Accelerating the delivery of climate targets

Technology and behaviour in the road to net zero

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This dissertation is submitted for the degree of
Doctor of Philosophy

Darwin College
July 2021

To my family, who taught me to love education, economics and the environment.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, footnotes, tables and equations and has fewer than 150 figures.

Sarah Nelson
July 2021

Acknowledgements

I owe a great deal of thanks to the people who have offered me their guidance and support over the last three years.

I would first like to thank my supervisor, Professor Julian Allwood, for his excellent guidance throughout the PhD. Coming into an Engineering Department as an economist was a gamble—one that, in Julian's group, has certainly paid off. In particular, I would like to thank him for his kindness during the Covid-19 lockdowns.

I extend my heartfelt thanks to Dr Toke Aidt, my advisor, whose economic guidance and general advice have greatly improved both this thesis and my PhD experience. A huge thanks also to Professor Hamish Low of the University of Oxford, who assisted in developing the arguments for the first research chapter and continues to support our ongoing research. I am very grateful to Hannes Gauch for his computational advice and assistance.

I am grateful also to the Engineering and Physical Sciences Research Council and my supervisor for their financial support over the last three years.

An ocean of thanks is due to the friends who have supported and cajoled me through the PhD. To my kiwi friends, thank you for your limitless kindness and encouragement from the other side of the world. To those I met at Cambridge, in the research group, at Darwin, and on the river Cam, thank you for the camaraderie and necessary distractions that have made my years in Cambridge some of the best. I am grateful in particular to Holly, Rose, Shelby, Michalla, Megan, Karla, Catherine, Simon, Harry, Matteo, Alicia, Diana, Chris, James and Tatjana. To the many others I have not named, thank you.

Finally, I owe the greatest debt to my family, particularly to Wendy, Chris, Jane, Ann and Adam. Travel restrictions due to the Covid-19 pandemic meant I was unable to see them for most of my studies, but their long-distance support has kept my course (relatively) straight and my keel (mostly) even. To my partner Tyler, thank you for your unwavering faith and encouragement.

Abstract

Governments have known for more than half a century that emitting greenhouse gases increases temperatures and puts lives at risk. Yet global mitigation is minimal, for all the feted net zero commitments: emissions from fossil fuels have risen in every decade since records began. Some countries have made progress, including the United Kingdom where emissions have halved since 1990. But progress has so far relied on low-hanging fruit—the closure of coal mines; offshoring of industry; the recent growth of wind power. Future decarbonisation will be more challenging. Interdisciplinary collaboration, between scientists, engineers and economists among others, is necessary to overcome our carbon addiction.

This thesis asks how best to achieve urgent mitigation. It focuses on public policy as a lever for decarbonisation; governments' cross-sectoral influence authority to enforce give them unique power to accelerate change. Research is undertaken in three parts.

The first part considers the political economy of slow mitigation. It considers how political institutions and public beliefs affect the urgency of decarbonisation. Climate action faces opposition from incumbents and vested interests. This has led to a culture of myopic climate policy, defined as a high long- to short-term mitigation ratio. Every year mitigation is delayed makes it harder to achieve in future, transferring the burden from today's citizens to the future's. Moreover, public views over the issue salience of climate policy are lower than scientists', implying biased voter beliefs that impede adoption of the urgent policies needed to create near-term mitigation. This thesis postulates that policy myopia and biased beliefs can be ameliorated by setting a binding target on cumulative emissions, known as a carbon stock budget. For politicians, a carbon stock budget is an effective commitment mechanism. For the public, carbon stock framing alludes to threshold risks and appeals to the concept of household budgeting, both of which increase support for urgent policy. An economic model is presented that compares outcomes under a carbon stock budget and incremental climate policy. Results show that a budget increases nominal output by 40% in 2100. Implementing a carbon stock budget would help overcome barriers to meaningful decarbonisation.

Mitigation can be achieved with new technologies, new behaviours or a combination of both. The second part of this thesis asks what history can teach us about technological and social transitions. Researchers have previously analysed past energy transitions, but no studies have yet reviewed social transitions for clues about future decarbonisation. Here, five large-scale energy and seven social transitions are assessed in detail. Historical reviews are combined with metrics on transition progress. Results show that all transitions go through common stages and face similar challenges and opportunities. These are summarised in two transition frameworks, which enable measurement of the duration and scale of each transition. Technological transitions tend to be slower than their social counterparts, and delays between conception and growth are four decades longer for new technologies. Uptake also tends to be slower: technologies averaged an annual growth rate of 1.6%, versus 4% for social transitions. History suggests that social change could play an important role in achieving net zero by 2050.

The final part of this thesis asks what current climate strategies imply for the UK's timeline to net zero. It considers decarbonisation through the lens of disruption. A novel metric is proposed, which quantifies technological and behavioural disruption by measuring the implied change in a market or activity. A review of twelve proposed decarbonisation strategies yields 98 mitigation options and 538 distinct proposals. Applying the novel metric to these proposals reveals a bias towards technological mitigation. Two thirds of mitigation options rely solely on new technologies, one fifth rely on behavioural change, the remainder on a mix of both. Given the evidence that technological change can be slower than social change, these results suggest that the prevailing technological bias may impede near-term mitigation in the UK.

This research contributes to a growing discussion of alternative approaches to net zero. It supports a new climate narrative: one in which policymakers can overcome political barriers to ambitious, near-term action, by reframing climate targets and matching technological deployment with effective behaviour change. The fundamental contributions of this thesis are threefold. It postulates a political argument for a carbon stock budget by linking theories of myopic policy and biased voting. It develops a new method to compare the pace of social and technological transitions, and illustrates the relative promise of social change. Finally, it proposes a novel metric to capture disruption in decarbonisation strategies and shows that proposals for the UK are technologically biased.

Governments across the globe have pledged to reach net zero emissions by 2050. To live up to these promises, they must create change in the present by matching investment in prospective technologies with policies that utilise existing technologies and behavioural change. Accelerating the delivery of climate targets will require a balanced transition that places urgency at the heart of climate policymaking.

Publications

The research presented in this thesis has been published in peer-reviewed journals and presented at conferences.

Journal articles:

- Nelson, S. & Allwood, J. M. (2021). The technological and social timelines of climate mitigation: lessons from 12 past transitions. *Energy Policy*, 152. https://doi.org/10.1016/j.enpol.2021.112155.
- Nelson, S. & Allwood, J. M. (2021). Technology or behaviour? Balanced disruption in the race to net zero emissions. *Energy Research and Social Science*, 78. https://doi.org/10.1016/j.erss.2021.102124.

Conference presentations:

- *The role of society in accelerating the net zero transition.* Cambridge Zero Research Symposia, February 2021 (virtual).

Other published work undertaken during the course of the doctoral programme, not directly included in this thesis:

- Weber, J., Budden, P., Gilmore, K., Nelson, S., Matharu, M., Hu, Y., Craglia, M. (2020). *Net Zero Cambridgeshire*. CUSPE & Cambridgeshire County Council. Available online https://data.cambridgeshireinsight.org.uk/dataset/cambridgeshire-policy-challenges-cambridge-university-science-and-policy-exchange-cuspe-8.
- Nelson, S. (2020). Expanding the policy menu: how demand-side interventions can help the UK reach net zero. *Cambridge Journal of Science and Policy*, 1(1). https://doi.org/10.17863/CAM.50309.
- Nelson, S. & Zardilis, A. (2021). Power and responsibility: the role of the sciences in reducing social inequality. *Cambridge Journal of Science and Policy*, 2(1). https://doi.org/10.17863/CAM.66531.

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Nomenclature

Acronyms / Abbreviations

BEIS	Department for Business, Energy & Industrial Strategy
CCC	Committee on Climate Change
CCGT	Combined-cycle gas turbines
CCS	Carbon capture and storage
CFC	Chlorofluorocarbons
CO_2	Carbon dioxide
DICE	Dynamic Integrated Climate-Economy model
DoI	Diffusion of Innovation
DPP	Deep Decarbonisation Pathways Project
EPC	Energy Performance Certificates
ETS	Emissions trading scheme
EU ETS	European Union Emissions Trading Scheme
EV	Electric vehicle
FUND	Climate Framework for Uncertainty, Negotiation and Distribution model
GDP	Gross domestic product
HCFC	Hydrochlorofluorocarbons
IAM	Integrated assessment model

IPCC	Intergovernmental Panel on Climate Change
MAC	Marginal abatement cost
$MtCO_2$	Megatonne of carbon dioxide
NG	National Grid
NIMBY	Not in my back yard
PAGE	Policy Analysis of the Greenhouse Effect model
R&D	Research and development
RICE	Regional Dynamic Integrated Climate-Economy model
SCC	Social cost of carbon
TFP	Total factor productivity
TRL	Technology Readiness Level
TWh	Terawatt hour
VaR	Value at Risk
WTO	World Trade Organisation

Chapter 1

Introduction

Climate change poses an unprecedented challenge for modern society. The industrial revolution and the resulting reign of fossil fuels in energy use has generated greenhouse gas emissions that will affect the Earth's climate for centuries to come. Global temperatures are set to reach 1.5°C above pre-industrial levels in the next three decades, and long-term impacts include changes to weather patterns, sea level rises, species loss and increased risk of large-scale disasters (Hoegh-Guldberg et al., 2018). Temperatures have already risen by around 1°C (Allen et al., 2018), driven by an increase in global greenhouse gas emissions of nearly 2000% since 1900 (Friedlingstein et al., 2020). Almost half of this increase has occurred since the early 1980s.

The Earth's climate has never faced a similar atmospheric forcing, and the scientific and social ramifications are clouded in uncertainty. Even during historical periods of high temperature, climatic changes occurred far more slowly, allowing ecosystems more time to adapt to their changing environment (Solomon et al., 2007). Without historical precedent, climate scientists must rely on assumptions over how modern society's penchant for fossil fuels will affect temperatures, rain patterns, ice stores and extreme events (Allen et al., 2018; IPCC, 2014). Different climate models adopt different assumptions and, as a result, often disagree on the magnitude of the planetary response to rising emissions (France et al., 2013). To add to scientific uncertainties, society's reaction to climate changes is a significant unknown. Governmental and individual actions to mitigate emissions will have a large impact on climate outcomes (Rogelj et al., 2018), but are a subject of persistent doubt.

Climate science—and climate concern—have a long history. The scientific concept underpinning global warming dates back to 1859, when John Tyndall proved that various gases trap thermal radiation from the sun (Weart, 2021). These gases include water vapour, carbon dioxide (CO_2) and methane, all present in the atmosphere. Tyndall hypothesised that this so-called greenhouse effect was responsible for Earth's transition from an ice-covered planet to today's temperate climate. In 1896, Svante Arrhenius related Tyndall's work to human activity with his theory that burning fossil fuels could emit CO_2 and increase Earth's temperature (Weart, 2021). Evidence of increasing atmospheric CO_2 concentrations emerged in the late 1960s, and concern grew that human activities were already affecting the global climate (Zillman, 2009). The following decade saw the World Meteorological Organisation convene the first of many global climate conferences. The declaration of the 1979 World Climate Conference called for an expansion of climate knowledge, and for world governments to "foresee and prevent potential man-made changes in climate that might be adverse to the wellbeing of humanity" (UNEP Information Unit for Conventions, 2000). The 1970s also saw study of the economics of climate change kick into gear (e.g., Nordhaus, 1975).

For all this history, progress on climate action has been dangerously slow. The last five decades have been littered with climate conferences, treaties and thousands upon thousands of academic studies. Yet emissions keep rising (Friedlingstein et al., 2020). Figure 1.1 illustrates the supposed milestones of international climate negotiations against a backdrop of relentless growth in global emissions.

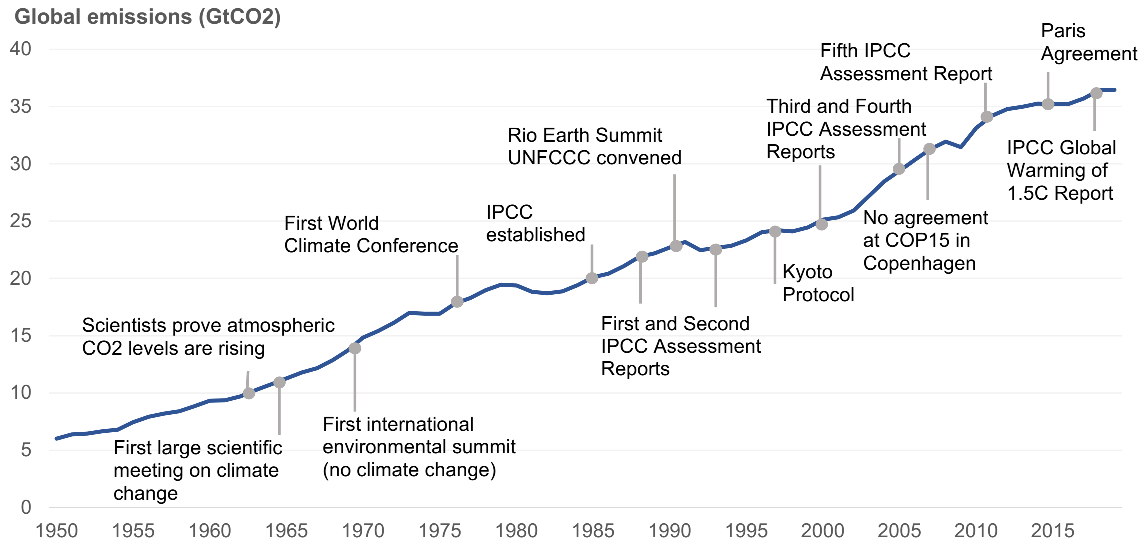

Fig. 1.1 Global emissions between 1950 and 2020. Relevant milestones of the climate science and international negotiations are marked. IPCC: Intergovernmental Panel on Climate Change. Emissions data sourced from Friedlingstein et al. (2020). Timeline based on Hirst (2020); Weart (2021).

