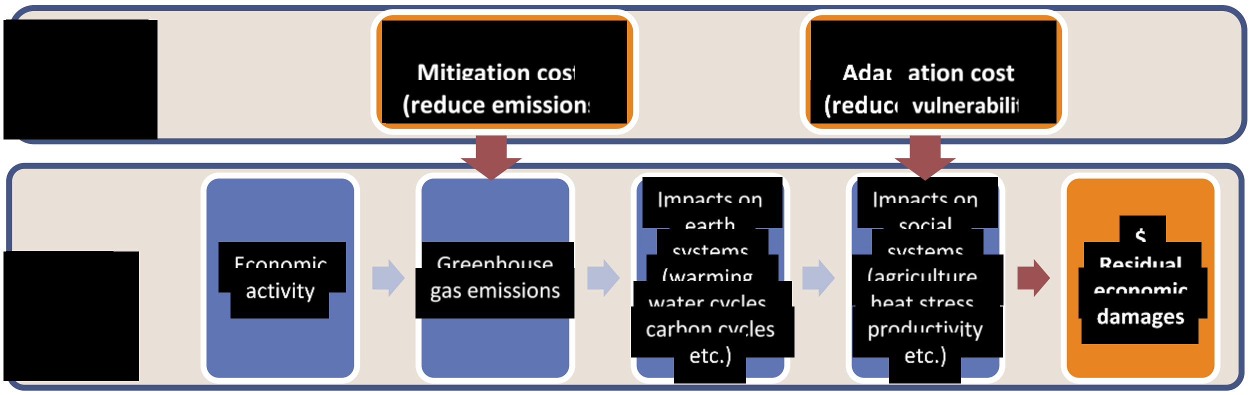
This contrasts with costing of mitigation activity, which is more 'bottom up', with individual nations able to determine the best and most effective 'fit' in line with wider economic and societal objectives and constraints. This review identified a small number of studies of Scottish mitigation costs, but it mainly focuses on global estimates of mitigation costs in order to provide a broader comparison of the balance between mitigation and damage costs, as well as providing some context to the work currently underway by the Scottish Government to assess in more detail the likely cost implications of its policy decisions on mitigation targets.

Mitigation, adaptation and damage costs: comparing apples and oranges?

Climate change economics is primarily concerned with assessing on the one hand the costs of climate change damages, and on the other hand the costs of reducing these impacts either through mitigating GHG emissions or taking adaption measures to reduce exposure and vulnerability. In principle these costs can be presented in comparable ways, as attempted in this report, although the following sections outline some of the methodological issues and complexities that need to be borne in mind when making such comparisons. Figure 5 illustrates the causal chain of events (in blue) leading to anthropogenic climate change impacts, and identifies the three points in this chain (in orange) where climate change economics assesses cost implications:

- **Mitigation**: the cost of reducing / abating emissions of GHGs, e.g. due to additional investment and operating costs arising from changes to the stock of buildings, vehicles, manufacturing equipment, behaviour etc. in the economy
- **Adaptation**: the cost of measures taken to reduce the vulnerability to social impacts of climate change, such as investing in research into drought-resistant crops, building sea-walls, flood defences, irrigation systems etc.
- **Damage costs** (or economic impacts). The monetised estimates of the residual economic damages to social and environmental systems. Damages can be reduced, but not eliminated through adaptation and mitigation.

Figure 5. Causal chain of climate damages, with different elements of climate change costs marked in orange (illustration: authors' own.)

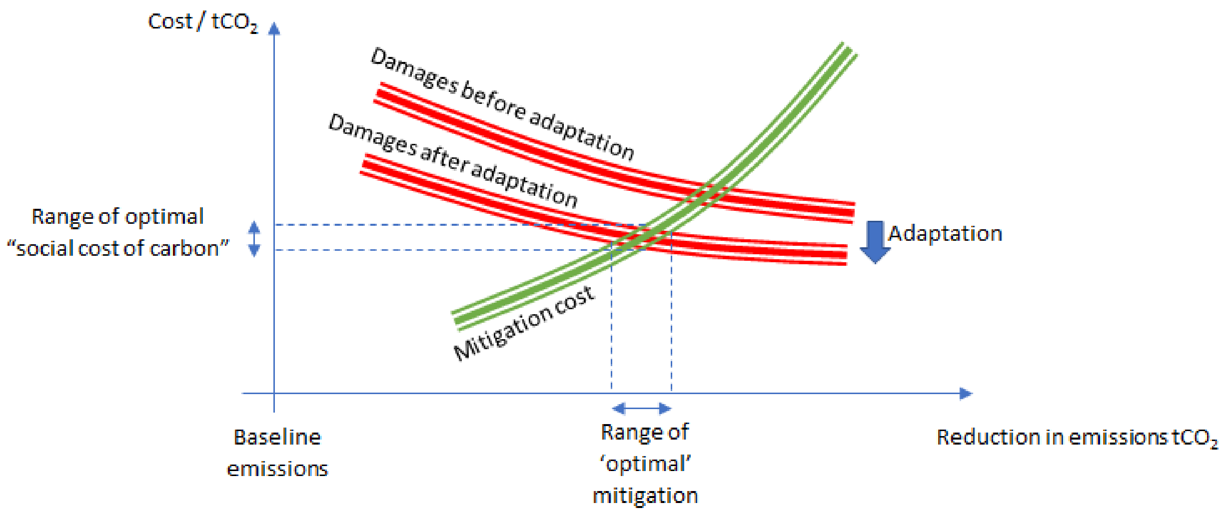


Mitigation costs generally increase for greater levels of emission reduction because of the law of diminishing returns, and because reductions need to be found from successively harder-to-reach sectors. Conversely, greater emissions reductions will result in a reduction in residual economic damages. Since mitigation and damage costs move in 'opposite directions', there is a balance point in the level of mitigation at which they are equal (see Figure 6). Since both cost functions are non-linear, this is the point at which combined costs to the economy (damages + mitigation) are minimised, and therefore considered optimal from an economic point of view. This balance point is called the "social cost of carbon" (SCC)[7], and measures both the value of damages incurred for each tonne emitted, and the value of saving a tonne of CO_2. Estimates of the SCC (as reported in Section 5)[8] can therefore, at least in principle, be compared with the marginal costs of abatement (as reported in Section 6) to give indication of the cost-effectiveness of investing in mitigation to reduce damage costs.

[7] SCC is theoretically a measure of both mitigation and damage cost along an optimal emissions pathway, but is commonly used to measure damage costs for optimal and non-optimal emissions pathways alike.

[8] SCC has a formal definition under which only some types of study apply, including integrated assessment models. In this report we use 'damage costs' as a more generic term so as to incorporate results from other studies which measure damages in a different way.

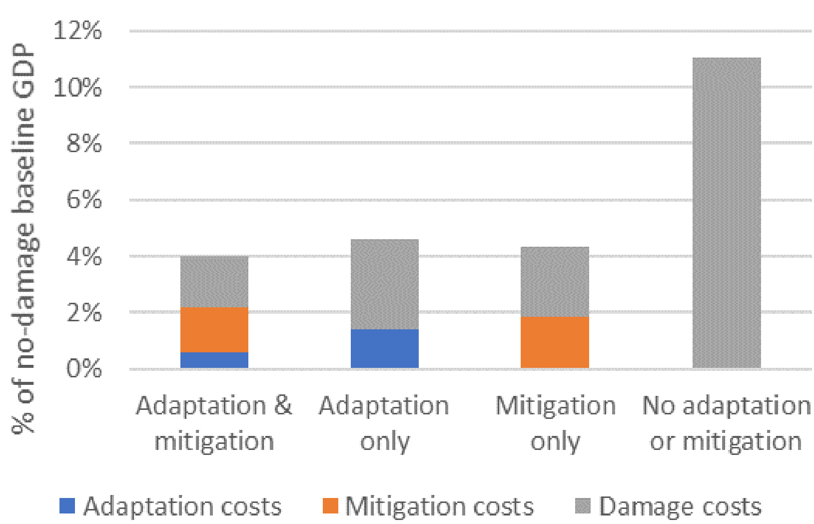
Figure 6. Schematic showing the balance point between damage costs and abatement costs per tonne of carbon. Width of bands illustrates uncertainty. (illustration, authors' own)



Integrated assessment models (IAMs) and computable general equilibrium (CGE) models are important classes of model that have played an influential role in policy-making because they cover all the elements in the causal chain, usually have global coverage, and are therefore designed to find the SCC by assessing the trade-offs between mitigation, adaptation and damage costs.

One example is the recent review of the economic consequences of climate change by the OECD (2015) which explicitly shows the total economic impacts across all three types of cost reproduced in Figure 7. These results illustrate an important conceptual point, that the total economic cost of climate change is the sum of all three cost types.

Figure 7. Estimates of total economic impact by 2100, combining mitigation, adaptation and damage cost: source (OECD, 2015)



In practice, defining optimal abatement levels in this way is complex, partly due to uncertainties in these cost functions. Single point estimates of cost do not adequately reflect economic risk and uncertainty. This is because the nature of these risks is different across the three types of cost. Risks cannot easily be added up in the same way as these central estimates. In addition, abatement costs and damage costs are not borne by the same people geographically, nor by the same generations in time. Trading off these costs against each other therefore raises important issues of intergenerational and international equity that are as much the domain of ethics and politics as they are of economics. Aggregated estimates of the cost of carbon or GDP impacts therefore need to be interpreted with care.

Whilst the SCC calculated by IAMs are still widely used to inform policy-making (Watkiss and Hope, 2011; IWG, 2016), and are central to the state-of-knowledge on climate change economics as reported by the IPCC (Arent *et al.*, 2014), other research efforts focus on understanding each type of cost more completely. Separating out the different cost elements allows policy-makers to engage more directly with the ethical and political dimensions of climate decisions, but makes it imperative that policy-makers are conscious of these complexities when comparing these different types of cost. These issues are discussed in the following sections.