Today's slow climate action threatens the welfare of future generations. This thesis considers underlying reasons for this inertia and avenues for accelerating meaningful mitigation. The remainder of Chapter 1 presents the motivation for this research: the importance of collaboration between economists, scientists and engineers (Section 1.1); and the costs of climate inaction (Section 1.2). It then discusses two complementary solutions to climate inaction: the potential for technology and behaviour each to achieve change (Section 1.3); and urgency as a basis for climate policymaking (Section 1.4). Finally, Section 1.5 describes the research aims and presents the overarching research question.

1.1 Science, engineering and economics in climate policy

Climate studies are often seen as the responsibility of scientists. However, climate change is a multidisciplinary problem that demands a multidisciplinary response (Doukas et al., 2019). It requires scientists to understand and forecast complex climate dynamics and provide predictions over temperature trends and changing weather patterns. Engineers are needed to develop mechanisms to reduce our impact on the environment, be that through new technologies or better use of existing ones. Translating the science of climate damages and the potential for engineering solutions into monetary values and policy responses is the purview of economists. Figure 1.2 summarises the role of scientists, engineers and economists in climate change studies.

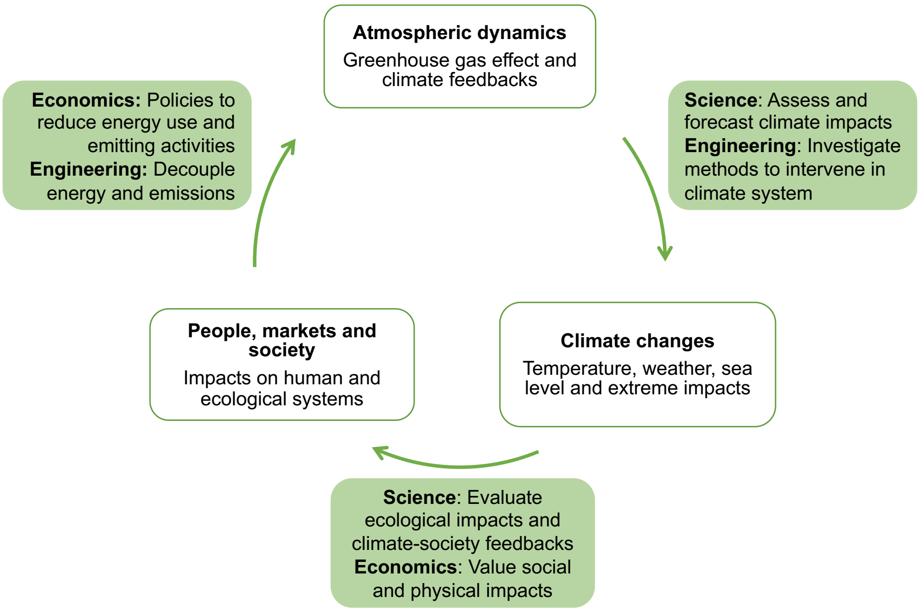

Fig. 1.2 The role of science, engineering and economics in interactions between the climate and society.

Economics is the lingua franca of politics. Economic theory yields many of the tax and spend policies of modern governance (Ahluwalia, 2015), and economists have long been at the heart of policymaking (Hirschman and Berman, 2014). In the age of the technocrat, metrics produced by climate economists are used by governments and policymakers to evaluate costs and benefits of proposed policies and estimate the impacts on industries and households.

One prominent metric captures the impact of an additional tonne of carbon emitted into the atmosphere, known as the social cost of carbon (SCC) (Pindyck, 2016). The SCC is used to evaluate and select climate policies (Rose et al., 2017). Economic models are even used to identify the 'optimal' temperature increase that best balances climate damages against the costs of action (Nordhaus, 2017). Economic quantification is therefore crucially important to achieving meaningful decarbonisation.

Given the interdependence of science, engineering, policy and society in the climate response, economic analysis requires insights from a range of different fields. However, economic models of climate change have been developed largely without input from scientists or engineers. As a result, several prominent models do not include recent scientific estimates of damages (Auffhammer, 2018) and fail to incorporate the risk of climate catastrophes (Aldy et al., 2010). Dietz et al. (2020) show that current models exclude crucial climate feedback loops and overestimate the delay between emissions and warming. The result is economic models that significantly underestimate the damages associated with climate change.

Despite their mutual dependence, economists, scientists and engineers tend to act largely independently of each other—and sometimes at odds. Achieving meaningful climate action will require more effective collaboration. This work, itself a product of interdisciplinary efforts, contributes to the development of a 'common tongue' to support urgent climate policy.

1.2 The costs of inaction and a muted policy agenda

The physical risks of climate change are immense. Rising atmospheric carbon concentrations increase temperatures and destabilise climate dynamics. The potential impacts include widespread drought, rising sea levels and increased frequency of extreme events such as hurricanes (Hoegh-Guldberg et al., 2018). These changes have the potential to lead to famine, health crises, mass migration and global conflict (Froese and Schilling, 2019; McMichael et al., 2012; Richards et al., 2021). Without meaningful steps to reduce emissions, the future of modern society looks grim.

The cost of inaction measures the economic harm of the business-as-usual emissions path. It aims to quantify in monetary terms the damages that would arise if emissions remained unchecked (OECD et al., 2015; Stern, 2006). That figure can then be balanced against the costs of action—funding for technical research, costly overhauls of infrastructure, individual sacrifices and so on—to evaluate the tradeoffs of global climate policy. However, this logic relies on clear and consistent estimation of the cost of inaction.

Conceptual arguments suggest the cost of inaction is infinite, because inaction could lead to a catastrophe that heralds the end of society as we know it (Weitzman, 2009a). Weitzman (2012) argues that, even without the possibility of catastrophe, inaction resulting in 6°C warming would reduce global welfare by 50% based on human reactions to heat stress. Sanderson (2020) shows that historical inaction has already been hugely costly—the price of achieving the Paris 1.5°C goal would have halved had we begun meaningful mitigation after the Rio Earth Summit in 1990.

In contrast to these clear warning signs, mainstream economics tempers cost estimates by taking generous assumptions over climate dynamics, technological development and the relative welfare of future generations. Costs of inaction are generally estimated in climate-economy models that aim to capture the complex relationships between society and science. Such models are notoriously opaque (Pindyck, 2013) and have been plagued by criticism. Lackadaisical approximation of atmospheric dynamics and tipping points mean they vastly underestimate climate damages (Auffhammer, 2018; Dietz et al., 2020). Optimism over speculative technologies obscures challenges in delivering negative emissions (McLaren et al., 2019). Heavy discounting of future welfare means long-run damages have little bearing on today's decisions (Heal, 2009). As a result, most mainstream climate-economy models put the cost of inaction at a few percent of global gross domestic product (GDP) (Stern, 2006), a stark contrast to Weitzman's (2012) welfare-based arguments. Figure 1.3 shows estimates from several well-known models of the long-run aggregate cost of different stabilisation temperatures.

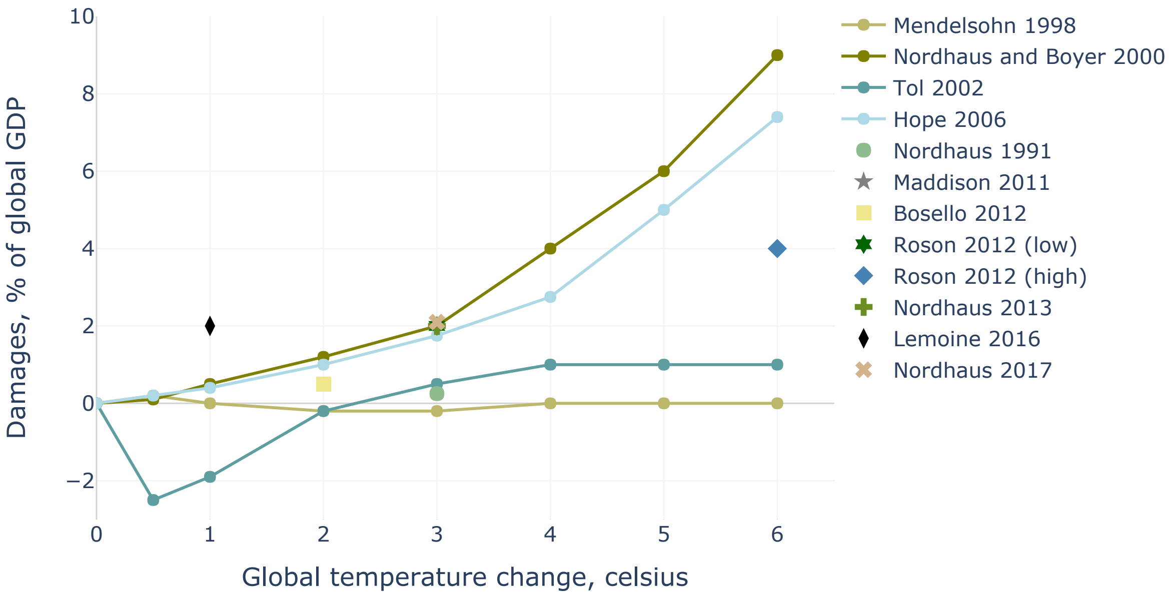

Fig. 1.3 Estimates of the costs of climate inaction from mainstream economic models of climate change. Based on reviews by Dietz et al. (2007) and Sanderson and O'Neill (2020), with additional data from Nordhaus (1991) and Nordhaus (2017).

Estimates of the cost of inaction vary wildly. Estimation models are afflicted by esoteric methodological and ideological clashes, which muddy both their results and their policy implications. Ongoing ambiguity about the economic impact of business-as-usual adds to the confusion concerning the best path out of the climate crisis (Geden, 2018), and fuels scepticism about the necessity of climate policy (Gillard, 2016).

Low and ambiguous estimates of the cost of inaction provide lacklustre motivation for decisive action. As a result, the climate policy agenda has been muted. While governments across the world have lined up to set increasingly ambitious emissions targets, they are yet to implement the meaningful policies necessary to achieve them (Bouckaert et al., 2021). In the United Kingdom, the *Climate Change Act 2008* legislated the government's targets, making its commitment to achieving net zero emissions legally binding (HM Government, 2008). Yet successive governments have failed to implement policies that will put Britain on the pathway to meeting that target (Climate Change Committee, 2020a).

The dissonance between stated ambition and realised action is emblematic of the biggest barrier to urgent climate action: time. The costs of climate action must be paid now, while the benefits—avoided damages—are accrued years into the future. Moreover, the delay of climate dynamics means that policies can take decades to change the temperature trajectory (Samset et al., 2020), a period well beyond the electoral horizon of most politicians. As a result, politicians are reluctant to impose policies which require sacrifices from today's businesses and individuals in order to protect future generations.

Inaction has two possible costs. It either increases the burden of carbon austerity for future generations, or it brings forward the potentially catastrophic impacts of climate change. Every year of inaction makes it harder to combat climate change. With that in mind, calls for meaningful climate action are growing (e.g., Ripple et al., 2019). But, in a world so deeply reliant on fossil fuels, the question remains—how can climate targets be achieved?

1.3 The way forward: technology, behaviour or both?

Mitigation strategies can be broadly categorised into two themes: replacing existing infrastructure, devices or processes with new technologies, and changing patterns of behaviour to reduce the energy-intensity of modern life. The first generally encompasses changes on the supply-side, affecting organisations and governments but flowing through to the consumer only through changes in prices. The second theme covers demand-side policies that require individuals to adapt to a low carbon lifestyle. For the most part, research efforts and policies have so far addressed supply-side climate interventions.

Supply-side transitions have achieved significant emissions reductions in the UK. Substitutions in generation technologies since 2000, from coal to natural gas and now to renewable generation, are illustrated in Figure 1.4 along with emissions over the same period. UK emissions fell by 49% between 1990 and 2020, almost exclusively achieved in the sectors of energy supply, business and industry (BEIS, 2021a). Energy sector mitigation is straightforward: electricity generation has been decarbonised and more energy use has been electrified. Business and industrial mitigation is more nuanced. Some of the emissions savings come from efficiency and electrification of industrial processes. However, the offshoring of British industry also plays a significant role. Figure 1.4 is based on territorial production—emissions generated in activities occurring within UK borders. When production moves elsewhere, its emissions are no longer included in the UK's carbon accounting, even if the resulting products are consumed here. Emissions associated with UK consumption, which include the carbon embodied in imports, fell by only 28% between 2000 and 2018 (Defra, 2021). Further reductions in UK emissions will require addressing consumption-based emissions with demand-side policies.