Choice of metrics and dealing with time

Emissions trajectories are measured in a number of different ways in the literature, and therefore reported differently in the results sections 5 and 6. Because the degree of warming that will occur for a given concentration of GHGs is uncertain, warming levels for a given trajectory are sometimes presented in probabilistic terms – e.g. a 66% 2°C scenario indicates that a certain emissions trajectory has a 66% chance (deemed 'likely' in IPCC terminology) of staying below 2°C warming. Not all studies specify this probability, making it hard to compare directly. Some studies get around this uncertainty by instead specifying targets in terms of atmospheric concentration levels. E.g. 450 parts per million (ppm) is a physical measure of GHG concentrations; models suggest this is equivalent to about a 50% chance of limiting warming to 2°C. A higher concentration of 550 ppm, representing a doubling of pre-industrial concentrations, would most likely raise warming to the range 3-4°C warming. More recent studies instead use what are called 'representative concentration pathways' (RCPs) which allow different models to standardise the way they model the trajectory of atmospheric concentrations over time. These include a high emissions pathway RCP 8.5, two moderate pathways RCP 6, RCP 4.5, and a low emissions pathway RCP 2.6[9] which is result in median temperature rises by end of century around 4.5°C, 2.9°C, 2.4°C and 1.5°C respectively (Rogelj, Meinshausen and Knutti, 2012).

In terms of measuring costs, the previous section shows that when damages are measured in terms of cost /tCO_2, they can in principle be compared with the abatement cost /tCO_2. However, there is an important time dimension to these costs. Concentrations of GHGs in the atmosphere are increasing over time, which means that the damage done by an incremental extra tonne of CO_2 emitted into the atmosphere also increases over time. Two ways to address this are:

i. Discount all future damages and abatement costs over the course of the century (or longer) back to present values using a discount rate
ii. Compare costs directly at different time horizons

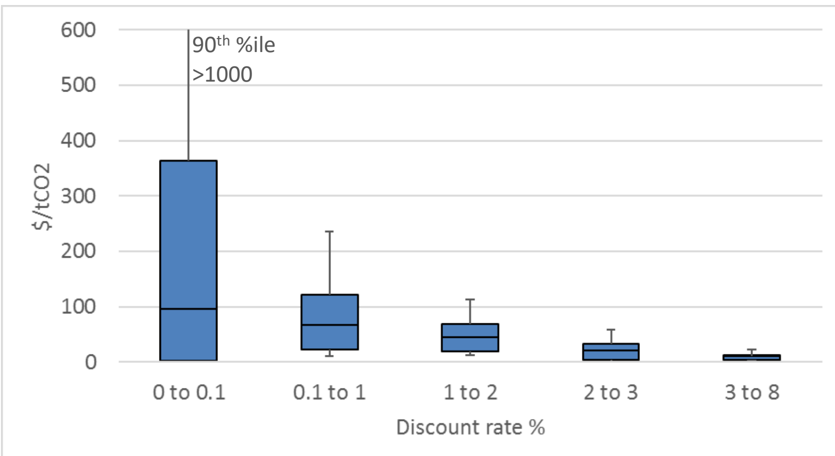
The first option is appealing, since it allows in principle all aspects of future costs to be summarized in a single figure that can be used to guide public policy on how much effort to put in to abating emissions in order to reduce damages. However, the choice of discount rate is highly controversial (Nordhaus, 2007;

[9] The numbers refer to the total radiative forcing caused by the cumulative emissions pathway, measured in Watts/m^2

Dietz and Stern, 2008), because it has a very strong impact on the present value of high future costs of climate change. For example, £100 worth of damages in 2100, discounted to present value at 5%, 2.5% and 1% discount rates would be worth around £2, £13 and £44 respectively today.

Figure 8 shows estimates of climate damages discounted back to present values reported by IPCC AR5. The figure illustrates that the choice of discount rate tends to be a dominant factor when reporting damages in present value terms, overriding differences in model design and other modelling assumptions. The choice of discount rate is also contentious because it reflects political and ethical issues of how costs borne by future generations weigh against costs borne by current generations, and how costs borne by poorer parts of the world weigh relative to richer parts of the world. In the UK, the 'social time preference rate' recommended by HM Treasury (2008) is 3.5% but with this declining when applied to periods beyond 30 years.

Figure 8. Effect of discount rate on the cost of carbon[10]*. Source:* (Arent *et al.*, 2014)



The second option avoids having to choose a discount rate, though does involve equivalent difficulties of choosing a future date at which to compare costs. In this report we look at mid-Century and end-Century costs rather than discounting them back to present values. This choice reflects the context of the study which aims to inform policy-decisions on mid-century emissions target. This approach is preferred by some commentators, who argue that a long-term view provides a more useful guideline for policy given the difficult and protracted process for actually agreeing on a climate policy (Pindyck, 2016), and the complex, uncertain and long-term process of enacting an energy sector transition (Foxon, 2011).

A different metric for costs is to measure the total cost of mitigation or damages per unit of GDP. This gives an indicator of the scale climate change costs relative to the economy as a whole. Some models, (such as the computable general equilibrium model used by the OECD as reported in the previous section) explicitly model economic growth, so that costs per unit of GDP are inherent within the model. Others, including some leading IAMs, simply make assumptions about economic growth rates and the size of the future economy, from which the costs per unit of GDP can be inferred. In Sections 5 and 6, both costs per tonne and costs as a percentage of future GDP are presented as reported in the literature – some studies report their results in both units.

[10] The figure shows values reported by IPCC in present value terms, differentiated by the discount rates used in different studies.

Assessing climate damages

Different categories of economic impact require different approaches to quantification. Hallegatte Henriet and Corfee-Morlot (2008) differentiate between *market impacts* (those that can be readily valued in monetary terms) and *non-market impacts* (those without a direct monetary value). Non-market impacts include impacts that are hard or even impossible to quantify, such as quality of life, biodiversity and ecosystem loss (Garnaut, 2011). Different approaches to economic analysis of such climate impacts were reviewed by Keating and Handmer (2011). Some models, including IAMs can incorporate welfare economics approaches such as willingness to pay (WTP) or willingness to accept (WTA) measures of value, often based on surveys. These can in theory include everything that is valued by people, including things that are not traded in a market place such as social and environmental impacts.

For other models, such as CGE models which deal more directly with the generation of GDP as a measure of economic activity and value, it is harder to incorporate these kinds of non-market costs, which sit outside of the measurement of an economy's recorded production, consumption and income generation. In general, however, and despite accounting (and discounting) advice provided by government bodies in publications such as the UK 'Green Book', the degree of confidence with which climate impacts can be translated into climate damages is not high, leading to calls for much greater levels of research in this area (National Academies, 2017).

Different types of economic impact may result from expected (mean) climate changes, changes in climate variability, and catastrophic changes. Some economic impacts may also be harder to measure because they are indirect, e.g. spatial or sectoral diffusion of economic losses into the wider economic system, rather than direct impacts on services or infrastructure (Hallegatte, Henriet and Corfee-Morlot, 2008). Because of this diversity, not all economic analyses include the same range of impacts, leading to considerable variation in estimates of economic damages, even when the same degree of warming is assumed. However, when viewed across all studies as a whole, reduced warming unambiguously leads to reduced damages, as is illustrated in the results Section 5.

IAMs combine climate damages, adaptation, and mitigation into a single model framework: Weyant (2017) provides a review. Because of their apparent completeness, these models have become widely adopted, and arguably represent the core of mainstream assessments of economic impacts e.g. (IPCC, 2014b). The main steps include Greenstone Kopits and Wolverton (2013):

(1) Projections of future emissions of GHGs under a ''business as usual'' and one or more abatement scenarios, and resulting future atmospheric concentrations
(2) Projections of the effects of GHGs on the climate system, and knock-on biophysical and social impacts
(3) Translation of these environmental impacts into economic damages (lost GDP and consumption)
(4) Estimates of the cost of abating GHG emissions by various amounts
(5) Assumptions about discount rate and social utility, so that lost consumption from abatement can be weighed against future gains in consumption from reduced warming

Each of these steps contains uncertainties, but the most significant relate to estimates of the damages (step 3), and the choice of discount rate (step 5). Estimates of damages, usually incorporated as a 'damage function' in the models, are uncertain because of the unprecedented nature (within human history) of the warming being assessed, the potential for much higher-than-expected outcomes[11],

[11] See Box 2

uncertainty over the extent of adaptation to change, and the highly localised nature of some climate damages.

A review undertaken by the US National Academies of Sciences, Engineering and Medicine (National Academies, 2017) into the methodologies used in IAMs found that improvements were needed to incorporate the latest research on climate impacts and damages, and also, that there were significant evidence gaps regarding these damages. This evidence base is however growing rapidly. As noted in Carleton and Hsiang (2016), historically, the damage functions used in these models were theoretical constructs whose structures were based on modelling intuition informed by some data, but the recent explosion of empirical work suggests that these global policy models can now be calibrated to real-world relationships that characterise the many social impacts of climate. The paper provides a review of recent studies of such impacts which include:

- **Health impacts**: mortality rates, morbidity, and especially early-life impacts
- **Economic impacts**: agricultural yields, labour supply and productivity, energy supply and demand, trade, and economy-wide effects
- **Social interaction**: interpersonal violence and aggression, intergroup violence, institutional breakdown and state failure, migration, population structure and growth

Some research is emerging which adapts the damage functions, but maintains the overall IAM structure (Dietz and Stern, 2015; Howard and Sylvan, 2016).

However, the intrinsic limitations of current IAMs have led some critics to question their suitability for informing public policy (Pindyck, 2017). Indeed, such concerns raise wider questions as to whether normal cost-benefit analysis is an appropriate tool to be applied to climate change (Millner, Dietz and Heal, 2010). If damages are severe enough to reduce future wealth compared to today's levels, a particular risk for more poorer and more vulnerable countries (World Bank, 2013; Burke, Hsiang and Miguel, 2015), this could at least in principle result in negative discount rates and 'infinite' damage estimates (Tol, 2003). The potential for such catastrophic effects creates extreme difficulties in carrying out traditional cost-benefit analyses (Weitzman, 2009; Stern, 2013).