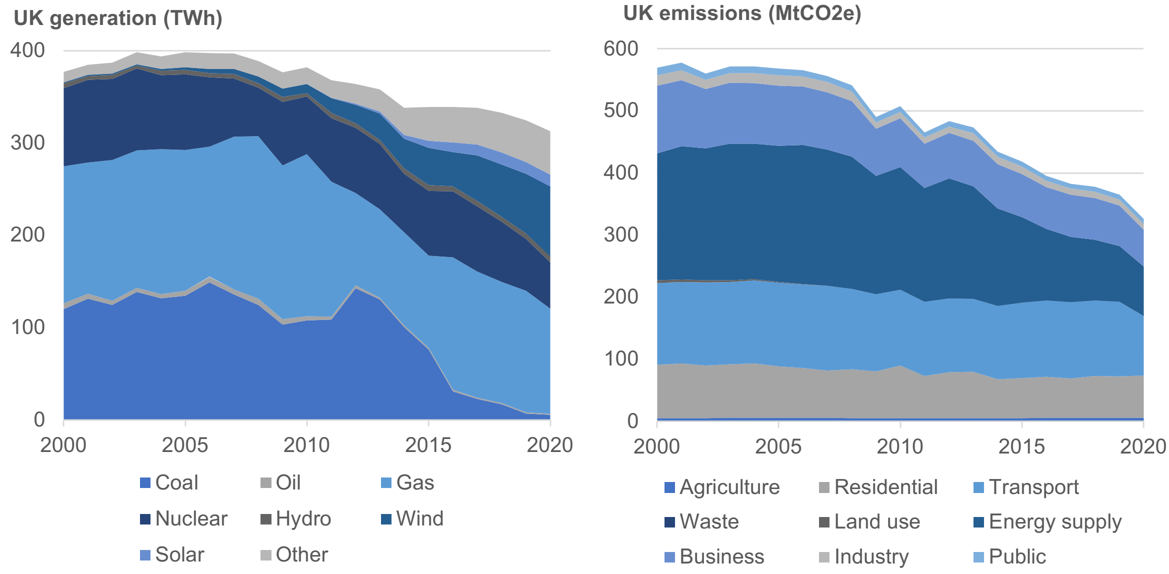

Fig. 1.4 The UK's electricity mix and greenhouse gas emissions between 2000 and 2020. Emissions are given in megatonnes of CO_2-equivalent ($MtCO_2e$), which translate non-CO_2 greenhouse gases into comparable emissions units. Electricity: BEIS (2021b). Emissions: BEIS (2021a)

Technologies will doubtless play an important role in decarbonisation on both the supply- and demand-side; indeed, they already have. Clean generation technologies have decarbonised electricity; technological developments have improved heating and transport efficiency. But technology cannot provide the panacea it is often claimed to be. In particular, the promise of long-awaited future technologies should be treated with caution. Historical evidence suggests technological transitions in the energy sector tend to take several decades (Gross et al., 2018; Smil, 2014). Smil (2016) argues that a rapid acceleration in the deployment of wind and solar generation, such as that proposed by the UK government (HM Government, 2020), is unlikely. For technologies which have yet to reach commercialisation, such as carbon capture and storage (CCS), the barriers are even more stark (Stephens and Markusson, 2018). Political backtracking on CCS innovation funds over the last decade illustrated the difficulty of bringing new technologies to market (Green Alliance, 2012; Kern et al., 2016).

Given the slow progress of supply-side technological substitutions, attention is turning to demand-side opportunities to reduce emissions (Capstick et al., 2014). A growing literature argues that systemic changes in consumption patterns across key behaviours—transport, housing, energy use and food—are required to meet the decarbonisation needs of the 21st century (O'Rourke and Lollo, 2015). In a broad sense, a low carbon social transition requires large-scale disruptive transformations of social norms and expectations (Loorbach et al., 2017). Zooming in, societal changes begin with shifts in individual behaviours, such as eating less meat, foregoing air travel or purchasing smaller cars. The widespread uptake of climate-conscious consumption habits could vastly reduce the materials needs of society and cut production emissions (Allwood et al., 2019; Carmichael, 2019).

Demand-side changes could drastically accelerate climate progress. However, without estimates of the rate of societal uptake of new behaviours, it is difficult to compare their potential outcomes with better-understood technological transitions. Figure 1.5 illustrates the widely accepted S-curve of innovation, describing the uptake of new technologies from early innovators to laggards (Brown, 1991). The gradient of the S-curve determines the speed of transition. However, there is no 'S-curve of behaviour'. The dynamics of behaviour change—mechanisms, rate and potential policy levers—are complex. Compared to the broad body of research on technological diffusion, behavioural diffusion remains under-explored.

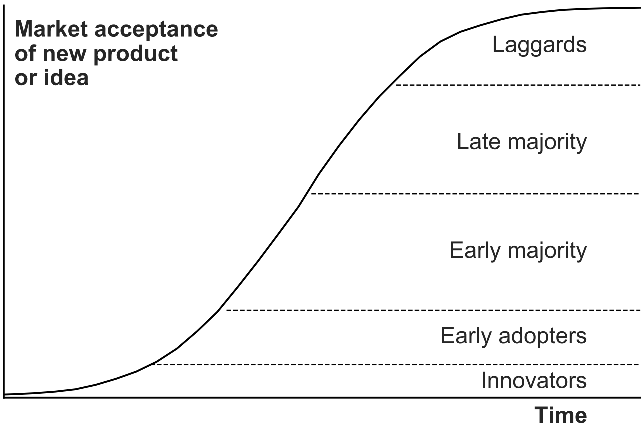

Fig. 1.5 The S-curve of innovation. Adapted from (Brown, 1991).

The lack of evidence on social transitions has contributed to politicians' reticence in implementing demand-side climate policies, and behavioural mitigation strategies remain relatively rare. The Climate Change Committee (CCC) estimates that only 16% of its suggested policies rely largely on behaviour change (Climate Change Committee, 2020b). Of the remainder, 41% rely on technology alone and the remaining 43% on a mix of both. The climate challenge requires a more balanced toolkit. Climate policy is slowly moving towards a middle ground where technological mitigation is compounded with social and behavioural changes. Understanding how to accelerate that shift is a key motivation of this research.

1.4 Urgency as a basis for climate policy

Climate policy has not yet set the planet on a path to net zero emissions (UNEP, 2020). To bring about the deep and wide-reaching changes necessary to accelerate mitigation, the framing of climate action must change. The focus needs to move from achieving mitigation as cheaply and painlessly as possible, to achieving it as quickly as possible. Meaningful climate policy can reduce the chances of catastrophic climate events, but must be implemented without delay (Ripple et al., 2019).

Urgent climate action is conceptually underpinned by the precautionary principle. The precautionary principle states that, in the presence of a sufficiently damaging risk, preventative intervention is justified even if the supporting evidence is uncertain or incomplete and the economic costs are high (European Commission DG Environment, 2017). It relates to the concept that the costs of climate change are infinite: if there is even a small risk of outright catastrophe, then no mitigation is too costly. This principle was enshrined in the United Nation's Framework Convention on Climate Change:

> Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation. — United Nations (1992)

Despite its apparent position at the heart of international climate negotiations, the precautionary principle has not been borne out in the ensuing decades. Our understanding of climate science continues to improve and avenues to technological and social mitigation continue to open up. But policy remains stalled.

The governmental response to the global Covid-19 pandemic set a precedent for urgent policy based on the application of the precautionary principle. In their efforts to avoid potentially disastrous health impacts, and in the face of many unknowns, governments across the globe implemented stringent lockdowns, funded some of the swiftest technological advances in medical history and offered huge fiscal stimuli (Hale et al., 2020; Torjesen, 2020). This ambitious, timely and varied policy response highlights governments' contrasting reluctance to meet the climate challenge. The tangible risks of a viral pandemic seem to give governments social license to take decisive, immediate action. Such license is not present in current public discourse around climate change.

Avoiding the most damaging impacts of climate change means closing the gap between ambitious policy rhetoric and actual mitigation. The last 30 years of climate policy has shown that traditional mechanisms of price incentives and supply-side technological diffusion cannot limit warming to 2°C (UNEP, 2020). Establishing urgency as the priority for climate action will encourage governments to pursue the consequential, disruptive, life-saving policies necessary to accelerate climate mitigation.

1.5 Research aims

Today's climate action is inadequate. As discussed in this chapter, scientists, engineers and economists all have important roles in the effort to decarbonise society. The main tool they wield is policy, or rather the influence they can have over policymakers and public climate discourse. So far, their efforts have yet to bear much fruit: climate mitigation remains minimal, despite ambitious rhetoric from politicians, in part facilitated by unclear estimates of the cost of business-as-usual. Where efforts have succeeded, this is largely in the pursuit of technological overhauls—which history suggests will be too slow to achieve the necessary abatement. This thesis proposes that adopting urgency as a basis for climate action, rather than cost minimisation or political advantage, could support efforts to reach net zero by 2050. Policy is still the strongest lever for change; government can influence more sectors, more cohesively, than any other organisation or movement. This research therefore considers the extent to which reframing the policy agenda towards urgency could accelerate decarbonisation. The overarching research question is:

RQ0. How can policy accelerate the delivery of climate mitigation?

This research is inherently interdisciplinary, drawing together literature, theories and methods from economics, engineering, sociology and political science. Quantitative methods include economic modelling, data analysis and the use of a novel metric. Qualitative approaches are used for systematic literature reviews and theoretical analyses. This research centres on lessons for the net zero transition in the United Kingdom. However, its results are broadly applicable due to similarities in policy context and decarbonisation strategies across countries, particularly those in the Western world. Data is drawn from a multitude of sources, including the British government, international organisations, private companies and academic institutions. Along with several novel insights and practicable policy recommendations, this research yields a database of proposed mitigation options for the United Kingdom.

Chapter 2

Literature review

Delivering climate targets will require technological development, new infrastructure, organisational overhaul, financial innovations and individual behaviour change (Bouckaert et al., 2021). Meeting these cross-sectoral challenges means developing a comprehensive, cohesive and urgent policy strategy. It also means tapping into the wealth of knowledge across the academic fields of economics, politics, engineering and sociology.

This thesis contributes to efforts to accelerate decarbonisation by drawing together methods and insights from these fields into a multidisciplinary approach to climate policy. The overarching research question introduced in Chapter 1 is *How can policy accelerate the delivery of climate mitigation?* Chapter 2 reviews the literature relevant to addressing this challenge. The first section (2.1) considers economics and politics, focusing on the theoretical and methodological literature of climate policy implementation. Section 2.2 reviews the literature on technological and social transitions, both of which will be necessary to achieve net zero by 2050. Transitions inevitably create disruption, and disruption studies are reviewed in Section 2.3. Each subsection closes with a short analysis through the lens of urgency, and each section concludes with a summary of the research gap. These gaps contribute to the three specific research questions posed in Section 2.4.

2.1 The economics and politics of climate change

The science of climate change is dominated by feedback effects, including the release of methane and weakening carbon sinks (Stern, 2006). The human response to climate change also generates feedback. As temperatures rise in much of the world, cooling requirements increase and more energy is used for air conditioning (Isaac and van Vuuren, 2009). As oceans rise, coastal populations migrate, generating additional construction and energy demand

(Zillman, 2009). These dynamics have financial, political and social ramifications, putting climate change within the purview of economists.

This section considers the theory and application of climate change economics. It covers an expansive literature: the aim is to provide an overview to inform the interdisciplinary approach of this thesis. Section 2.1.1 reviews the economic approaches to climate change. Methods of economic damage quantification are reviewed in Section 2.1.2. Climate policy and the political economy of climate change are discussed in Sections 2.1.3 and 2.1.4. The research gap is identified in Section 2.1.5.

2.1.1 Economic approaches to climate change

Climate change economics is a branch of environmental economics, developed in response to the environmental revolution of the 1960s (Cropper and Oates, 1992). Climate economics, like the discipline at large, is a broad and varied field. The neoclassical approach is to consider climate change a market failure, which can be corrected using market mechanisms. Alternative approaches consider the resource-emissions duality, behavioural psychology, planetary limits and organisation theory.

Climate change as an externality

The two fundamental principles of mainstream climate economics is that the climate is a global public good, and climate warming is a global externality (Nordhaus, 1991). Public goods are resources that belong to everyone: it is costly or impossible to prevent people from using them, and one person using them does not preclude another from doing the same (Kaul, 1999). *Global* public goods are those that impact people across countries and, in some cases, across time (Nordhaus, 1991). Externalities exist when the full impacts of a decision are not borne by the decision-maker (Pigou, 1920). A negative externality means that the decision maker imposes a cost on society which is not captured in the private market—their decision has implications in the public sphere. Public goods can be thought of as a special case of externalities (Kaul, 1999). In economic terms, externalities mean that the private marginal cost of a decision is not equal to the social marginal cost. This results in a market failure, and the outcome will be socially inefficient (Pigou, 1920). This discrepancy is illustrated in Figure 2.1.

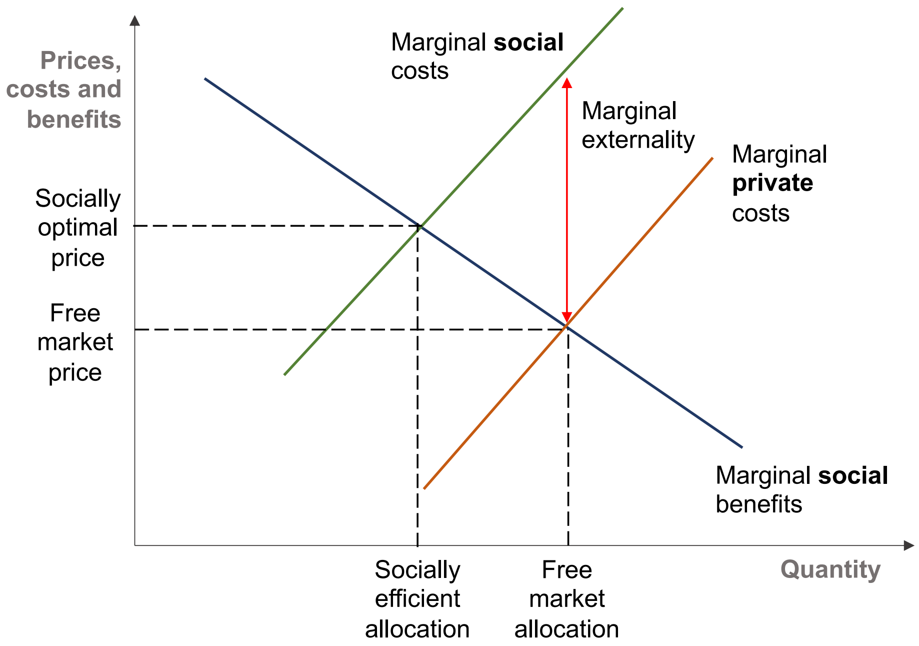

Fig. 2.1 A simple diagram showing the effect of an externality. 'Marginal' means that the prices, costs and benefits refer to the last additional unit. When the private (marginal) cost of a decision is lower than the social cost, the free market results in an equilibrium where the product is under-priced and over-supplied. In climate economics this under-priced, over-supplied product is greenhouse gas emissions. Based on theory from (Pigou, 1920).

The climate is not *just* a public good; climate warming is not *just* an externality. They are the superlative examples of both. As Nordhaus (1991, p. 146) put it, "greenhouse warming is the granddaddy of all public goods". Stern (2006, p. i) describes climate change as "the greatest and widest-ranging market failure ever seen". Moreover, climate change has several thorny features which distinguish it from other global externalities: the impacts are long-term, highly uncertain and could include major, irreversible catastrophes (Stern, 2006). This raises two vital issues: how to value welfare across generations, and how to deal with deep uncertainties.

For long-term economic tradeoffs, economic analysis requires a judgement about the relative importance of today's consumption versus tomorrow's, next year's or our children's consumption (Stern, 2006). The parameter that captures this judgement is the discount rate. Discounting means that future consumption is worth less than present consumption in today's decisions, and is generally justified for two reasons (Stern, 2006). First, under the assumption of continued economic growth, our children will be (financially) better off than we are—meaning that they will value an additional unit of consumption less, based on the concept of marginal diminishing returns (Heal, 2009). Second, people simply prefer to consume now. This second component, known as the pure rate of time preference, presents an ethical dilemma at long time scales: is our children's welfare less important than our own (Heal, 2009)? The discounting question has engendered a heated debate in the economic literature, and has long been shown to have significant effects on estimates of economic outcomes and optimal policy (Nordhaus, 1991).

Uncertainty dominates economic analysis of climate change. However, it is not the sort of uncertainty present in most economic quandaries (Heal, 2009). Typically, uncertainty is quantifiable and is more accurately termed risk. In climate analysis, the probabilities of different outcomes are themselves unknown. The latter is known as Knightian uncertainty (Stern, 2008). In essence, Knightian uncertainty means we do not know the shape of the distribution of climate impacts (Heal, 2009). This affects the optimal response to climate change. Say we assume that climate impacts take a normal distribution, or a bell curve, when in fact the distribution is 'fat tailed': giving slightly more weight to high-impact outcomes in the tail. Weitzman (2009a) shows analytically that under a fat failed distribution of outcomes—including low probability catastrophes—expected damages are infinite and nothing is more important than reducing emissions. Assumptions over the type and scale of uncertainty therefore have significant ramifications for economic analysis of climate change.

To economists, the global climate externality is a market failure. In theory, market failures can be corrected by adjusting prices to 'internalise the externality' (Pigou, 1920). This is the underlying principle behind putting a price on carbon emissions: apply the right price and rational decision makers will reduce emissions to the socially optimal level (Stern, 2006). Determining the right price requires quantifying the costs associated with climate damages, and with abatement activities. Foley (2007, p. 1) points out that, in the presence of such a wide ranging and long term externality, "there is no real opportunity cost to mitigation", so the right price is potentially infinite. Nonetheless, much of the economic debate on climate change centres on finding the balance between the costs and benefits of climate mitigation. These concepts, along with the quantitative impacts of discounting and uncertainty, are discussed further in Sections 2.1.2 and 2.1.3.

Exhaustible resource theory

Most economic analysis uses the externality approach to climate change described above. A complementary literature explicitly considers the links between exhaustible fossil fuels and emissions. Exhaustible resource economics deals with assets that are finite in supply. The theory builds on Hotelling's *The Economics of Exhaustible Resources* (1931), which presents a model that characterises the optimal price and extraction path of an exhaustible resource. The fundamental result is the price-indifference condition: the price of a resource will grow such that the owner is indifferent between extracting the resource now or in the future. The increase in price is induced by the limited supply of the resource, and is also referred to as scarcity pricing. Despite the fact that empirical work since the 1970s has shown that scarcity pricing is not observed in resource markets (Hart and Spiro, 2011), it has remained a popular tool for modelling resource markets. Over the last 20 years the field has turned its attention to the impact of climate change on fossil fuel use.

In climate Hotelling models, consumption of energy reduces the stock of a resource, increases the stock of pollution and imposes a social cost of climate damage. In an early study, Withagen (1994) shows that energy use, and therefore emissions, decrease in the presence of an environmental externality. The magnitude of this effect depends on the chosen climate damage function, which vary widely. Farzin (1996) uses a threshold damage function under which emissions are only harmful once they reach a certain stock. Gjerde et al. (1999) consider an alternative damage function where emissions do not harm society directly but increase the likelihood of some catastrophic event which reduces utility to zero. Prieur et al. (2013) assume a threshold over which the atmosphere can no longer reabsorb emissions through carbon sinks such as oceans and forests, meaning emissions become irreversible. The form of the damage function affects the timing and extent of emissions cuts.

Instead of classing climate change as a negative externality of exhaustible resource use, some models impose a ceiling on the stock of carbon. Koopmans (1973, p. 18) describes this approach: “regarded as a resource itself, the environment is exhaustible if subjected to irreversible damage”. Such an assumption implicitly imposes a binary damage function in which the effect of the carbon stock is negligible below the cap and catastrophic above (Coulomb and Henriet, 2010). A ceiling can therefore be justified as either a binding policy constraint or a threshold condition above which catastrophic outcomes occur with certainty.

Two considerations are important in exhaustible climate resource models. First, use of emitting resources will drive up scarcity prices of carbon over time (Hotelling, 1931). Second, emissions will tighten the constraint on the carbon concentration (Chakravorty et al., 2006). These simultaneous effects were first explored in a Hotelling framework by Chakravorty et al. (2006). They model the extraction of coal when a policy constrains atmospheric carbon. There is also a non-polluting renewable energy source (solar power) and an abatement technology (carbon capture and sequestration). Results show the polluting resource and abatement technology are heavily utilised up to and after the carbon ceiling, after which point the economy transitions entirely to the clean backstop technology. The carbon stock will fall to zero as remaining atmospheric carbon is reabsorbed by natural carbon sinks and technological sequestration. This progression of atmospheric carbon is common among Hotelling models with a carbon ceiling, and is depicted in Figure 2.2. Chakravorty et al.’s (2006) model generated subsequent research considering technological change (e.g., Grimaud and Rouge, 2008; Kollenbach, 2015a,b), differently polluting resources (e.g., Amigues et al., 2014; Smulders and Van Der Werf, 2008) and different implementations of the carbon ceiling (e.g., Amigues and Moreaux, 2013; Coulomb and Henriet, 2010; Lafforgue et al., 2008; Prieur et al., 2013).

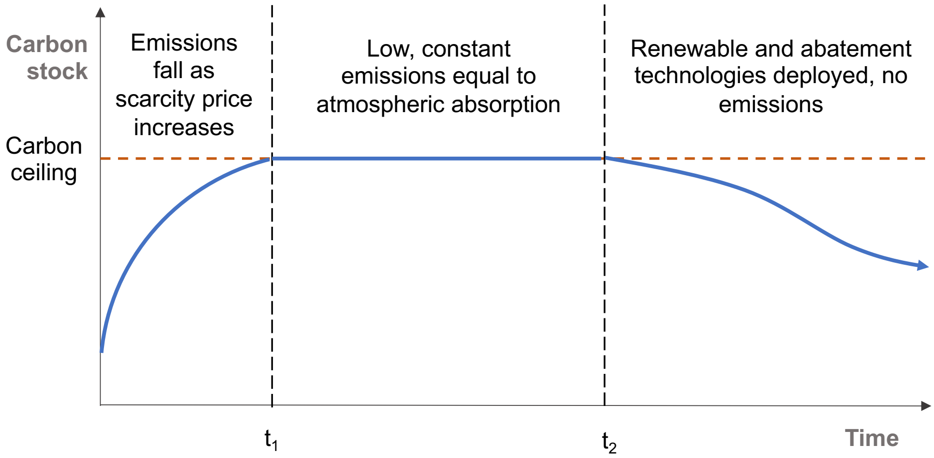

Fig. 2.2 A stylised optimal path of carbon stocks with a carbon ceiling. Non-polluting renewable energy and abatement technologies become mature at t_2. This depiction assumes a non-trivial rate of atmospheric carbon reabsorption. Adapted from results in Chakravorty et al. (2006), Kollenbach (2015b) and Kollenbach (2015a).

Alternative approaches to climate economics

The majority of climate economic literature follows the neoclassical school, which assumes individuals make rational decisions given their preferences and all available information. Rational choice theory has been criticised for its unrealistic psychological assumptions and implausible behavioural predictions (Green and Shapiro, 1994). Several different approaches consider the applications of bounded rationality to environmental challenges.

Ecological economics encapsulates the idea of a non-growth economy with a focus on throughput and stocks rather than production and on equality rather than growth (Daly, 2008). A major theme in ecological economics is the inadequacy of cost-benefit methodology for environmental problems (Anderson and M'Gonigle, 2012). Ecological economics places intrinsic value on environmental goods, which contradicts the monetisation of life, ecosystems, the future and uncertainty. Ecological economics is currently failing to provide practicable solutions to climate change capitalism or convincing critical analyses of the mainstream approach to climate change (Anderson and M'Gonigle, 2012).

Behavioural economics acknowledges that humans make irrational decisions, are not solely motivated by material gain and are influenced by social context (Brekke and Johansson-Stenman, 2008). The temporal and geographical mismatch of climate change costs and benefits make it rich ground for behavioural analysis (Croson and Treich, 2014). Behavioural approaches have contributed to the debate on appropriate social assumptions, policy and economic modelling. Kesternich et al. (2017) assesses current evidence on behavioural 'nudge' interventions, finding that they are effective, but generally have short term results.

Evolutionary economics applies the theory of natural selection to the transformation of economic organisations (Winter, 1964). It assumes firms are motivated by both profits and long-term survival. For individuals, evolutionary economics places more emphasis on habit formation alongside utility maximisation. Climate evolutionary economics primarily contributes into the literature on technological change. Maréchal (2007) proposes an evolution-inspired paradigm for innovation, which assumes bounded rationality and endogenous technological change. Marechal and Lazaric (2010) make three climate policy recommendations based on evolutionary economics: maintain solution diversity in technological innovation, use demand-side incentive systems aside from carbon pricing, and target influential users to lead by example for green habit formation. Evolutionary economists remain largely focused on firms, industry dynamics and technological innovation (Nelson, 2020).

Summary: Conventional climate economics does not enable non-market, systemic changes

Mainstream climate economics is founded in welfare economics, which largely deals with market decisions about consumption and production. Like much of modern economics, its recommendations can be summarised as *get the incentives right and the market will solve the problem*. However, climate decisions deal with the possibility of highly non-linear (and highly uncertain) catastrophes, and the climate is a non-market good (despite attempts to make it otherwise, see Section 2.1.3). The traditional approach of designing market incentives is therefore not appropriate for instigating urgent climate mitigation. Alternative schools such as exhaustible resource economics present promising frameworks, but have yet to be adopted into mainstream climate economic literature.

2.1.2 Quantifying climate damages

The second core contribution of climate economists is the quantification of damages. Quantification places a value on the impacts of climatic changes on human welfare. Recent studies also aim to quantify the ecological damage to natural capital resources, which may not impose direct economic costs (Bastien-Olvera and Moore, 2021). The quantification of damages implicitly assumes that climate damages can be 'weighed up' against the costs of abatement in a classic cost-benefit framework, thereby delineating how much time, effort and money should be optimally spent on decarbonisation (Anderson and M'Gonigle, 2012). Given the deep uncertainties inherent in damage quantification, this doctrine runs counter to the precautionary principle enshrined in the founding document of the United Nations Framework Convention on Climate Change (United Nations, 1992). Nonetheless, quantification is central to climate economics and this section reviews the main themes.

The social cost of carbon and the marginal abatement cost

The social cost of carbon (SCC) is the core metric used by economists to represent climate damages. The SCC captures the monetary cost associated with an additional unit of carbon emitted into the atmosphere (Stern, 2006). The SCC is calculated by comparing an indefinite stream of global damages from a tonne of carbon emissions to a baseline economy that did not emit that marginal tonne of carbon (Auffhammer, 2018).

The marginal abatement cost (MAC) captures the economic cost of abating an additional unit of carbon. MAC is increasing in abatement, as the cheaper low-hanging fruit of abatement become exhausted and more difficult methods are necessary (Stern, 2006). The MAC curve describes the costs of cutting emissions at various levels of abatement. Perhaps the most famous MAC curve was produced by McKinsey & Company (2010), which shows negative costs—ie, savings—for many abatement measures.

The SCC and MAC are complementary, and mutually important for climate policymaking. The theoretically optimal abatement level is that which balances the cost and benefit of abatement (Stern, 2006). If the SCC is higher than the MAC at a given abatement level, then the cost of abating one more unit of carbon would be less than the damages it generates—so it would be optimal to abate a little more. These seemingly abstract concepts therefore have significant political influence. By putting a value on the SCC, economists and policymakers can evaluate public projects or regulations in a traditional cost-benefit framework. If the SCC is high, many abatement activities will be valuable. Conversely, if damages are small then, as Stern and Stiglitz (2021, p. 1) put it, "the SCC makes sure that we don't do anything foolishly expensive".