Because of the skew of probability distributions towards high damages, incorporation into the analysis of these uncertainties and possible tipping points leads to higher optimal carbon prices (i.e. greater levels of abatement) than would be the case in a deterministic world where damages were know for certain; see e.g. (Kopp *et al.*, 2012; Cai, Judd and Lontzek, 2013; Cai *et al.*, 2015).

As noted by the International Monetary Fund (IMF), there is a crucial distinction to be made between output impacts vs. growth *rate* impacts. Output impacts assume there is a damage impact in a particular year, whereas impacts on growth rates accumulate over time. Two of the three main integrated IAMs currently assume that the impact of climate is on the level of output only, with the growth of total-factor productivity continuing unaffected (Dell *et al.*, 2014). However, because growth rates compound exponentially over time, even modest impacts on growth rates would accumulate into large effects on welfare over the course of the century compared to a 'no-damage' baseline, and would ultimately dwarf the output level effects measured in most traditional assessments of climate damages (IMF, 2017).

Evidence of such impacts on growth rates is emerging across a number of sectors, as reviewed by the ACT (ACT, 2017). For example, analysis of historical weather-based evidence from (Dell, Jones and Olken, 2012) suggests that, for poor countries, temperature shocks appear to have long-lasting effects on factors such as industrial value-added and political instability, leading to long-term economic and social impacts, including reductions in growth rates. Hsiang and Jina (2013) find similar long-lasting effects for cyclones; they find robust evidence that national incomes decline as a result of major storms, relative to their pre-disaster trend, and do not recover within twenty years. Both rich and poor countries exhibit a small but persistent suppression of annual growth rates spread across the fifteen years following disaster, generating large and significant cumulative effects. Linking these results to projections of future cyclone activity, they estimate that the cost of "business as usual" climate change is roughly $9.7 trillion larger than previously thought.

Other studies show that whilst harder to measure, indirect effects can be larger than the direct effects that tend to be included in IAMs: for example, using a CGE model, (Houser *et al.*, 2015) found that the long-term growth impacts of capital destruction caused by coastal storms on the United States as a whole were several times larger than the initial cost. Evidence that economic impacts in the agriculture sector may also be higher than previously estimated are also emerging: Moore *et al.* (2016) find negative effects of warming on most crops in most places and very limited potential for adaptation to offset declines, leading to revised estimates of damage functions which more than triple the SCC based on the FUND IAM from $7 per ton to $23 per ton.

The results (Section 5) show some global estimates emerging from this new literature, though such studies are still relatively few in number, and it is not clear yet that they have changed the more traditional consensus view expressed in the IPCC review (IPCC, 2014b).

Assessing adaptation costs

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities. People who are socially, economically, culturally, politically, institutionally, or otherwise marginalised are especially vulnerable to climate change. High exposure and vulnerability are generally the outcome of skewed development processes such as those associated with environmental degradation, rapid and unplanned urbanisation in hazardous areas, failures of governance, and the scarcity of livelihood options for the poor (IPCC, 2012, 2014b).

Adaptation is the process of adjustment to actual or expected climate and its effects. Adaptation measures typically aim to increase resilience, and reduce exposure or vulnerability in order to reduce the damaging effects of climate change. Some of these measures will incur additional cost in terms of capital goods and infrastructure, though some 'low-regret' measures may also be available at no- or low-cost, requiring changes to the type and timing of investments, but not necessarily incurring significantly greater costs that would otherwise have been made.

Low-regrets measures that provide benefits under current climate and a range of future climate change scenarios are available starting points for addressing projected trends in exposure, vulnerability, and climate extremes. Many of these low-regrets strategies produce co-benefits, help address other development goals, such as improvements in livelihoods, human well-being, and biodiversity conservation, and help minimise the scope for maladaptation.

Potential low-regrets measures include early warning systems; risk communication between decision makers and local citizens; sustainable land management, including land use planning; and ecosystem management and restoration. Other low-regrets measures include improvements to health surveillance, water supply, sanitation, and irrigation and drainage systems; climate-proofing of infrastructure; development and enforcement of building codes; and better education and awareness (IPCC, 2012).

Effective risk management generally involves a portfolio of actions to reduce and transfer risk and to respond to events and disasters. Such integrated approaches are more effective when they are informed by and customised to specific local circumstances. Successful strategies include a combination of hard infrastructure-based responses and soft solutions such as individual and institutional capacity building and ecosystem-based responses. Investments in capital goods such as coastal protection infrastructure (sea walls), water storage and irrigation facilities, disaster early warning systems, are all examples of 'stock adaptation' that accumulate upfront investments that then offer a stream of benefits well into the future. 'Flow adaptation' creates immediate benefits which only last for the duration of the expenditure. These actions are typically reactive, such as changes in agricultural practices, energy expenditures for space heating and cooling, treatment of climate related diseases and disaster relief and recovery costs (Agrawala *et al.*, 2010).

Estimating and modelling the costs of adaptation at global level is particularly problematic because adaptation measures are so localised, the nature of the climate impacts being adapted to at local level are still so uncertain, and are dependent on the uncertain dynamics of economic development, urbanisation and demographic trends[12]. However, in general the literature on global adaptation costs is relatively sparse: the IPCC AR5 review in 2014 includes just two literature sources with aggregate estimates of future adaptation costs:

- The UNFCCC (2007) estimates the additional investment and financial flows in the context of climate finance needed to support adaptation globally $48-171 billion per year by 2030, of which $28-67 billion is for developing countries.
- The World Bank (2010) estimates aggregate adaptation costs for World Bank regions (i.e. low-income and middle-income countries) at $70-100 billion per year on average between 2010 and 2050. The report notes that this is the same order of magnitude as the foreign aid that developed countries now give developing countries each year. But it is still a very low percentage (0.17%) of the wealth of these countries, though the study does not include a full range of sectors.
- The OECD (Agrawala *et al.*, 2010) uses a global economy-wide IAM to estimate global adaptation costs of 0.18%-0.3% of global GDP by 2050, growing over time to around 0.6-1% of global GDP by 2100. These investments in adaptation are estimated to lead to a net reduction in total climate change costs (damages plus adaptation costs) of around 1.4%-2% of GDP by 2100.

Some authors suggest that methodological difficulties are effectively insurmountable, and little weight or effort should be given to global estimates of adaptation costs (Patt *et al.*, 2010; Watkiss, Benzie and Klein, 2015). Because of the strong interlinkages between adaptation and damages, most IAMs do include assumptions about the extent of adaptation, but do not separate out the costs of these measures. This is the reason adaptation costs are not further reviewed in the results section of this report. Box 1 outlines the approaches and challenges as described in IPCC (2012).

Box 1. Challenges with estimating global adaptation costs (from IPCC, 2012)

Global assessments of adaptation costs have used two approaches: (1) determining the pure financial costs, that is, outlays necessary for specific adaptation interventions; and (2) economic costs involving estimating the wider overall costs and benefits to society and comparing this to mitigation, often using IAMs. One way of measuring the costs of adaptation involves first establishing a baseline development path (for a country or all countries) with no climate change, and then altering the baseline to take into account the impacts of climate change. Then the potential effects of various adaptation strategies on development or growth can be examined. Adaptation cost estimates are based on various assumptions about the baseline scenario and the effectiveness of adaptation measures. The difference between these assumptions makes it very difficult to compare or aggregate results.

An example illustrating methodological challenges comes from agriculture, where estimates have been made using various assumptions about adaptation behaviour. These assumptions about behaviour range from the

[12] For a review of approaches to adaptation modelling, see: Bosello, Carraro and De Cian (2011); Dobes, Jotzo and Stern (2014); Landauer, Juhola and Söderholm (2015); Jurgilevich *et al.* (2017).

farmers who do not react to observed changes in climate conditions (especially in studies that use crop yield sensitivity to weather variability), to the introduction of selected adaptation measures within crop yield models, to the assumption of 'perfect' adaptation – that is, farmers have complete or 'perfect' knowledge and apply that knowledge in ways that ensure outcomes align exactly with theoretical predictions, and that actual climate outcomes also conform to these theoretical predictions . Realistic assessments fall between these extremes, and a realistic representation of future adaptation patterns depends on the in-due-time detection of the climate change signal; the inertia in adoption of new technologies; the existence of price signals; and assessments of plausible behaviour by farmers.

Assessing mitigation costs

Estimates of the aggregate economic costs of mitigation vary widely and are highly sensitive to model design and assumptions as well as the specification of scenarios, including the characterisation of technologies and the timing of mitigation. Idealised scenarios in which all countries of the world begin mitigation immediately, there is a single global carbon price, and all key technologies are available, have been used as a benchmark for estimating cost-effective macroeconomic mitigation costs. Under these assumptions, mitigation scenarios that reach atmospheric concentrations of about 450 ppm CO_2 equivalent by 2100 (50% chance of limiting to 2°C) entail costs relative to global GDP of 1% to 4% (median: 1.7%) in 2030, 2% to 6% (median: 3.4%) in 2050, and 3% to 11% (median: 4.8%) in 2100 (IPCC, 2014a). In practice, the cost of mitigation will deviate from these idealised conditions.

Mitigation costs are sensitive to the rate of decarbonisation. Delaying mitigation generally increases the cost of reaching a particular level of atmospheric concentration of GHGs because it implies steeper reductions in the future (IPCC, 2014a). Global estimates of mitigation costs generally either come from IAMs, or from partial equilibrium analysis using data-rich bottom-up models. These latter models look in detail at sectors of the economy where emissions reductions are most prevalent (energy, transport, land-use etc.) and include more detailed technology analysis.

A recent report from the IEA and IRENA for the German G20 Presidency illustrates some of the issues (IEA and IRENA, 2017). The report shows that reaching a 2°C scenario with 66% probability would require an unparalleled ramp up of all low-carbon technologies in all countries. An ambitious set of policy measures, including the rapid phase out of fossil fuel subsidies, robust carbon prices, extensive energy market reforms, and stringent low-carbon and energy efficiency mandates would be needed to achieve this transition. Such policies would need to be introduced immediately and comprehensively across all countries to achieve the 66% 2°C Scenario, with CO_2 prices reaching up to $190 per tonne of CO_2. The scenario also requires broader and deeper global efforts on technology collaboration to facilitate low-carbon technology development and deployment.

IEA and IRENA (2017) also show that, from an investment perspective, the energy sector transition in the 66% 2°C Scenario would require not only more capital expenditure, but also a fundamental reallocation of capital compared with today's portfolio. The report compares what would be needed to reach the 66% 2°C Scenario with a 'New Policies Scenario' – in simple terms all current policies plus current commitments and targets. The report argues that a large, sustained increase in the capital flows for low-carbon energy options and efficiency measures would be an essential prerequisite. Cumulative energy supply- and demand-side investment in the 66% 2°C Scenario is over USD 120 trillion, 25% more than the USD 99 trillion needed in the New Policies Scenario. There is also a marked difference in the destination of this capital between the two scenarios: in the New Policies Scenario, 65% of the total is spent on energy supply, compared with less than 50% in the 66% 2°C Scenario, largely because energy is used more efficiently in the 66% 2°C Scenario. Furthermore, in the New Policies Scenario, nearly 45% of total energy supply investment is still spent on fossil fuel extraction. In the 66% 2°C Scenario, less than 20% of total energy supply investment would be for fossil fuel extraction.

Typically 1.5 °C scenarios do not manage to keep temperatures below 1.5°C for the entire duration of the 21st century, because of the very small remaining window for allowable emissions. Instead scenarios tend to allow temperatures to go higher temporarily but return to below 1.5°C by 2100. This is referred to as a temperature 'overshoot'. Limiting warming to below 1.5°C by 2100 generally requires similar transformations in the energy system as holding warming to below 2°C during the 21st century, but the decarbonisation of the energy system needs to be faster and more pronounced. Scenarios that keep temperature increase to less than 2°C with a 'likely' (a more than 66%) chance already rely on deep emission reductions (40-70% below 2010 levels by mid-century), particularly in the energy-supply sector (reductions of 90% or more below 2010 levels between 2040 and 2070) (Schaeffer *et al.*, 2015).

In addition to what is already needed for keeping warming 'likely' below 2°C, 1.5°C scenarios are characterised by (Rogelj *et al.*, 2015):

- Both 1.5°C and likely 2°C scenarios emit almost zero carbon emissions from electricity by 2050. This transformation is achieved more quickly in 1.5 °C scenarios, with CO_2 emissions from electricity in 1.5 °C scenarios being already about 35%-55% lower in 2030 than in 2 °C scenarios due to greater use of renewables, nuclear and carbon capture and storage (CCS).
- Both 1.5°C and likely 2°C scenarios assume increased use of electricity in the transport sector where 5%-30% (median 25%) of global transport could be electrified by 2050. In addition, the 1.5°C scenarios assume greater demand reductions and use of biofuels, leading to further emission of 40% by 2050.
- Energy efficiency also plays a crucial role in other end-use sectors. Emissions reductions by 2050 are 25% lower in the industrial sector and 50% lower for residential and commercial buildings in the 1.5°C compared to the likely 2°C scenarios.
- Much greater deployment of negative emissions or GHG reduction technologies, especially after 2030/2050
- Aggregated long-term mitigation costs that are about 1.5 to 2.1 times higher for 1.5°C than for 2°C scenarios, with a larger effect on near-term costs than on long-term costs;

In the short term, emission scenarios consistent with 1.5°C and 2°C have been shown to overlap until the 2020s. However, by 2030, emissions levels would need to be significantly lower, requiring greater investments in low-carbon technologies in the coming decade, and further reducing the energy intensity of the economy. 1.5°C scenarios reduce global primary energy intensity by 2.6% per year on average over the period 2020-2040, compared to 2.3% for the below 2°C scenarios. Historically, global primary energy intensity over the period 1970-2010 has reduced at 1.2% per year, so each of the scenario groups explored here represents an approximate doubling of this rate (Gambhir, 2017).

The deeper and more rapid emission reductions from the 2030s onwards in 1.5°C scenarios would not only aim to hold warming below 1.5°C by 2100, but also hedge against technological uncertainties or ensure a high chance (around 85%) of limiting warming below 2°C. This is significantly better than a minimum 66% chance of a 'likely' 2°C pathway (Schaeffer *et al.*, 2015).

Like most 2°C scenarios, 1.5°C scenarios depend on the availability of technologies leading to negative CO_2 emissions, with virtually no flexibility to "opt out" of such technologies. This means significantly greater use of BECCS. These scenarios are controversial because of the significant switch to biomass energy and the implications for land-use change.

Some authors question the suitability of models that aim to impute mitigation costs as far into the future as 2050 or 2100, arguing that such costs are so uncertain that there is little value to policy-makers in making such estimates (Rosen and Guenther, 2015). Several organisations identify technology pathways (GEA, 2012; IEA, 2017; IRENA, 2017), and aim to assess how the costs of low-carbon technologies will evolve, though cost projections usually only go out to 2030 or less. These studies provide useful guidance to modellers and policy-makers alike, especially for planning technology support policies in the near term.

Such assessments are by definition confined to currently-identified technologies, which is a problem when looking at the more distant future. In addition, there is an inherent difficulty in predicting the outcome of non-linear learning effects whereby increased levels of uptake of a technology create economies of scale and cost reductions, which in turn leads to further increases in uptake. Such learning curve effects have been behind the dramatic reductions in the costs of solar photovoltaic (PV) and offshore wind seen in recent years which have outstripped modellers' forecasts (Candelise, Winskel and Gross, 2013). . This illustrates a risk of status quo bias when looking into the future of technology development. However, it is important to also avoid the opposite mistake of hindsight bias; not all energy technologies will experience similar cost reduction pathways. Rubin *et al.* (2015) outlines considerable shortcomings in the ability of current 'learning curve' models to represent the complex drivers of technology cost reductions. Future technology cost estimates remain highly uncertain.

The Global Commission on the Economy and Climate (2014) conclude that actions and policies which can reduce GHG emissions are not inevitably damaging to growth and other economic goals, and that better economic management can deliver growth and less climate risk at the same time. They suggest this is made possible by structural and technological changes unfolding in the global economy and opportunities for greater economic efficiency. The capital required, around US$90 trillion, will need to be invested in infrastructure in the world's urban, land use and energy systems and will shape future patterns of growth, productivity and living standards.

Likewise, economic modelling by the OECD (2017) suggests that for G20 countries (excluding the EU), climate mitigation policies in line with a 50% chance of 2°C scenario can be combined with pro-growth investment strategies to boost GDP levels by up to 2.8% by 2100 (or 4.8% total GDP increase if the benefits of avoided climate impacts are included). This result depends on tackling market failures through targeted government spending to support structural reforms and close infrastructure investment gaps which currently limit growth. This allows the negative economic impacts of mitigation (higher energy prices and regulatory costs) to be more than offset by the growth effects of higher net investment, structural reform and enhanced levels of technical innovation, though it should be noted that such growth pathways might also be available that do not involve these levels of mitigation.

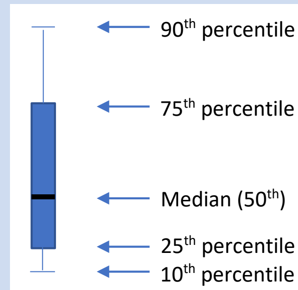
Mitigation costs may also to some extent be offset by 'co-benefits' i.e. reductions in other impacts such as air pollution and other environmental externalities, which tend not to be included in mitigation cost estimates. These co-benefits can be considerable, worth in the region of \$2-196/tCO_2 (mean \$49/tCO_2) (Nemet, Holloway and Meier, 2010), and could therefore cover a sizeable part of mitigation costs in OECD countries (Bollen *et al.*, 2009). Some authors also argue that environmental controls can drive wider improvements in efficiency that can have positive benefits to companies, despite the apparent additional costs, the so-called 'Porter hypothesis' (Porter, 1991). A recent review of evidence of the Porter hypothesis (Ambec *et al.*, 2013) suggests that whilst it does not always hold, there is evidence that it *can* hold when policy is introduced in a non-disruptive way allowing businesses time to plan, invest, and adjust effectively.

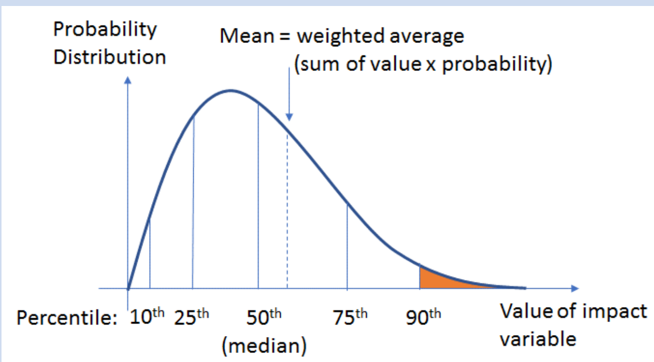
5. Global estimates of climate change damage costs

This section provides a summary of the results of studies which have estimated quantitatively the economic impact of climate change. An overview of the approach to representing uncertainty in these results (and more widely in the report) is given in Box 2.

Box 2. Treatment of uncertainty

Uncertainty is an inherent feature of climate change economics. Although probabilities cannot always be strictly defined, the language of probability provides a useful way of referring to the likelihood of various outcomes occurring. We cannot observe probabilities of future events, but probabilities can sometimes be inferred from model results when they are run with multiple scenarios. In these cases, they can be presented as ranges using a 'box and whisker' format where the box represents the 25th-75th percentile range, the 'whiskers' mark the 10th and 90th percentiles, and the median (50th percentile) is shown as a line within the range as shown to the right. When just upper and lower bounds are reported, these are shown as a simple bar, and point estimates are represented as a point on the chart





Percentiles indicate the value of the variable below which a given percentage of observations fall. The expected value of an outcome is the mean (probability weighted average) of the distribution, whilst the median shows the value which has a 50% chance occurring.

The distribution shown here is asymmetrical, showing a 'fat-tail' or skew, illustrated here by the top 10th percentile of outcomes shaded being shifted to the right towards higher impact values.