Quantification of the social cost of carbon has come to dominate economic literature on climate change. Table 2.1 summarises a selection of estimates of the SCC using several methods. Early estimates used analytical calculations to estimate the SCC (e.g., Nordhaus, 1991). More recent estimates are based on complex computational methods, known as integrated assessment models (see below).

Table 2.1 A range of estimates of the social cost of carbon

Source	Model type	Model year	SCC (US$/tCO$_2$)
Nordhaus (1991)	Analytical	1991	15
Rose et al. (2017)	RICE	2010	53
Rose et al. (2017)	PAGE09	2011	96
Rose et al. (2017)	FUND3.7	2013	28
Waldhoff et al. (2014)	FUND3.9	2014	13
Moore et al. (2017)	FUND3.9 + updated agricultural damages	2014	23
van der Ploeg (2014)	Analytical + abrupt climate feedbacks	2014	109
Nordhaus (2017)	DICE	2016	48
Ricke et al. (2018)	Country-level IAMs	2018	417

Consistent with the climate literature, SCC estimates are given in US$.

The highest estimates of SCC are generated in models which apply more granular or more stringent assumptions about climate damages. Ricke et al. (2018) estimate country-level SCC in order to capture the geographical heterogeneity of climate causes and impacts. The median global estimate was US$417/tCO$_2$, far higher than mainstream estimates (Rose et al., 2017). In some cases, updating the scientific estimates of climate damages drastically increases the SCC. Moore et al. (2017) find that updating the assumptions about agricultural damages increases estimates of the SCC by up to 129%. van der Ploeg (2014) uses an analytical model to show that the SCC increases from US$25/tCO$_2$ to US$95/tCO$_2$ by including the possibility of abrupt climate feedbacks.

The huge variability in damage estimates weakens the SCC as a policymaking metric. Moreover, the complexity of estimation methods means that end users may not have a clear view of what an estimate of the SCC captures. This had led some prominent climate economists to call for alternative approaches to climate quantification (e.g., Stern and Stiglitz, 2021). However, Wagner (2021) counters that the SCC remains a useful tool despite its shortcomings, and that abandoning it could in fact reduce impetus for urgent climate action. The following sections review the primary method used to estimate the SCC and summarise the methodological issues.

Integrated assessment models

The SCC is usually estimated using complex models called integrated assessment models (IAMs). IAMs combine socioeconomic scenarios with climate impacts to estimate damages. Crucially, IAMs capture the feedback effects between economic activity and climate change (Auffhammer, 2018). IAMs usually comprise of four modules, illustrated in Figure 2.3.

Generally the most important—and subjective—is the damage module. This module includes modellers' choice of damage function, which maps climate effects into economic damages at the global or regional level (Auffhammer, 2018). Damage functions are critical to the determination of SCC.

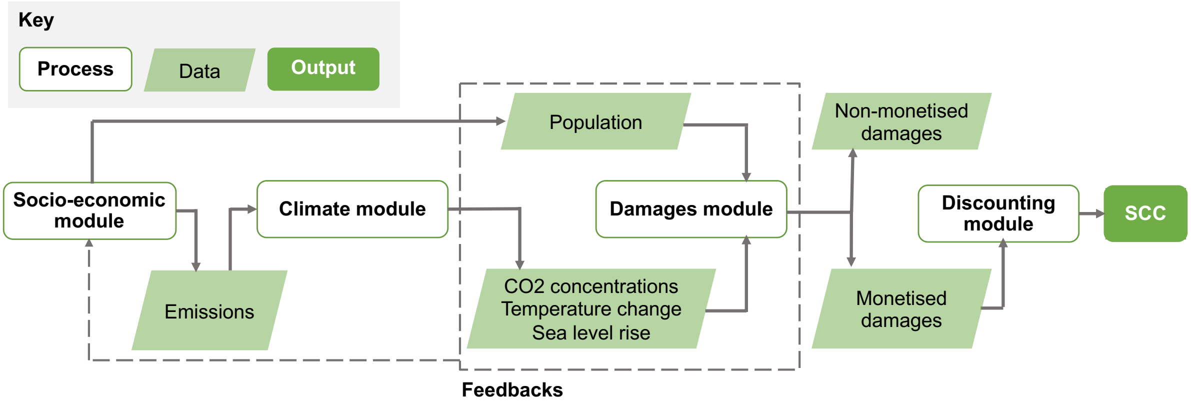

Fig. 2.3 The integrated framework for estimating the social cost of carbon (The National Academy of Sciences, 2017)

The most prominent IAMs are: the Dynamic Integrated Climate-Economy model (DICE) by William Nordhaus; the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) by David Anthoff and Richard Tol; and Policy Analysis of the Greenhouse Effect model (PAGE) by Chris Hope (Auffhammer, 2018). All three integrate climate considerations into standard neoclassical optimal growth models. However, the models generate significantly different results. Rose et al. (2017) use component-level diagnostic assessments to compare the models' outputs under consistent input assumptions. They find significant variation in model behaviour and SCC estimates, driven by differences in structure and implementation of the three IAMs.

Methodological issues in damage quantification

Estimates of the SCC are central to climate policymaking. However, methods of quantifying climate damages are very sensitive to assumptions (Pindyck, 2013). Even proponents of the SCC acknowledge the many methodological issues in damage quantification (Wagner, 2021). The core empirical issues are the approach to climate science in economic models, subjectivity of modelling assumptions, and the 'black box' complexity of IAMs.

A central critique of IAMs is they do not use recent and realistic scientific estimates of climate impacts in the damage function (Auffhammer, 2018). A review by The National Academy of Sciences (2017) concluded that the damage functions currently used in FUND, PAGE and DICE fail to include best available scientific estimates of climate impacts, including both marginal and catastrophic damages. Specifically, Dietz et al. (2020) argue that economic models assume too long a delay between emissions and warming, and exclude positive feedback effects. This means that these models severely underestimate climate damages. Moore et al. (2017) illustrate the potential magnitude of this effect with their analysis showing that updated agricultural damage assumptions—only one aspect of climate impacts—increase the SCC by up to 129%.

Mainstream climate-economy models do not have a plausible way of considering catastrophic risk (Aldy et al., 2010). Extreme temperature increases in the range of 8-10°C are known as catastrophic damages. The risks of such an outcome are generally considered to be vanishingly small, so are not included in damage functions (Nordhaus, 2017). However, Weitzman (2009b) shows that if the distribution gives even slightly more weight to low probability catastrophic events then the social cost of carbon is much larger than previously thought. In their broad critique of mainstream SCC quantification, Stern and Stiglitz (2021) conclude that accounting for extreme risk is necessary and not currently adequate.

Calculation of the SCC requires assumptions about the discount rate, which gives the relative valuation of current and future consumption (Ackerman et al., 2009). Selection of the discount rate can be considered an ethical choice, or simply an application of the market rate of return (Stern, 2008). Heal (2009) labels discounting an act of intergenerational discrimination: a non-zero rate means that the value of the utility of future people is less than that of present people, solely based on the year they were born. In contrast, Nordhaus (2007) highlights the importance of the return on capital investments for driving efficient emissions reductions, and uses market investment return as a proxy for the discount rate. Nordhaus (2017) calculated estimates of the SCC under his own discount rate, and the discounting used in Stern (2006), yielding estimates of US$37 and US$266 respectively.

Climate change and its interactions with society and the economy are very complex (Stern, 2008). Since the first IAM developed by Nordhaus (1991), understanding of climate change has progressed hugely. In response, economic modellers have continued augmenting their IAMs, and models have become larger and increasingly indecipherable (Pindyck, 2013). However, given that a lot of the uncertainty lies in how climate change affects social outcomes, new IAMs have not necessarily produced more reliable predictions of the SCC (Pindyck, 2013). Instead, they rely on subjective modelling assumptions, which are generally not made explicit in climate policymaking (Wagner, 2021). Instead of including more and more climate-economic feedbacks in models, Weitzman (2009b, p. 26) reflects that "perhaps in the end, the climate economist can help most by not presenting cost-benefit estimates.... as if [they are] accurate and objective".

Alternative metrics to quantify climate damages

The SCC is the most common method for quantifying damages in climate economics. However, there are alternative approaches, including the cost of inaction and the climate value at risk. As discussed in Section 1.2, the cost of inaction measures climate damages by comparing a business-as-usual trajectory to one with successful climate policy (Stern, 2006). Costs of inaction are a cumulative measure of damages across geographies and time, rather than a marginal estimate like the SCC. They capture the 'big picture' of climate change, and can be used to evaluate the tradeoffs of global climate policy in aggregate, rather than at the margin (OECD et al., 2015). Estimates of the cost of inaction are often calculated in IAMs, but reported as a secondary result (e.g., Nordhaus, 2017).

Climate value at risk (VaR) takes an entirely different approach to damage quantification with a focus on the financial sector. In general, VaR is a financial metric which captures the level of risk within a firm or portfolio over a period of time (Linsmeier and Pearson, 2000). Climate VaR measures the specific risks associated with climate damages or climate policies. Economist Intelligence Unit (2015) estimates a global climate VaR of between US$4.2trn and US$43trn, or between 6% and 60% of global GDP in the year the report was published (The World Bank, 2021b). Like conventional measures of climate damages, the wide range of estimates reflects variation in modelling assumptions and temperature outcomes. Climate VaR has recently been trialled by UNEP Finance Initiative (2019) for estimating climate risks across various sectors. Overall, it estimates a 5% value loss for a market portfolio of 30,000 companies in a 1.5°C scenario. This loss is driven primarily by policy-related business disruptions, but is ameliorated by technology opportunities. In the academic literature, Battiston and Monasterolo (2020) has used climate VaR to assess the financial risks of transitional climate policy. This metric remains relatively obscure, but the growing focus on climate risk management in the financial sector (Network for Greening the Financial System, 2020) may increase its appeal in future.

Summary: Quantification of the social cost of carbon obscures aggregate tradeoffs

The quantification of society's interactions with the climate is mind-bendingly complex, so ongoing debates about methods and assumptions come as no surprise. Yet the main problem of economic damage quantification is more fundamental: the aggregate impact of climate change is overshadowed by the prevalence of marginal damage estimates—the SCC. This in turn dampens the motivation for the transformative change necessary to avert long-run disaster. Other metrics, including the cost of inaction and value at risk, go some way in countering this marginal narrative, but are not yet included in policy analysis.

2.1.3 The three pillars of economic climate policy

Climate change presents an environmental externality on an unprecedented scale (Stern, 2008). To economists, government interventions can correct the climate externality in three ways (Goulder and Parry, 2008). First, carbon pricing can reduce the gap between the private and social marginal costs of carbon by imposing a cost on emitters. Carbon pricing has come to dominate the literature on climate economics. Second, regulations can be used to protect environmental quality by imposing technology or performance standards on producers. Finally, governments can encourage the development of new technologies by subsidising research.

Policy evaluation depends on many factors: cost-effectiveness, environmental efficiency, distributional impacts and public acceptability, among others. This section considers each criteria throughout the discussion of climate policy. The overarching question of this research, however, poses another crucial principle: urgency. The limited time remaining to eliminate emissions means that any policy must precipitate swift change and have only a short delay between proposal and implementation.

Carbon pricing

Carbon pricing is the core tenet of economic climate policy. It is based on the ‘polluter pays’ principle, which states that the financial responsibility for emissions falls on the emitter (Ekins and Barker, 2001). Carbon prices are therefore applied to upstream polluters—fossil fuel companies, industrial manufacturers—with incentives assumed to flow through to consumers through product prices. In theory, pricing carbon encourages the deepest emissions reductions where abatement is cheapest, thus minimising the aggregate cost to society (Harrison, 2010).

Carbon pricing policy can be separated into taxation and tradeable permits for emissions. They are sometimes called the price and quantity approach respectively, referring to the variables that regulators control under each scheme (Nordhaus, 2005). These policies are theoretically equivalent, both achieving the socially optimal level of emissions (Coase, 1960; Pigou, 1920). However, market distortions and politics means the two approaches face different constraints and generate different outcomes in practice.

Carbon taxation relies on prices to incentivise emissions reductions. Although economic theory concludes that taxes reduce emissions, the empirical evidence is more mixed. Computable general equilibrium models show tax-induced abatement in several country-level studies, including in Australia (Meng et al., 2013), New Zealand (Scrimgeour et al., 2005), and South Africa (Devara et al., 2011). However, several different approaches have shown that the impact of taxes on CO_2 emissions may be limited, including econometric analysis of implemented taxes in Nordic countries (Lin and Li, 2011), analytical analysis using game theory (Kuo et al., 2016), and industry-level case studies (Skelton and Allwood, 2017). Collectively, these studies present two main arguments for the limited impact of taxes on emissions. First, low cost pass-through limits the effect on prices and downstream demand. Second, compensation schemes offered to polluting firms in order to reduce opposition to carbon taxing reduce incentives to abate.

An important consideration is whether the carbon tax burden is distributed equally across the economy. Empirical analysis shows that households in general bear a disproportional share of carbon taxation (Eurostat, 2003). Moreover, there is evidence that carbon taxes are regressive. Grainger and Kolstad (2010) conclude that carbon taxes are regressive by nature because emissions-intensive goods take up a relatively large portion of a low-income person's budget. An early study on the impact of carbon taxes simulated the impact of a carbon tax on households in the United Kingdom (Symons et al., 1994), finding that a carbon tax sufficient to reach the Toronto target of a 20% reduction in emissions would increase inequality by 3%.

The second type of carbon price policy is emissions trading schemes. Coase (1960) shows that tradeable permits are theoretically as efficient as taxes at reducing emissions, with the appealing feature that they give the regulatory body direct control over the quantity of emissions (Weitzman, 1974). Tradeable permits are also known as cap-and-trade or emissions trading schemes (ETS).

The market price for permits balances the demand for emissions against the supply of permits, set by the market operator. Theoretically, this means that price will reflect the marginal abatement costs of the firms who buy the 'marginal permit' (Coase, 1960). However, the complete inelasticity of supply imposed by the permit constraint can lead to significant price fluctuations, which make planning difficult for firms, hindering trade and blocking an efficient allocation of permits (Nordhaus, 2005). Indeed, highly volatile prices have been observed in both the European Union Emissions Trading Scheme (EU ETS) (Weisbach, 2012), and the USA sulphur emissions trading scheme (Nordhaus, 2005). Given the importance of carbon pricing in key industries, permit price fluctuations have severe ripple effects in the wider economy (Zhang et al., 2017). On the other hand, Goulder (2013) argues that price volatility can play a useful countercyclical role: in downturns, demand for allowances will fall, putting downward pressure on prices and softening the impact of pollution regulation.

The economic efficacy of ETS depends on the initial allocation of permits and the equilibrium market price. Tradable permit schemes can be designed so that initial allocations of permits are freely allocated or auctioned to polluters. Either method should theoretically lead to the same permit price and final allocation, a feature known as the independence property (Fowlie and Perloff, 2013). However, freely allocating permits transfers the economic benefits of supply from the regulator to the polluters that it is regulating (Goulder and Parry, 2008).

Despite the economic argument for carbon pricing and its prominent position in climate policy debates, carbon pricing schemes still cover less than a quarter of global emissions (The World Bank, 2021a). This is in part due to the reluctance of governments to implement new taxes (Nordhaus, 2011). Emissions trading schemes, which tend to be more popular with the public (Goulder and Parry, 2008), cover more emissions but have a lower market price. Figure 2.4 show the price level and greenhouse gas coverage for all implemented or scheduled carbon pricing policies as of 2021. Tax levels range from almost nothing to more than US$130 per tonne of CO_2 in Sweden. The highest permit price is US$30 in the EU ETS. None of the trading schemes have market prices anywhere near the tax levels seen in Sweden, Switzerland and Liechtenstein.

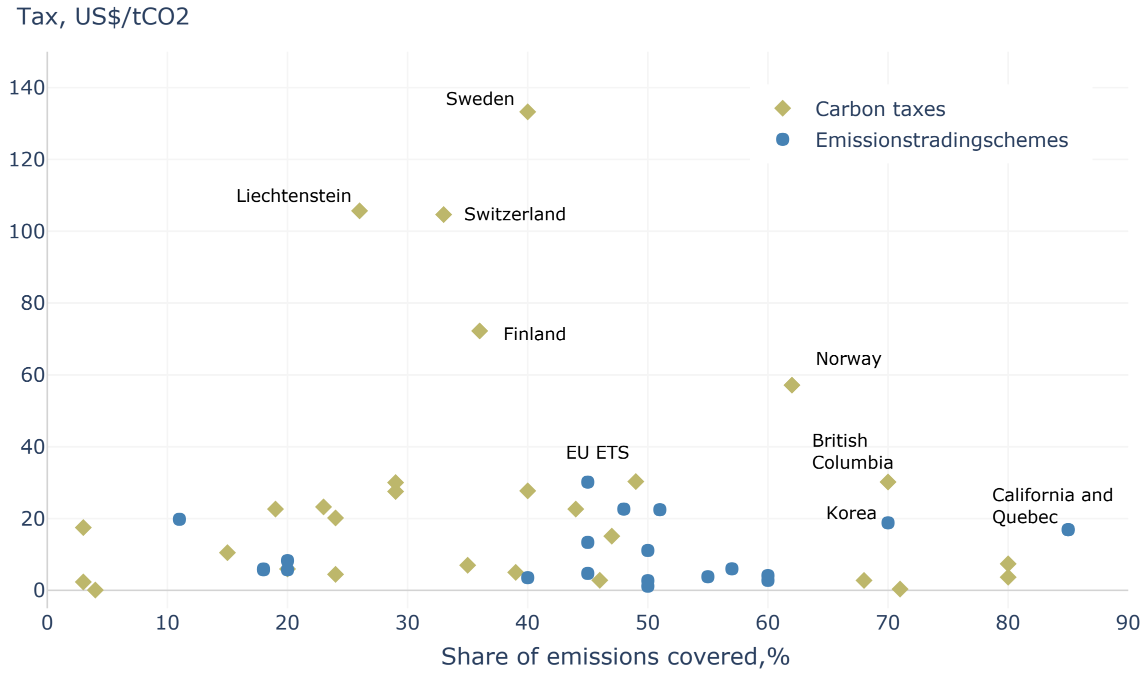

Fig. 2.4 The prices and share of emissions covered by implemented and scheduled carbon price policies. Data from The World Bank (2021a).

Opponents of carbon pricing policies—both taxes and permits—note that they reduce the competitiveness of the enforcing country's economy and production. By increasing costs of production, carbon prices make other countries' energy and products relatively cheaper (Aldy and Stavins, 2012). They may also prompt domestic firms to offshore carbon-intensive production to countries where carbon prices are low or non-existent (Goulder and Parry, 2008). This effect, known as carbon leakage, reduces the home country's emissions but results in no global abatement. Aichele and Felbermayr (2015) estimate that carbon pricing policies increase imports from a non-regulated country by 8%, and the carbon-intensity of these imports is about 3% higher than if the importing country did not price carbon. The competitiveness effect therefore reduces the environmental benefits of carbon pricing (Scrimgeour et al., 2005). It is also a source of public opposition to carbon taxes (Carattini et al., 2017).

An oft-cited solution to the competitiveness concerns of carbon prices is the possibility of carbon-related border adjustments (Aldy and Stavins, 2012). For carbon taxes, this would involve an import tariff proportional to the imports' emissions intensities. Under ETS, importers would be required to purchase allowances to cover the embodied emissions of their products. The aim of border adjustments is to impose similar regulatory costs on imported goods to create a level carbon playing field (Dissou and Eyland, 2011). However, opposition to border adjustments is strong. Import tariffs can increase the regressivity of carbon pricing policies, by raising the prices of imported goods. Dissou and Eyland (2011) show this effect increases the welfare loss of a domestic carbon policy by 25%. Moreover, as Aichele and Felbermayr (2015, p. 104) points out, they have an "air of green protectionism" and could lead to a tariff war. They are also plagued by questions of their legality under World Trade Organisation (WTO) rules (Aldy and Stavins, 2012). The European Parliament recently adopted a resolution to pursue a border adjustment mechanism which it claims is compatible with WTO and EU trade rules (Jadot, 2021). However, no carbon border adjustments have yet been successfully implemented.

Without border adjustments, and in the absence of a global authority to impose and enforce multilateral climate policy, domestic economic concerns are likely to thwart meaningful carbon pricing. The countries which have managed to implement high taxes are wealthy, have secure, independent energy networks, and offer sufficient social security to soften the welfare impacts (The World Bank, 2021a). Their success is not easily replicable, evidenced by the glacial progress of carbon pricing policies over the last 30 years. Carbon pricing has not enabled urgent climate action.

Regulation

Regulation is the conventional policy tool to enforce climate-friendly practices, and includes product or process bans and standards. Standards can be either technology-based or performance-based (Aldy and Stavins, 2012). Technology-based regulations require the use of special equipment or processes. Performance regulations specify a particular standard, for example, an allowable level of tail-pipe emissions for cars. They are more flexible than technology-based regulations, allowing regulated firms to meet standards in the most efficient manner (Aldy and Stavins, 2012).

In the economic literature, regulations are generally termed 'command and control' or 'direct regulatory' instruments, in contrast to market mechanisms which utilise price incentives (Goulder and Parry, 2008). Command and control approaches have traditionally been popular in policy, but Aldy and Stavins (2012) argue that the wide use of fossil fuels means they cannot be relied upon to reduce climate impacts. To economists, conventional regulatory approaches are considered less cost-efficient than carbon taxes or permit markets (Cropper and Oates, 1992; Nordhaus, 2005). Goulder (2013) reviews a series of studies which show that cap-and-trade schemes for sulphur dioxide and emissions yielded cost savings of 2% to 90% compared to regulatory approaches. However, he notes that these studies considered only inflexible forms of conventional regulation, potentially inflating the relative benefit of trading schemes. Moreover, interactions with other regulations and taxes can reduce the environmental benefits of carbon pricing (Goulder, 1998, 2013).

Cost effectiveness is only one of the criteria in determining the appropriate policy. Environmental outcomes and political acceptability are also crucial (Snyder Bennear and Stavins, 2007). Goulder and Parry (2008) compare incentive-based price policies to the direct regulatory instruments of technology mandates and performance standards. They highlight the many considerations in instrument choice, including administrative costs, distributional impacts among both firms and households, and the practicalities of enforcing policies under conditions of uncertainty. Their results, summarised in Table 2.2, show that regulations can be more politically appealing, and impose a lower burden on low-income households. Given the overarching research question of this thesis, this table also provides an indication of how quickly they incentivise or enforce abatement. This urgency criteria is judged based on the literature in this review, along with evidence from implemented environmental policies.

Table 2.2 Comparing price-based and direct regulatory climate policies. Based on Goulder and Parry (2008) and review of implemented policy literature.

Instrument	Cost efficiency	Equalise MAC (1)	Minimal tax interaction	Political feasibility (2)	Distributional effects (3)	Urgency (4)
Emissions tax	✓	✓	✓		✓	
Abatement subsidy		✓				✓
Tax on carbon-intensive goods		✓	✓			
Auctioned permits	✓	✓	✓		✓	
Freely allocated permits	✓	✓		✓		
Technology mandates				✓	✓	✓
Performance standards				✓	✓	✓

Notes: (1) Equalising MAC achieves efficient abatement across heterogeneous firms. (2) Policies are considered politically feasible if a low share of the regulatory burden falls on emitters, reducing the likelihood of lobbying. (3) Distributional efficacy means a policy limits any disproportionate burden on low-income households. (4) Urgency refers to the time between policy proposal and realised abatement.

A combination of policies can often be optimal, particularly when market imperfections or policy interactions limit the efficacy of economic instruments (Snyder Bennear and Stavins, 2007). Toolkits of multiple instruments, including command and control approaches, have proven successful in the past for addressing energy efficiency, toxic chemicals and fisheries management (Snyder Bennear and Stavins, 2007). Today, most proposed and implemented climate strategies include both incentive-based and command and control instruments, along with policies to support the deployment of low carbon technologies (e.g., Bouckaert et al., 2021; Stark and Thompson, 2019).

Technology policy

Before reviewing the economic literature on technology policy, it is useful to distinguish the economic and engineering definitions of technology. Engineers, and indeed most people, tend to consider technology to be the practical application of mechanical or scientific discoveries, particularly in industry or manufacturing (Oxford English Dictionary, 2019). Economists take a broader definition, which includes any product, process, device or practice used in a market, including social and institutional processes that enable the use of physical equipment (Grubler et al., 1999). Technological change is therefore any change to a production process that increases output. Explicating the different definitions is important for 'translating' between engineering and economics. This section reviews the economic literature on technological change and policies. Sections 2.2.1 and 2.2.2 reviews research from other disciplines.

In economic theory, research and development (R&D) generates positive externalities (or 'spillovers') because the benefits of knowledge and innovation are shared in the public domain (Hall, 2002). Public investment in R&D is therefore considered key to correcting this market failure and reducing the carbon intensiveness of the economy. Popp et al. (2011) uses empirical analysis of renewable investment in several countries to show that investment is driven more by policy than demand, consistent with the theory that government has a role to encourage costly R&D as a public good. Baranzini et al. (2017) argue that carbon prices can provide profit incentives and motivate environmental innovation. However, stimulating optimal investment requires carbon prices to be far higher than they are currently. Until an optimal carbon price is politically acceptable, there is a consensus in economic literature that government intervention in climate R&D is an optimal mitigation strategy (Montgomery and Smith, 2007).

A commonly cited win-win of technology policy is that improving energy efficiency in sectors such as manufacturing, transport and heating can both reduce emissions and save money (Allcott and Greenstone, 2012). This 'energy efficiency gap' is the apparent wedge between cost-minimising energy use and what is actually realised. Most economists are sceptical of the energy efficiency gap, as it would mean firms and consumers fail to make profitable energy efficiency investments (Gillingham and Stock, 2018). Predicted efficiency gaps have been shown to shrink under empirical analysis (Fowlie et al., 2015).

Technological change is considered the ‘line of least resistance’ to addressing climate challenges (Azar and Dowlatabadi, 1999). In climate modelling, technology often heralds an escape from climate-induced constraints to production (e.g., Henriet, 2012; Kollenbach, 2015b), despite scant evidence that these technologies will be realisable in the near term (e.g., Smil, 2014). This reliance on future technologies can create a moral hazard effect that delays abatement, which Markusson et al. (2018) calls ‘mitigation deterrence’ in the context of carbon capture technologies. Wilbanks (2011) recognises the danger of techno-optimism in climate economics: models that rely on future technological developments absolve politicians of the responsibility to make difficult trade-offs in the present. This view is not widely held by climate economists.