In the report, we refer to this situation as having a significant probability of a higher-than-expected impact. Some of the climate literature, reflected in this report, refers to 'catastrophic' impacts. Although there is no explicit definition of this term, it is taken to mean impacts major and largely irreversible impacts from which the communities affected would struggle to recover.

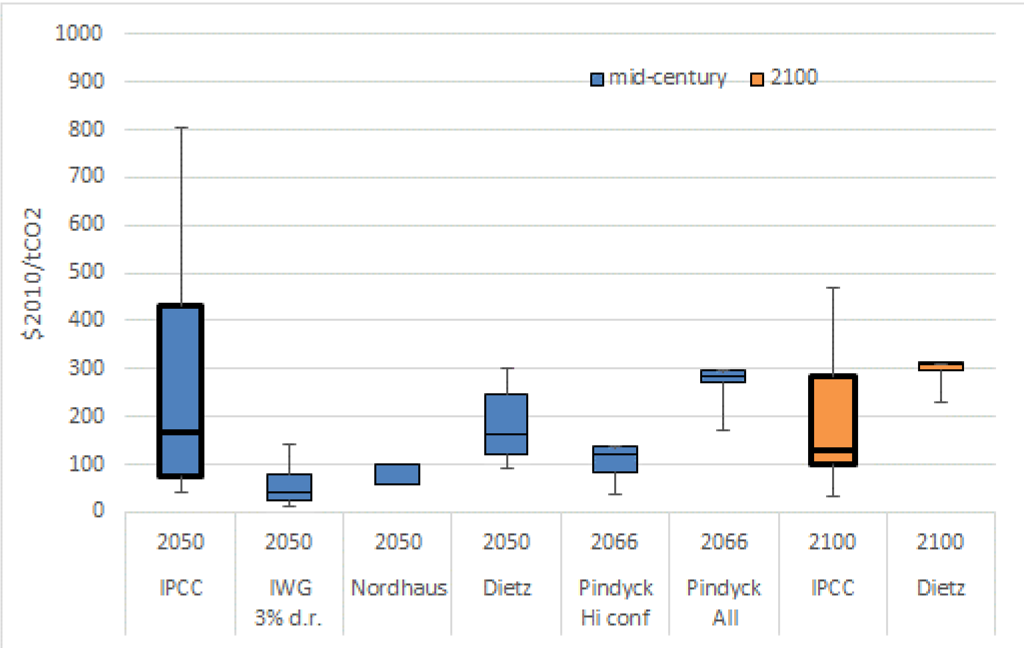
A number of caveats need to be borne in mind when interpreting the results in this section. Firstly, results are only shown for papers that have estimated damages in financial terms. Not all studies do so, and several important studies which take a more risk-based approach to decision-making (King *et al.*, 2015) are therefore not included in the comparison chart. Secondly, although an attempt has been made here to align results into common units, because of the different methodologies used, the comparison between studies is only approximately on a like-for-like basis. Differences are explained in the footnotes.

Two charts are given. The first shows impact costs[13] per tCO_2, and the second shows impact costs as a percentage of GDP, depending on how they are reported in each study, with Pindyck and IPCC reporting in both units. The year to which the costs refer is included in the x-axis title. It should be noted that IPCC results are shown in these charts as single bars, but are outlined in bold to emphasise that in reality these represent a summary across many different studies, so should be accorded more weight when

[13] Costs from different studies are normalised to a common currency value of 2010 US dollars.

interpreting the chart than the single study results. Notes on each of the studies are given in the table following the chart, including the reference, comments on the methodology and the type of climate scenario assumed[14].

Figure 9: Global climate damage cost estimates per unit of emissions



Notes to Figure 9.

Author / Institution	Reference	Climate scenario	Comments on Methodology
IPCC	(Arent *et al.*, 2014) and (Arent, D.J., R.S.J. Tol, E. Faust, J.P. Hella, S. Kumar, K.M. Strzepek, F.L. Tóth, and Yan, 2014)	Optimised emissions	IPCC 5th Assessment Report (AR5) Working Group II provides a key source of data, incorporating a systematic review of economic analyses of climate change impacts. The percentile statistics shown here relate to the range across the set of studies covered by the IPCC which report undiscounted future damages.
IWG	(IWG, 2016)	Optimised emissions	The US government includes a shadow price of carbon in its policy assessments, and the value of the carbon price is regularly updated by the Interagency Working Group (IWG). The carbon price is based on an IAM model estimates of the SCC. Central case of 3% discount rate is reported for 2050.
Nordhaus	Nordhaus (2014)	Optimised emissions	Includes additional results to those reported in IPCC AR5, based on the DICE IAM, with moderations to the damage function, though not incorporating tipping points explicitly. The paper includes a range of different scenarios. We show the upper and lower range of scenario outcomes. The paper does not explicitly address uncertainty or the range of possible climate change damage values.

[14] IAMs often assume an optimised level of emissions that balance damages and mitigation costs differently according to model assumptions, rather than targeting a particular climate scenario; we denote these as 'optimised emissions' in the table.

Dietz	(Dietz and Stern, 2015)	Optimised emissions	Includes the potential impacts of non-linear tipping points by incorporating these effects within the DICE IAM by revising the damage function above critical temperature thresholds. A number of different damage functions are explored, which are reported here as a range of outcomes, though the paper does not explicitly address the issue of uncertainty or the full range of possible CC damage values. They include endogenous growth effects, linking climate impacts to the drivers of long-term growth rather than just instantaneous damage effects.
Pindyck	(Pindyck, 2016)	Business as usual emissions	Uses an alternative valuation methodology, linking the SCC to the probability of extreme outcomes, and using expert elicitation to quantify these risks. Results reported in terms of average rather than marginal SCC, making estimates less sensitive to the choice of discount rate. Impacts are reported here for the year 2066 for the full sample (marked 'All'), and for the sample trimmed down to those experts giving a higher confidence rating to their own estimates (labelled 'Hi conf').

The first point to note from Figure 9 is the wide range of results within many studies (i.e. the height of each bar), reflecting the fundamental uncertainties associated with climate change damages, and in particular for the IPCC results which reflect the wide range of models and scenarios that are included. These distributions are skewed towards higher damages, reflecting the chance of low-probability high impact events. The variation between studies is less pronounced, though still quite wide.

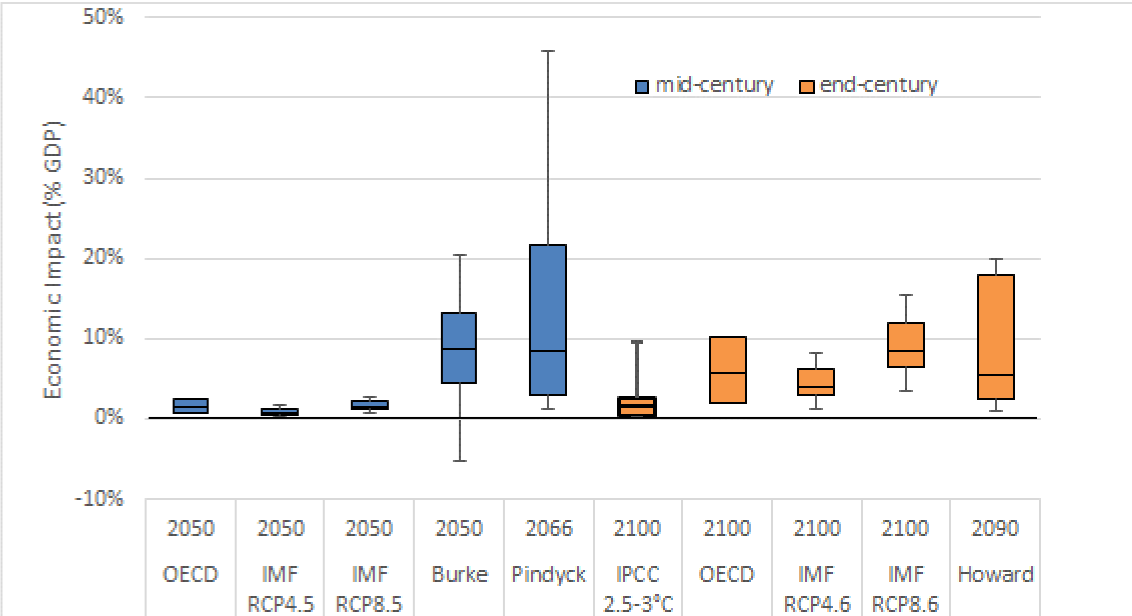
The Pindyck results warrant some additional comment, as they are derived from a quite different methodology using expert elicitation. Although he finds considerable heterogeneity across experts, many view the likelihood of an extreme outcome — a climate-induced reduction of GDP 50 years from now of 20% or more — as quite high (e.g., could occur with a probability of 20% or greater). As a result, Pindyck's estimates across all experts of the average SCC are large, well above \$200/tCO_2 (marked 'All' in the chart). Estimates from economists' responses are lower (around \$170/tCO_2), but those based on responses of climate scientists and residents of Europe were \$300/tCO_2 or more. The median drops to around \$120/tCO_2 when based on a trimmed sample that excludes outliers, and is limited to respondents who expressed a high degree of confidence in their answers (marked 'Hi conf' in Figure 9).

In summary, these studies give median values of mid-century[15] undiscounted damages in the range \$60-285/tCO_2. The median for IPCC studies with zero discount rate is also in this range, at \$96/tCO_2. The full probability distribution of damage values is significantly wider, with 90th percentile values on average 3.5 times the median, and 25th percentile values on average 0.5 times the median.

Figure 10 presents the results of studies which report climate damages as a percentage of GDP.

[15] 2050 for most studies except Pindyck which reports values for 2066

Figure 10: Global climate damage cost estimates per unit GDP



Notes to Figure 10.

Author / Institution	Reference	Climate scenario[16]	Comments on Methodology
OECD	(OECD, 2015)	2.2°C by 2050, 3°C by 2100	Presents results of a major assessment of global climate impacts across all sectors, using a computable general equilibrium model combined with analysis from the DICE IAM.
IMF	(IMF, 2017)	RCP 4.5 RCP 8.5	Uses regression analysis on historical data to assess how countries' GDP has responded in the past to temperature fluctuations, and uses this to calibrate a damage function under two future warming scenarios, RCP 4.5 (50% change of limiting warming to 2°C) and RCP 8.5, a business as usual emissions scenario consistent with warming in the region of 4.5°C by end of century.
Burke	(Burke, Hsiang and Miguel, 2015)	RCP 8.5	Incorporates non-linear impacts of climate change, not in terms of instantaneous damages, but on drivers of growth, leading to larger long-term economic impacts than traditional IAMs
Pindyck	(Pindyck, 2016)	Business as usual	As above for Fig 9.
IPCC	(Arent *et al.*, 2014)	2.5-3°C	A subset of IPCC studies report damages in terms of impacts on GDP for particular temperature rise scenarios, many of these do not specify a timeframe. Here we report studies with warming in the range 2.5-3°C, and assume that these warming levels and the resulting damages relate to end-of-century timeframes.
Howard	(Howard and Sylvan, 2016)	Optimised emissions	Also use expert elicitation, but this time to evaluate alternative values for the damage function which they then use back inside the DICE model, reaching significantly higher estimates of total damages as a % of GDP than the original DICE formulation.

The ranges in Figure 10 expressed in terms of impacts per unit of GDP show greater divergence than those in Figure 9 expressed in $/tCO$_2$. Again, the Figure 10 shows results reported in IPCC AR5 as a single

[16] RCP 4.5 and RCP 8.5 are equivalent to median temperature rises of 2.4°C and 4.5°C by 2100 respectively (Section 4)

range, outlined in bold to emphasise the fact it contains the results of 19 separate studies. Of these, 7 studies were undertaken during or subsequent to the Stern Review, whilst the other 12 were carried out between the period 1994-2005. Of the 19 studies, 10 were based on IAMs, 5 on statistical methods, 2 on computable general equilibrium models, and 1 on expert elicitation. Results shown here are restricted to 14 studies that assumed a similar degree of warming, in the range 2.5-3°C. These studies show reasonably close agreement on GDP impacts, with a mean of 2.2%, median 1.5%, and 10th to 90th percentile range of 0.0% to 9.5%. Excluding a single study with outlying results[17] from the sample further narrows the range across 13 studies to a mean of 1.5%, median 1.5% and 10th to 90th percentile range of 0.0% to 3.5%.

This relatively close agreement may however be quite closely driven by a general assumption used in most IAMs that GDP will continue to grow unabated over the course of the century. This assumption means that climate damages, whilst large in absolute terms, appear modest in comparison with GDP.

Emerging literature is starting to challenge this by assessing whether climate change can reduce growth *rates* rather than just incurring instantaneous damages. Because growth rates accumulate exponentially over time, this leads to a strikingly higher estimate of relative damages in Burke, Hsiang and Miguel (2015) compared to the IPCC AR5 results as shown in the chart. Although the Burke results show the potential for positive global GDP impacts of climate change, over 75% of runs have negative impacts. The possibility of positive results is driven by benefits in rich countries under some model runs, with overwhelmingly negative impacts in most poor countries. Mean and median outcomes are negative in all regions.

This focus on growth rate impacts is a fairly recent development in the literature and there are relatively few studies[18], so it is not possible at this stage to assess emerging consensus on these figures. Not all authors agree that the overall economic impacts will have a significant impact on growth over the course of this century (Mendelson, 2009). However, it is interesting again to note that Pindyck taking a very different approach with expert elicitation, also arrives at relatively high estimates of the probability of catastrophic[19] economic impacts from unabated warming by mid-century. Amongst economists, his most conservative group, estimates of the most likely GDP impact by 2066 were above 10%, with risk ranges significantly higher.

[17] (Maddison and K. Rehdanz, 2011)

[18] Dietz 2015 also assumes growth impacts, but does not report in terms of damages as % of GPD, so is not included on the chart

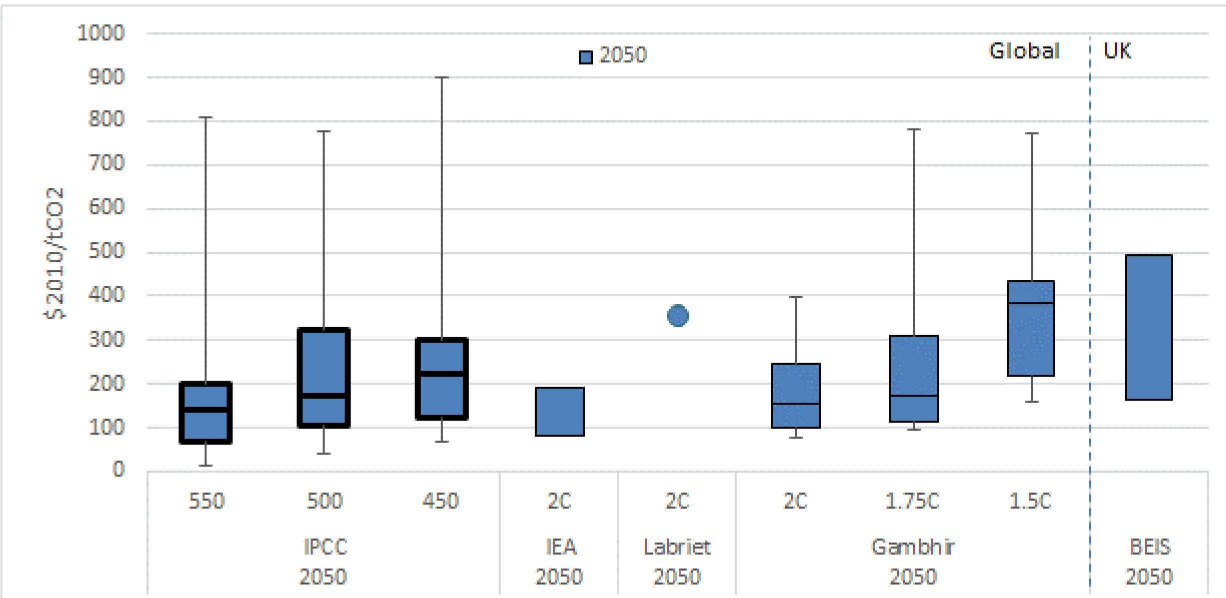
[19] Pindyck defines catastrophic impacts as greater than 20% GDP loss, Howard defines it as 25% GDP loss, and Agrawala defines it at 30% GDP loss.

6. Global estimates of climate change mitigation costs

Stabilising GHG concentrations will require large- scale transformations in human societies, from the way that we produce and consume energy to how we use the land surface (Clarke *et al.*, 2014). This section reviews studies which focus specifically on the costs of mitigation, thereby providing a comparison with the damage estimates presented in Section 5 (subject to the caveats discussed in Section 4 about comparing mitigation and damage cost estimates).

As in the previous section, the charts are separated into two indicators, the first chart (Figure 11) shows impact costs per tCO_2, and the second (Figure 12) shows impact costs as a percentage of GDP, depending on how they are reported in each study, with IPCC reporting in both units. The year to which the costs refer is included in the x-axis title.

Figure 11: Global mitigation cost estimates per unit of emissions



Notes for Figure 11

Author / Institution	Reference	Climate scenario[20]	Comments on Methodology
IPCC	(IPCC, 2014a)	550, 500, and 450 ppm CO_2	IPCC Working Group III focuses on climate change mitigation, including a systematic literature review assessment of mitigation costs, and therefore is a key data source for this assessment. As was the case above for climate impacts, the IPCC results are treated in this analysis as a single data source. The data ranges shown here represent the range of results presented across all studies included in IPCC AR5.
IEA	(IEA and IRENA, 2017)	2°C (66% likelihood)	Bottom-up technology modelling of the pathway to limiting warming to 2°C, focussing particularly on the energy system. Range indicates lower and upper cost limits reported.

[20] For a discussion of different warming units, see Section 4. 450 parts per million (ppm) is equivalent to about a 50% chance of limiting warming to 2°C, 550 ppm raises warming to between 3-4°C.

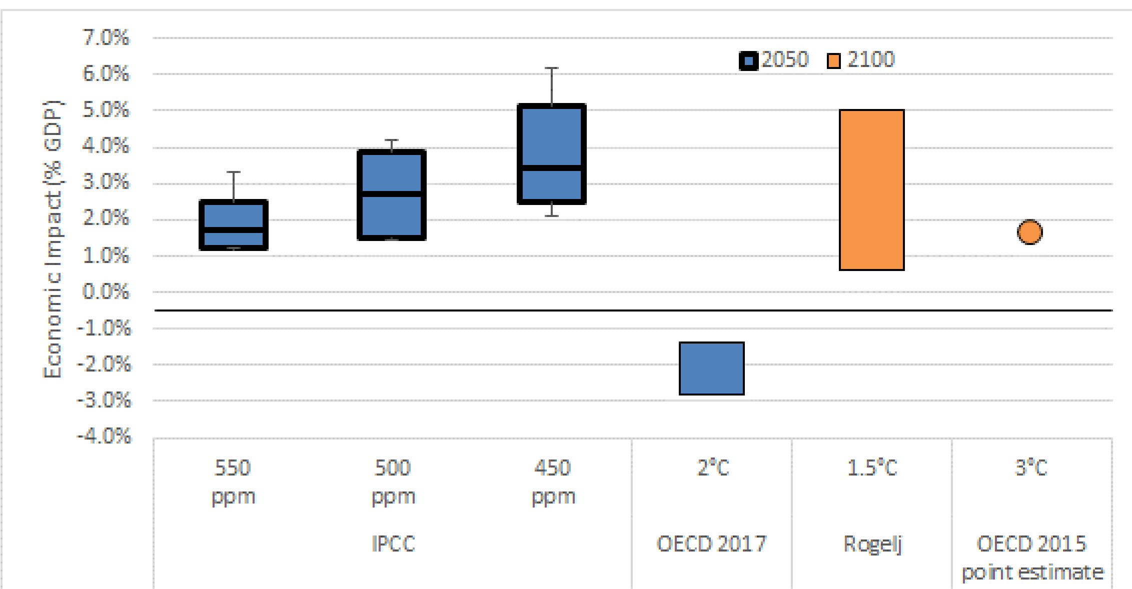
Labriet	(Labriet *et al.*, 2015)	2°C	Uses a top-down global general equilibrium model (GEMINI) combined with bottom-up model (TIAM) to assess the technologies, costs and wider economic consequences, provides a point estimate.
Rogelj	(Rogelj *et al.*, 2015)	1.5°C	Assesses the results of two different IAMs run to achieve 1.5°C target by 2100. Results shown here are the minimum and maximum of the range of outputs reported
Gambhir	(Gambhir, 2017)	1.5°C, 1.75°C and 2°C	assesses the costs of achieving scenarios consistent with warming in the range 1.5-2°C as inputs to the forthcoming IPCC special issue report on 1.5°C
BEIS	(BEIS, 2017)	UK costs for 2°C consistent pathway	Included here are the UK carbon price projections from BEIS which are based on modelled estimates of the cost of abatement required to reach a 2°C-consistent pathway.