Whether technology policy can create urgent mitigation depends on the duration of technological diffusion. Slow diffusion means innovation subsidies will create new technologies—and support abatement—only years or decades in the future. Technologies which can be developed and scaled up quickly offer significant climate promise. Picking winners, however, is notoriously difficult and politically risky (Wilson, 2018). Evidence of the duration of new technologies is reviewed in Section 2.2.2. The global climate response doubtless requires technological innovation. But achieving urgent mitigation requires immediate and guaranteed emissions savings. With three decades remaining to net zero, it may no longer be appropriate to rely on technology policy.

Summary: Economic climate policy has not motivated urgent mitigation

Economic theory yields three central policy recommendations: price carbon to incentivise efficient abatement, regulate polluters where incentives fail, and support innovation. The first and third streams rely on marginal adjustments and price stimuli, and have so far dominated climate policy agendas. They are not working quickly enough. Figure 1.1 shows that emissions keep rising, even as domestic targets get more ambitious and international agreements more frequent. Urgent mitigation requires a different approach. It could draw on the second tenet of economic climate policy, regulation, which has successfully been deployed in past environmental challenges including the phase out of ozone depleting substances, asbestos and leaded petrol.

2.1.4 The political economy of climate policy

The economic literature on climate policy apparently presents policies which achieve both carbon abatement and economic efficiency. Of course, this begs the questions: why have they not been implemented? And why are emissions still too high? The 'first best' world of the economic analysis reviewed above is analytically useful, but largely ignores the significant political barriers to optimal climate policy. This section reviews the political economy of the climate debate, which goes some way to explaining the limited implementation of economic climate policy.

Policy myopia and vested interests

The fundamental barrier to timely climate policy is that the benefits, in the form of avoided climate damages, will mostly be accrued decades or centuries in the future, while the costs are paid now (Stern, 2006). This mismatch dampens political incentives to shoulder abatement costs or regulate lifestyle changes in the present, especially when evaluating the success of interventions is difficult. Samset et al. (2020) show that the lag between emissions and warming means that today's policies will take more than a decade to affect temperatures, creating a feedback delay between current climate policies and future climate relief. Adding to the feedback delay, international culpability and the complexity of decarbonisation mean that politicians can freeride on the actions of neighbouring countries while shifting the domestic policy burden onto their successors (Tol, 2017). The combination of these effects results in suboptimal levels of abatement determined by myopic climate policy.

In general, policy myopia describes the inefficiently low public investment that occurs due to shortsighted political decisions (Leblanc et al., 2000). Myopic policy arises for several reasons. Nordhaus (1975) show that political incentives to please voters before elections can give rise to a short-term political business cycle, also known as pork barrel spending. When political instability means governments have a positive chance of losing power, incumbents place a lower value on future outcomes, inducing myopia (Devereux and Wen, 1998). Similarly, uncertainty over the likelihood of reelection means politicians are inclined to pick inefficient short-term policies over long-term investments (Darby et al., 2004; Gersbach, 2004). Mechanisms to limit myopia aim to adjust political incentives by setting performance standards for reelection (Ferejohn, 1986) or second-term earnings (Gersbach, 2004).

Environmental policy is also particularly susceptible to industrial lobby groups that oppose intervention. Political economy models have been used to illustrate that if industrial lobby groups are better organised (Aidt, 1998) or more persuasive (Prieur and Zou, 2018) than environmentalists, climate policy is suboptimal. For voters, the influence of lobby groups can exacerbate climate scepticism and reduce public support for ambitious policies (Tol, 2017). Where support is strong, McGrath and Bernauer (2017) argue that small but powerful industrial lobbies are responsible for the mismatch between a public appetite for climate action and lethargic implementation of meaningful policies.

The role of voters

Politicians make climate policy. However, they are elected by voters. Individual beliefs and attitudes can influence voters' perception of how important climate change is—and their decisions in the ballot box. As Millner and Ollivier (2016, p. 226) put it, "the beliefs of the general public are ground zero for the battle to implement environmental policies". Myriad factors affect the formation of individuals' climate beliefs. Acceptance of anthropogenic global warming generally increases with education and knowledge of climate issues (Kahan et al., 2012). Worldview and ideology also play a significant role in belief formation and updating (Cook and Lewandowsky, 2016; Rhodes et al., 2014), as do emotional outlook (Sarabia-Sanchez and Rodriguez-Sanchez, 2016) and media influences (Millner and Ollivier, 2016). The role of beliefs and behaviours is reviewed in more detail in Section 2.2.3.

The public acceptability of climate policies are critical to their success. General aversion to taxes and a lack of confidence in the economic efficiency of environmental taxes hinder efforts to implement or increase carbon taxes (Carattini et al., 2018). Phasing in taxes over time, information sharing and earmarking tax revenue to go to environmental interventions can improve public support (Carattini et al., 2018) and reduce the perception that taxes have limited impact on emissions (Gevrek and Uyduranoglu, 2015).

The political constraints on tradeable permits are less tight than those on taxes, primarily due to the flexibility of how permits are allocated. When emissions permits are freely allocated with the number of permits usually based on past emissions, known as 'grandfathering', political support for the scheme is significantly greater than for taxation or auctioned permits (Snyder Bennear and Stavins, 2007). Grandfathered permits reduce the cost to firms, thus increasing stakeholder support for the scheme. However, this approach can introduce perverse incentives to increase emissions in the allocation year (Stern, 2006).

Voters tend to oppose policies that are highly regressive, placing an inequitable burden on low-income families (Baranzini et al., 2017). This has been shown to be the case for carbon taxes (Grainger and Kolstad, 2010; Symons et al., 1994), a fact which contributes to the political opposition to carbon pricing policies. The 'gilet jaunes' movement in France is a stark example of the political risk of imposing climate solutions with uneven social impacts. The proposed tax hike would have disproportionately affected poorer rural residents, who tend to drive further distances and own diesel cars (Chamorel, 2019). After three weeks of violent protests, the tax increase was abandoned. Carbon tax regressivity, and the public concern surrounding it, can be reduced by allocating tax revenue to spending to reduce inequality (Rausch et al., 2011), such as lump-sum payments to residents (Carattini et al., 2018).

Supply-side versus demand-side policy

Climate policies can be delineated into those that affect the supply-side—upstream producers of goods, services or electricity—and those that influence consumption patterns on the demand-side. Current climate research and policies primarily address how the supply-side can reduce emissions by imposing carbon prices on industrial emitters and setting ambitious targets for low carbon innovation (Creutzig et al., 2018). As discussed above, carbon pricing has so far not been implemented at a price or scale sufficient to reduce emissions (The World Bank, 2021a). Moreover, the promise of low carbon innovation is dampened by the time delay between invention and widespread use (e.g., Gross et al., 2018, see Section 2.2.2). Ambitious deployment of existing low carbon technologies like wind and solar generation could reduce reliance on polluting fossil fuels (IRENA, 2019). But widespread uptake of renewable energy requires extensive changes to the electricity grid to accommodate intermittent generation (Bunn and Muñoz, 2016), which we can expect to be slow and pricey (Smil, 2016).

The worldwide dominance of supply-side approaches has eclipsed other policy options over the last three decades (Twomey, 2012). Gilbertson and Reyes (2009) argue that the focus on carbon pricing narrows the vision of domestic and international policy negotiations. Low carbon innovation and carbon taxes are important. However, even under optimistic assumptions of technological development, Bryngelsson et al. (2016) show that technology can only reduce European emissions by a half. Remaining abatement must be achieved by reducing demand for carbon-intensive products (Anderson et al., 2014).

Demand-side policies offer a relatively low risk approach to reducing emissions, but can have both positive and negative welfare implications (Creutzig et al., 2018). Some emissions-saving choices have non-environmental cobenefits, such as improvements in health and lifestyle. For example, a shift to low meat diets would improve cardiovascular health (Aleksandrowicz et al., 2016). Urban planning overhauls could slow urban sprawl, resulting in fewer driving hours and healthier transport options (Jørgensen et al., 2013). However, reducing energy and material use could also reduce living standards, particularly in the developing world. Steinberger et al. (2012) point out that the need to reduce emissions must be balanced against the importance of improving human development across the world.

The scale of the climate challenge means that both supply-side technologies and demand reductions are essential to achieve emissions targets (Anderson et al., 2014). So far, this balance has not been struck in domestic climate policy and attention remains firmly on technological mitigation. Section 2.2 reviews the literature on technological and social responses to climate change

Summary: Political economy impedes urgent action and requires new approach

Climate economists have for 30 years presented policies which they argue would solve the carbon challenge by aligning private incentives with the social optimum. However, their suggestions face stringent political economy constraints: the vested interests, political incentives, voter beliefs and supply-side preferences that obscure the climate policy agenda. Achieving urgent climate change will require new approaches to climate communication, targets and policymaking that counteract interference from the political economy.

2.1.5 Research gap: New economic approach to rapid decarbonisation

The economic approach to climate policy is grounded in the theoretical bedrock of environmental economics and externalities (Section 2.1.1). Modern climate economists largely focus on estimating the damages of climate change and the optimal carbon price (Section 2.1.3). This is important, and involves the mammoth task of estimating and valuing the impacts of climate change, from physical damages to financial disruption, from biodiversity loss to the psychological costs of migration (Section 2.1.2). But the focus of economic literature on climate change has become highly technical and relatively narrow.

This is, of course, an oversimplification. This section has reviewed other perspectives on climate economics, from exhaustible resources, behavioural and evolutionary approaches (Section 2.1.1) to the political realities of long-term problems (Section 2.1.4). However, these literatures are small compared to those dedicated to evaluating carbon pricing and the concomitant task of quantifying climate damages.

Perhaps a judgement of conventional climate economics can be drawn from its policy achievements. Economists have been calling for a carbon price to correct the climate externality for almost three decades. There were early successes—the first carbon taxes were implemented in the 1990s (The World Bank, 2021a). Since then, however, the political and social barriers to carbon pricing have slowed progress. Meanwhile, global emissions have continued their upward trudge (Friedlingstein et al., 2020).

A stark and salient contrast to the slow progress of climate policy is the response to the Covid-19 pandemic. As discussed in Section 1.4, governments met this global health challenge with broad fiscal support, strict social interventions, and huge research spending. Their response to Covid-19 dwarfed current efforts to avert climate catastrophe. However, the response yields an important—and somewhat reassuring—lesson: when a crisis is seen as urgent enough, governments, organisations and individuals can rise to the challenge. Despite pronouncements of a climate crisis in a growing number of jurisdictions, policymakers and economists have so far failed to achieve the sense of urgency necessary to motivate transformative decarbonisation.

In summary, the traditional economic framing of climate change does not yield a comprehensive, cohesive and timely strategy for urgent climate action. Climate economists' aspirations are worthy: reducing emissions at least cost. However, decarbonisation is no longer a question of cost—scientific evidence shows it is a necessity—but rather a question of time. How fast can we decarbonise? Answering this question means going beyond the theoretical boundaries of mainstream economics, to political economy, sociology, engineering, and science, for lessons on how to overcome barriers to rapid, far-reaching climate policy.

Climate economics provides useful tools for quantitative and policy analysis, but must look past its preoccupation with price incentives. Overcoming the political hurdles to meaningful carbon pricing has made some progress in the last 30 years, but we no longer have time to deconstruct oil lobbies and social opposition to taxes. The time appears ripe for an alternative approach: Stern and Stiglitz (2021), two giants of the field, recently published a searing critique of economic methods for damage quantification (although still taking a very technorational approach to climate policy).

Proposing an alternative economic framework for climate change is no small task; this thesis certainly cannot hope to achieve it. However, from the literature reviewed in this section, two particular research gaps arise. First, an economic framework that takes an explicitly long-term perspective on the policies, politics and implementation of climate action. Second, the absence of a meaningful demand-side carbon price necessitates an alternative approach to convincing individuals of the urgency of climate action. These two research gaps contribute to the first research question, addressed in Chapter 3.

2.2 Technological and social transitions for mitigation

Achieving net zero requires deep, structural changes to the global economy. Section 2.1.4 reviewed the role of supply-side and demand-side policies, which are generally achieved using technologies or behaviour changes respectively. Technological mitigation uses new methods, systems or devices, usually aimed at reducing the emissions intensity of energy use. Behavioural mitigation is achieved by changing the way we use energy, consume goods and services and travel. Many mitigation strategies, of course, combine technologies and behaviour change to reduce the emissions-intensity of individuals' activities and choices.

This section reviews the literature on the potential for mitigation through technology and behaviour. Section 2.2.1 reviews theories of technological change, followed by a survey of studies quantifying the duration of energy transitions in Section 2.2.2. Section 2.2.3 discusses the theory and determinants of socio-behavioural transitions, and Section 2.2.4 identifies the research gap.

2.2.1 Technological transition theory

Technological change describes the conception, development, commercialisation and diffusion of new technologies, processes or ideas. Existing models of technological change generally fall into two categories: detailed models of the initial stages of invention, or broad, generalised models that cover adoption across the whole diffusion period.

Theories of research, development and innovation

The first category of technological transition theory focuses solely on the innovation period before commercialisation, in which a technology or process is being developed. A common model for classifying the stages of technological development is the technology readiness level (TRL) scale. TRLs were developed in the aeronautical industry to measure the maturity of new technologies before they reach commercialisation (Mankins, 2009). Figure 2.5 provides the TRL scale in relation to the wider theory of technological diffusion typified by the S-curve of innovation introduced in Section 1.3. TRLs provide detailed technological assessments and are used to effectively compare between similar technologies during the early stages of development (e.g., Watson et al., 2019). Peisen et al. (1999) use the TRL scale to estimate the duration of innovation for new aeronautical technologies.