As would be expected, the results show that achieving lower temperature or lower concentration targets will generally incur higher costs.

Whilst there is quite a wide variation within each of the studies, reflecting some of the inherent uncertainties of mitigation costs, there is less variation between studies than for the damage cost estimates shown in Section 5. The relatively close agreement in Figure 11 between IPCC 450 ppm scenario and the Gambhir 2°C scenario reflects the similarity both of the target and the set of models covered in both studies. Using different approaches, the IEA estimates a slightly lower range of abatement costs for 2°C, whilst Labriet shows a significantly higher estimate. The BEIS figures are also at the upper end of the range of estimates for 2050.

Figure 12 below presents the results of studies which present mitigation costs as a share of GDP.

Figure 12: Global mitigation cost estimates per unit GDP



Notes for Figure 12

Author / Institution	Reference	Climate scenario[21]	Comments on Methodology
IPCC	(IPCC, 2014a)	550, 500, and 450 ppm CO_2	As above for Figure 11
OECD	(OECD, 2017)	50% chance of 2°C	Covers the G20 (excluding EU countries), and combines costs of mitigation with effects of pro-growth policies (including structural reform, increased public infrastructure investment and enhanced innovation rates). Lower end of the range relates to net fuel exporters, upper end is for importers and G20 average.
Rogelj	(Rogelj *et al.*, 2015)	1.5°C	Assesses the results of two different IAMs run to achieve 1.5°C target by 2100. Results shown here are the minimum and maximum of the range of outputs reported
OECD	(OECD, 2015)	2.2°C by 2050, 3°C by 2100	Results of a major assessment of global climate impacts across all sectors, using a computable general equilibrium model combined with analysis from the DICE IAM. Presented here is a point estimate of the cost of the optimised level of emissions reductions.

Fewer studies report abatement costs relative to GDP. Again, the IPCC results show the expected relationship between abatement cost and increasing stringency of target, with costs of the 450 ppm scenario (50% chance of 2°C) being in the range 1.5%-5% of GDP. However, the Rogelj study shows end-of-century costs for 1.5°C as being in a lower range of 0.6%-5% to the IPCC 450ppm scenario, despite requiring more stringent emission reductions. The outlier here are the results of the OECD (2017) study which conflate pure mitigation cost effects with pro-growth policies of structural adjustment and increased public infrastructure investment, as noted in Section 4.

Comparing these results with the results in Section 5, the evidence suggests that the probability distribution in the range of climate damage estimates is wider and more skewed to high values than the range of abatement cost estimates. For studies included in the IPCC 450 ppm CO_2 scenarios (consistent with about 50% chance of limiting warming to below 2°C), median **abatement costs** were 3.4% of GDP by 2050, with an upper (90^{th} percentile) estimate of 6.2% of GDP by 2050. The Rogelj study found abatement costs in a similar range to achieve the more ambitious target of limiting warming to 1.5°C. This contrasts with IPCC estimates of **climate damages** which have a median value of 1.5% of GDP, but with a significantly higher upper (90^{th} percentile) estimate of 9.5% of GDP by 2050 for warming of between 2.5-3°C. If judged simply on the basis of most likely outcomes, this evidence suggests that abatement costs are likely to be higher than the likely damages over the course of the century. However, a considerable part of the value of abatement lies not just in reducing likely damages, but in reducing the probability of higher-than-expected damages which are raised because of the skew towards higher damages shown in the results. This supports the conclusions of studies reviewed in Section 4 which suggest that because damage estimates are inherently so uncertain, mitigation provides an important risk management function.

[21] For a discussion of different warming units, see Section 4. 450 parts per million (ppm) is equivalent to about a 50% chance of limiting warming to 2°C, 550 ppm raises warming to between 3-4°C.

7. Implications for national / sub-national decision making

Evidence for Scotland

An extensive set of evidence on Scotland's exposure to climate change impacts, and potential adaptation is provided by the Committee on Climate Change (ASC, 2016) as part of the second UK Climate Change Risk Assessment (CCRA). This report does not ascribe financial costs to these impacts, but instead identified the highest priority risks needing more action in the following areas, most of which apply across the UK:

- Natural environment and natural assets
    - Risks to species and habitats due to inability to respond to climate change, and opportunities from new species colonisation
    - Risks to soils from increased seasonal aridity and wetness
    - Risks to natural carbon stores and carbon sequestration
    - Risks to agriculture and wildlife from water scarcity and flooding
    - Risks of land management practices exacerbating flood risk
    - Risks to habitats and heritage in coastal zone from sea-level rise and loss of natural flood protection
- Infrastructure
    - Risks of cascading failures from interdependent infrastructure networks
    - Risks to infrastructure services from river, surface water and groundwater flooding
    - Risks of sewer flooding due to heavy rainfall
    - Risks to transport networks from slope and embankment failure
- People and the built environment
    - Potential benefits to health and wellbeing from reduced cold
- International dimensions
    - Risks from weather-related shocks to international food production and trade
    - Risks to the UK from climate-related international human displacements

Box 3 reviews in more detail the evidence on health impacts of climate change in Scotland.

BOX 3: Impacts of climate change on Health in Scotland. Source: excerpt adapted from (Ebmeier, 2012)

Climate change will have major impacts for health on a global scale, acting as an amplifying factor for many causes of ill health. It will affect the poorest populations in the world disproportionately, primarily because of their lack of capacity to adapt, whereas health impacts will be much smaller in the developed world, including Scotland.

Nevertheless, several factors make some parts Scotland's population vulnerable to the health impacts of climate change, including those who are ageing and/or with poorer health. Within Scotland, health impacts will be distributed unevenly, having the greatest effect in areas of high deprivation.

It is probable that direct impacts of climate change on health in Scotland can be almost entirely countered by public health policies. The most significant impacts are changing patterns of temperature-related mortality (slightly reduced in winter and increased in summer), increased incidence of respiratory, water-borne and food-borne diseases and the effects of more frequent flooding.

It has been suggested that there are alignments between policies to reduce GHG emissions and to improve public health. Such measures are expected to be particularly powerful in tackling obesity, cardiovascular and respiratory disease. However, whether the transition to a lower carbon economy will have significant effects on the health of Scotland's population depends on policy decisions.

Over the longer term, the global impacts of climate change will begin to be felt in Scotland, affecting many parts of life, including health. Falling crop yields globally, may reduce the security of Scotland's food supplies, potentially causing price increases that would affect the diet of the poorest people in Scotland. Patterns of migration are expected to change, although there is no evidence to suggest that this will result in a substantially larger flow of people into Scotland. Increased conflict due to scarcity of water and other resources is expected to increase volatility of international markets, with consequences which are difficult to predict.

Regarding climate change mitigation, considerable work has been undertaken by the Fraser of Allander Institute (FAI), and Centre for Energy Policy (CEP), (both University of Strathclyde) concerning potential GDP and other co-benefits of different mitigation actions. In work commissioned by the Scottish Government, Allan *et al.*, (2008) considered the impacts of increased energy efficiency on the production side of the Scottish economy. This work used the energy/environment variant of the Scottish AMOS CGE model also used by the Office of the Chief Economic Adviser for economic policy analysis. CGE is an economy-wide simulation framework that incorporates interactions between different markets and sectors across the economy.

A key finding of Allan *et al.*, (2008) was that energy efficiency is likely to boost Scottish GDP and decrease its CO_2 intensity, as well as generally reducing absolute levels of total energy use and CO_2 emissions at the economy-wide level (though there may be gross increases in some sectors as the economy expands). This finding is consistent both with other CGE studies in the academic literature, including but not limited to studies for Scotland and the UK conducted by the Strathclyde team, and with the broader arguments and wider range of economic analyses reported by the IEA (2014).

In terms of energy efficiency in the household sector, the same report found that actions involving the imposition of costs on private households would have negative impacts on Scottish GDP through reduced real household incomes. The research reported does not include consideration of impacts of actually making energy efficiency gains, which will impact real incomes via reduced energy spending and, thus, induce changes in the level and composition of household spending. Attention has been given to this issue in subsequent research (funded by EPSRC) at FAI and Strathclyde's Centre for Energy Policy, which suggests that sustained positive economic impacts (on GDP and other key indicators, including the Government budget) would be realised, potentially fully offsetting the costs involved (SPREEE, 2016; Turner *et al.*, 2017).

The Allan *et al.* (2008) report also considered impacts of increasing the share of electricity generated in Scotland from renewable sources. The findings suggested that, while CO_2 emissions would be a general outcome, positive impacts on Scottish GDP may only be realised over time, and are dependent on strong up-stream supply chain linkages within the Scottish economy. Where subsidies are required, GDP gains are more difficult to realise.

Much of this work used CGE modelling techniques which are able to study interactions across the wider economy. Another type of system-wide approach that has been adopted in Scotland more recently focuses attention on energy system models. For example, Anandarajah and McDowall (2012) analyse the cost-effective share of mitigation between Scotland and the rest of the UK, as well as the share of renewable energy generation in Scotland under different scenarios that reflected policy options being considered at the time. The analysis used the UK MARKAL energy system model, a data-rich bottom-up partial equilibrium model.

The Scottish Government has invested in the TIMES energy system model that builds on the earlier MARKAL framework. This model was used to inform the 2017 draft Climate Change Plan (Scottish Government, 2017a), and extensively used in under-pinning the 2017 draft Scottish Energy Strategy (Scottish Government, 2017b), and led to estimates of a 2% cumulative Scottish GDP impact of the energy system resource requirements to meet the 2050 targets, broadly in line with wider UK estimates.

This type of result provides a useful scaling indicator of the resource costs involved, although the partial rather than general equilibrium nature of this framework means that any estimation of GDP impacts are based on mapping the results of cost minimisation in the energy system to exogenously determined GDP estimates rather than the 'cause and effect' captured endogenously in general equilibrium economic system models. Nonetheless, the two approaches may be regarded as complementary and there are currently several projects underway internationally considering how economic and energy systems models may be used alongside one another and/or integrated to some extent (Fæhn, 2017). Research to support further development of the Scottish TIMES framework to consider energy system impacts of energy efficiency actions (Calvillo *et al.*, 2017) is complemented by parallel work involving development of the AMOS CGE framework (Figus *et al.*, 2017).

Decision frameworks, and learning from other national / sub-national approaches

The Paris Agreement sets a global goal for limiting warming, but each country has to decide how much to contribute to the global mitigation effort in line with this goal. Peer review processes then aim to ratchet the ambition of these national contributions. In declaring their contributions, countries will be sensitive to the costs of achieving these reductions, but countries with higher-than-global-average emissions will be expected to bring emissions down more quickly. As seen in Section 6, this can lead to mitigation costs that are higher than the global average.

In addition, countries also need to decide how to adapt to local climate damages. The ASC (2016) assesses climate damage risks for Scotland (as set out above). Lessons can also be drawn from other national and sub-national approaches. Hallegatte, Henriet and Corfee-Morlot (2008) review climate policy and impact assessment at city scales. They note that optimal adaptation is unlikely considering the barriers to adaptation to climate natural variability that can be observed in many locations, which reflect a wider lack of risk reduction investments globally. However, adaptation planning can help.

Adaptation is designed at the local scale and yields local benefits associated with a reduction in exposure and vulnerability to local impacts. Local impact assessment requires socio-economic downscaling with respect to global models, and the development of a local scenario that describes the socio-economic conditions at a pertinent scale. While socio-economic scenario development is complex, their construction at local scale is both a necessary input and an essential part of any local climate impact and policy assessment and they thus require research attention. Moreover, the fact that future impacts depend on these factors makes it possible to use them as policy levers to reduce future climate change vulnerability and increase resilience.

Similarly, Keating and Handmer (2011) provide an assessment of how adaptation policy and investment decisions can be supported based on down-scaled impact assessments for the state of Victoria, Australia. They note that comprehensive assessments of the costs of climate change impacts are needed if decision-makers wish to utilise economic decision-support tools to assess adaptation options. Information about the costs of climate change impacts at local level can inform adaptation decision-making on many levels and sectors, not only for government. For example, industry or community groups may utilise information on the cost and location of expected climate change impacts, reflecting the fact that adaptation is very much local and context-specific. Once the costs of climate change impacts are estimated, they can be compared to the cost of adaptation initiatives to determine which adaptation initiatives would be most cost effective, and where.

Both mitigation and adaptation decisions involve inherent uncertainties about future costs which need to be factored into the decision-making process by creating credible scenarios upon which to base decision-making (ECA, 2009). Considering the profound impacts that are predicted due to climate change, and the major infrastructure change needed to achieve deep decarbonisation over the course of the century, decisions need to be made now despite uncertainty.

One approach for dealing with inherent uncertainty in assessing climate change impacts and adaptation initiatives is to favour initiatives that increase the flexibility of systems or enhance adaptive capacity. Sensitivity analysis is in fact essential for any analysis. It can help explore the breadth of uncertainty in estimates. In economic modelling the usual practice is to vary key parameters individually and analyse the impact on outcomes. Sensitivity analysis by varying discount rates is one such example. Sensitivity testing can lend much to the quality of the analysis, particularly in relation to highlighting the profound impact of the uncertainty of assumptions underlying parameters (Tol, 2002b).

Another important feature of localised mitigation decisions is to focus on the localised benefits. As noted in previous sections, localised benefits can include reduced energy costs through energy efficiency, improved air quality benefits, as well as potentially employment opportunities, which can often justify considerable levels of mitigation ambition, and tend to feature strongly in localised low-carbon studies such as the 'mini-Stern Reviews' carried out for Bristol and Leeds (Gouldson and Millward-hopkins, 2012; Gouldson *et al.*, 2012).

8. Conclusions

Global average atmospheric temperatures are currently 0.9°C higher than pre-industrial temperatures, and climate change impacts and damages are already being experienced. Impacts are unevenly distributed. Negative impacts are being experienced particularly in developing countries which have higher levels of risk exposure and vulnerability. At low levels of warming, some northerly countries will experience some benefits relating to warmer winter temperatures (e.g. reductions in cold-related deaths) and CO_2 fertilisation effects which can increase some crop yields. Future climate change impacts however are set to become negative for all regions of the world. Continuation of current emissions trajectories would lead to temperature rises by late 21st century of 4-5°C, whilst warming over this period would be limited to 3-4°C under current policies, reducing to below 3°C with the additional pledges agreed at Paris. Limiting warming to 2°C will require very considerable reductions in emissions and carbon intensity for the global economy relative to current commitments.

Although research is constantly improving the quality of information, the impacts of climate change remain inherently uncertain. The risk of high-impact, low-probability events is an important factor in decision-making. Various potential tipping points exist which could lead to abrupt changes to the climate, oceans, and other Earth systems. Similarly, there is a risk of very adverse impacts in socio-economic systems. Expert elicitation methods suggest there is more than a 20% risk of extreme climate damages[22] within the next 50 years.

Despite the risk of such major events, the IPCC AR5 (2014) review suggests the cost of climate damages are moderate when measured as a share of GDP, with median damages of 1.5% of GDP[23]. This is partly because many of the models reviewed assume that baseline GDP growth continues unmoderated by climate change. Emerging research indicates that there may in fact be ways in which climate change can reduce economic growth *rates* (as opposed to creating instantaneous damages in a particular year). Since growth rates accumulate exponentially over time, this leads to much higher damages. Estimates from a small number of studies indicate median damages of 9% and 16% of GDP for 2050 and 2100 respectively[24]. This is an active area of research, and it is too early to say whether these growth rate effects will be adopted as a mainstream view. All studies agree that both median impacts, and the probability of much stronger-than-expected damages are significantly reduced if warming levels are limited to 2°C, and decrease further at 1.5°C, though are not eliminated entirely.

Limiting warming to 2°C will require very significant acceleration of decarbonisation rates, and even further acceleration to achieve 1.5°C. This will require much faster uptake of low-carbon technologies than current global trends, including a greater role (and little chance of opt-out) of negative emissions technologies such as BECCS. Mitigation costs increase with the rate of decarbonisation, so delay leads to higher costs at a global level. However, mitigation strategies need to be developed at national or regional level, to take account of local circumstances, and wherever possible make use of natural capital replacement cycles.

The long-term costs of mitigation technologies are hard to predict because of non-linear learning effects which can (and have) dramatically reduced the costs of some energy technologies, but will not do so for all technologies equally. Mitigation strategies therefore need to be flexible, and adapt over time to respond to global and regional trends in technologies, markets and behaviours.

[22] Where 'extreme' damages are taken to be equivalent to 20% or more of GDP

[23] Range of estimates: 75th percentile damages 2.6% of GDP, 90th percentile damage 9.5% of GDP

[24] 75th percentile damages 17% and 31% of GDP for 2050 and 2100 respectively

The total cost of climate change to an economy is the sum of mitigation costs, adaptation costs, and the costs of economic damages. To some extent, these costs can be traded off against each other; increasing the levels of mitigation and adaptation will reduce damages, and *vice versa*. However, this is only true to a certain extent. Beyond certain levels of warming, damages may escalate to levels where mitigation and adaptation expenditure may provide little protection. Comparing these costs is also complicated by the fact that they are incurred over different timescales and geographies. The burden of mitigation costs fall predominantly in the near-term on developed and rapidly emerging energy-intensive countries, whilst the main burden of climate damages will fall on future generations and be felt disproportionately by poorer developing countries. This raises important ethical and political considerations which go beyond simply finding an economic optimum.

The Paris Agreement directly addresses these concerns by committing countries to work towards limiting warming to well below 2°C. At face value, this answers the ethical question about the level of warming society should be willing to tolerate. Nevertheless, national governments still have to make the case to justify the necessary allocation of resources to achieve these levels of mitigation, and it is therefore important for the public to understand the kinds of global risks that are being reduced as a result of these commitments.

Bearing in mind all of the above caveats, the balance of evidence assessed in this review suggests that the avoided global costs of climate damages over the course of the 21st century are of a similar order of magnitude to the costs of limiting warming to 2°C, which supports the case for the strong actions required to achieve this goal, particular in view of the importance of managing risks of much higher-than-expected impacts. However, there is a high degree of uncertainty and a broad range of estimates of both these figures. Broadly speaking, in narrow cost/benefit terms, limiting warming to 1.5°C will incur higher costs and produce relatively lower marginal gains when compared to limiting to below 2°C. However, the state of knowledge is not strong enough (and may never be strong enough) to determine more precisely where the 'optimal' level of mitigation lies.

Finally, there is strong evidence that decision-making should be driven by an analysis of risk, not just an assessment of costs and benefits based on expected or average outcomes. The long-term nature of climate change, and the potentially large systemic risks and irreversibility it creates make application of normal cost-benefit analysis methods difficult, and perhaps inappropriate. Further research is helping to understand the range of these risks, and information will emerge over the coming years and decades. While taking a long-term outlook and managing the energy transition, policy will need to maintain flexibility to adapt the new circumstances and emerging evidence.

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