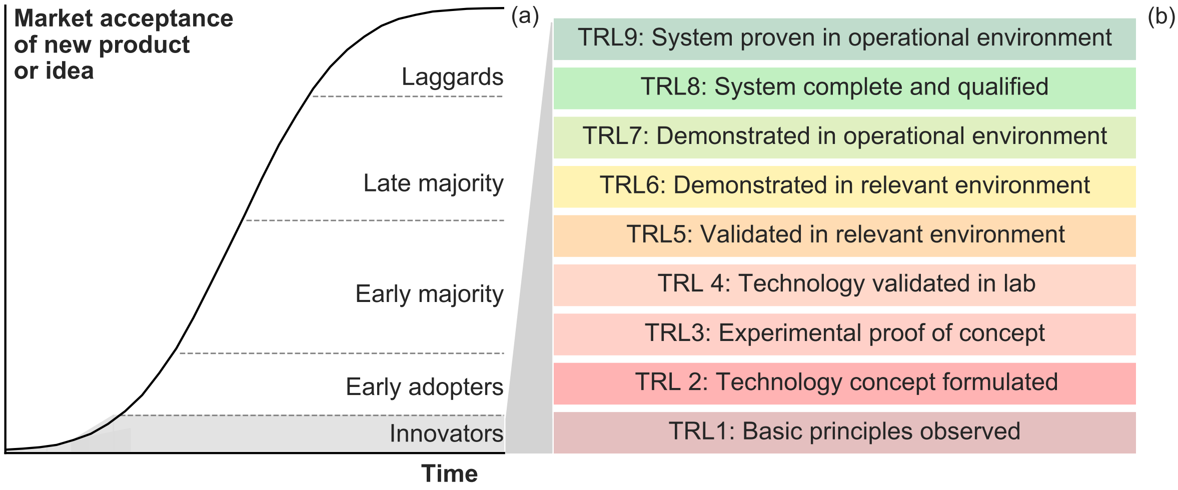

Fig. 2.5 The relationship between the full chain of innovation and the TRLs. (a) The S-curve of innovation, adapted from Brown (1991). (b) TRL scale, adapted from Mankins (2009).

TRLs are useful for evaluating how close a particular innovation is to reaching market readiness. However, two features of the TRL scale limits its usefulness for assessing technological development. First, the scale is ordinal rather than cardinal, meaning that comparisons between different technologies and mathematical ‘translations’ of levels are fraught with error (Conrow, 2011). Second, TRLs do not consider the process of commercialisation, deployment or market saturation. Straub (2015) suggests introducing TRL Level 10, to describe a technology proven through extended operations. However, TRL9 and even TRL10 mark only the *beginning* of mass deployment. Mitigation depends on the complete transformation of existing systems: the TRL model provides little insight into the large-scale technological deployment necessary for low carbon transitions.

A second approach to technical development piggybacks on Brown’s (1991) S-curve theory. While the S-curve of innovation was developed to improve marketing and strategic business management, Brown (1991) also proposed a second curve, the ‘technology S-curve’ which relates research and development spending to technological performance improvements and defines three stages of R&D. This curve is illustrated in Figure 2.6(a). The curve’s S shape reflects the fact that early performance improvements are arduous and expensive, as are late improvements. The highest return for R&D comes from investing in developing technologies. Nordhaus (2011) calls this the *appropriability* of the gains from innovation. He defines an innovation spectrum illustrated in Figure 2.6(b), which relates the stages of R&D into the researching firm’s ability to capture its full value. Appropriability is important because commercial researchers are motivated by their ability to profit from the results.

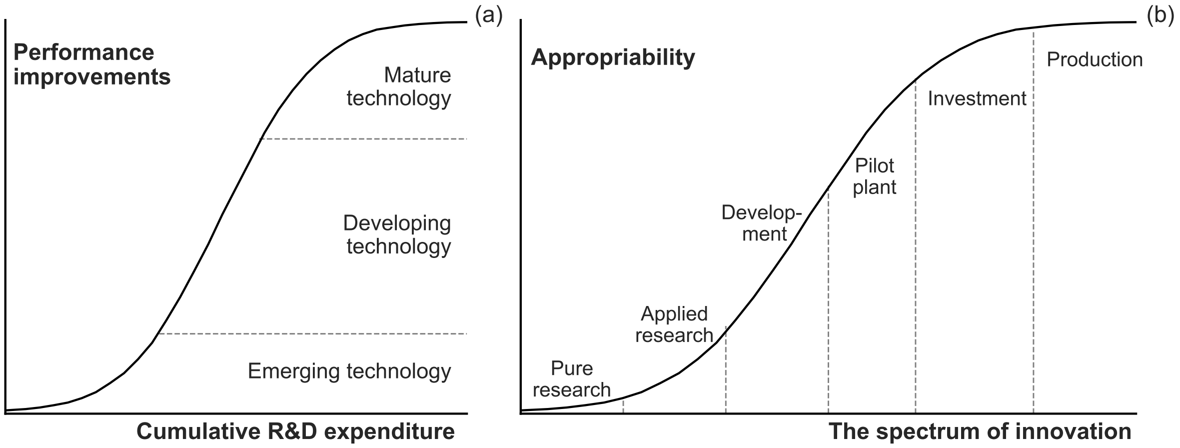

Fig. 2.6 Models of technological innovation. (a) The S-curve of technological innovation relates research and development spending to performance, based on Brown (1991). (b) The appropriability of innovation translates those innovation stages into profitability for innovators, based on Nordhaus (2011).

Some empirical support exists for a non-linear relationship between R&D spending and productivity improvements at a firm level (d'Artis Kancs and Siliverstovs, 2016). At a country level, the results are more mixed. Johnstone et al. (2010) finds a strongly positive relationship between R&D spending and the number of patents filed, while Ugur et al. (2016) finds that the returns to R&D are less than depreciation, making it a poor investment. Despite the empirical attention on R&D investments, the S-curve of technology remains a relatively obscure theory of innovation, perhaps due to the generality of its predictions.

The path from technological research to commercialisation is treacherous, so much so that it is often referred to as the 'valley of death' (Weyant, 2011). Particularly for publicly-funded innovation, risks from from R&D tend to accelerate around the same time that government support is ending, creating a major barrier in commercialising technical developments (Hug and Duer, 2009). Even providing additional funding cannot always bridge the valley of death. Goldstein et al. (2020) show that funding from the US government to support clean technologies increases patent filings, but does not seem to have any impact on the developers' ability to secure follow-up capital for commercialisation.

Theories of market diffusion

The second category of technological transitions theories considers the market penetration of new technologies. These theories are related to concepts of invention—a product clearly cannot be diffused if it has not been developed—but tend to be both broader and more generalised. The diffusion of innovation (DoI) approach was developed in the 1960s to describe the propagation of new ideas and practices (Rogers, 1962). While DoI has come to be synonymous with technological innovation, the original theory focused on social adoption of new ideas. Rogers (1962) identifies four key elements in his definition of diffusion: an *innovation* being transferred between members of a *social system*, through different *communication channels* and over *time*. Each element is necessary for the successful diffusion of a new idea or product.

Innovation theory yields a model of the cumulative number of individuals adopting the new technology, as a function of time (Kuandykov and Sokolov, 2010). This concept was first proposed by Rogers (1962), who used a normal distribution to describe the uptake of a new technology based on different types of adopters. This theory proposes that a population is made up of five types of consumer: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%) and laggards (16%). The original theory was critiqued for assuming 100% diffusion: for most innovations, not everyone will choose to adopt, due to individual differences in perceived value of an innovation (Robertson, 1967). By focusing on individual consumers, DoI theory also omitted some of the dynamics of organisational change, such as leadership and system openness (Lundblad, 2003).

Modern interpretation of diffusion theory is exemplified by the ‘S-curve’ of innovation (Brown, 1991), illustrated in Figure 2.5(a). This theoretical model is essentially a cumulative distribution of Roger’s (1962) proposal for diffusion of innovation, but is more recognisable as describing the growth of a new product (Brown, 1991). The S-curve does not assume 100% adoption, rather considering the product’s maximum market penetration, which depends on the individual innovation and market forces (Grubler et al., 1999).

The S-curve theory of innovation has been applied to empirical studies of technological diffusion. Grubler et al. (1999) use S-shape logistic curves to model the processes of diffusion and substitution, distinguishing the former as the spread of a new technology to provide services in wholly new markets. The authors illustrate these related processes by mapping the share of horses and cars as a fraction of road vehicles in the US, showing downwards and upwards S-curves respectively. Wilson et al. (2013) parametrise the S-curve with a logistic function dependent on three variables: the market saturation level (the curve’s asymptote), diffusion rate (steepness of the curve) and the time of maximal growth (the inflection point). In contrast, Kuandykov and Sokolov (2010) use agent-based modelling techniques to capture the social network effects that are crucial to Rogers’ (1962) original theory. Though they do not calibrate their results with real world data, Kuandykov and Sokolov (2010) show that innovations spread more quickly amongst randomly clustered groups than uniform groups, and when they are adopted by agents with many social connections (‘hub’ adopters). Some empirical studies in climate research have used S-curve theory as evidence that the deployment of renewable energies can be rapidly scaled up (Grubb et al., 2020).

Summary: No unified model of technology transition exists

Models of technological development and diffusion abound. They provide theoretical guidance about the possible dynamics of technological transition. However, they tend to be generalised, as in the case of DoI theory and S-curves, or highly focused, like TRLs. There is no ‘unifying theory of technological change’ which identifies detailed stages throughout the process from conception to maturity and provides practicable lessons for future technologies. In particular, none of the models reviewed demonstrated the role of policy in the various stages of technological transitions. Nonetheless, theories provide a basis for empirical studies of technological transitions. The following section reviews the literature on the pace and scope of market deployment of new technologies.

2.2.2 Quantifying the duration of energy technological transitions

Technologies for climate mitigation take many forms, from smart devices for home energy use to large-scale deployment of carbon capture and storage. Historically, mitigation has been achieved mostly by significant technological change in electricity generation and industry (BEIS, 2021a), and this approach continues to dominate the political rhetoric around climate strategies (e.g., HM Government, 2020). This review therefore focuses on large-scale and supply-side technological transitions in the energy sector.

The literature on energy technology transitions builds on the theoretical approaches reviewed above. Before reviewing research on historical transitions and determinants of duration, it is useful to summarise several key innovation terms as they relate to energy technologies in particular (see Table 2.3). This review is focused primarily on the processes described by the final term: diffusion or deployment of new energy technologies.

Table 2.3 Key terms in the process of energy technology diffusion, adapted from Wilson and Grubler (2013).

Key term	Definition
Invention	Origination of an idea as a technological solution to a perceived problem or need
Innovation	Putting ideas into practice through an iterative process of design, testing, application and improvement
Research and development	Knowledge generation by directed activities aimed at developing new or improving on existing technological knowledge
Demonstration	Construction of prototypes or pilots for testing and demonstrating technological feasibility and/or commercial viability
Niche markets	Application of a technology in a limited market setting based on a specific relative performance advantage or public policy incentives, and typically protected in some way from full market competition
Market formation	Activities designed to create, enhance, or exploit niche markets and the early commercialisation of technologies in wider markets
Diffusion/deployment	Widespread uptake of an energy technology throughout the market of potential adopters

Historical examples of technological transitions

Technological transitions depend on the underlying causal processes. Grubler et al. (1999) argue that these complex dynamics are unique to each technology and context, so looking to past trends provides little guidance for the future. However, major technological change is rare in a market as large and integral as energy supply, and experimentation is difficult. Fouquet (2016) therefore contends that historical transitions provide crucial evidence for future changes, and a large body of literature uses qualitative and quantitative analyses of past energy technology deployment.

The generalised nature of the innovation theory reviewed above means there are numerous definitions of widespread diffusion for energy technologies. Several examples are provided in Table 2.4. The variety of definitions make comparisons between studies somewhat challenging. With this caveat in mind, this section reviews the literature on historical energy transitions.

Table 2.4 Examples from the literature of different definitions of widespread diffusion. Adapted from Gross et al. (2018), with additional sources.

Study	Metric	Definition of widespread market diffusion
Gross et al. (2018)	Widespread commercialisation	When installed capacity first reaches 20% of peak installed capacity
Bento and Wilson (2016)	Formative phase	10% of eventual market saturation (units produced and capacity installed); or 10% of maximum unit capacity
Grubler et al. (1999)	Pervasive diffusion	5–50% commercial market share
Lund (2006)	Take-over time	1–50% market potential or adoption ceiling
Rogers (1962)	Early majority	15–50% of potential adopters taking up an innovation
Smil (2010)	Time for a new 'fuel or prime mover' to achieve given share of total global energy supply	25% share of global energy supply
Fouquet (2010)	Market dominance	Time to achieve highest market share out of substitute technologies

There are two main methodological approaches to assessing historical energy transitions. The first uses observational data and qualitative analysis to benchmark stages of diffusion using market penetration and historical events. Gross et al. (2018), Smil (2014) and Fouquet (2010) use this method to assess large-scale energy transitions. Gross et al. (2018) consider the diffusion of nuclear generation, closed-cycle natural gas turbines, wind and solar power to find a median time from innovation to commercialisation of 43 years. Fouquet (2010) argues for an even longer scale based on 13 past transitions with an average time to widespread use of 155 years for a more expensive but superior energy substitute. Smil (2014) finds that major energy sources of coal, oil and natural gas each took between 50 and 60 years to reach market dominance, and each subsequent transition has achieved a lower energy share as the market becomes more fragmented. Bento and Wilson (2016) also use the observational method, but focus solely on the pre-commercial 'formative phase'. They assess a broader range of energy transitions, from steam engines to nuclear power to e-bikes, finding an average duration for the formative phase of 22 years. They also assess the duration by various characteristics. Energy supply technologies take longer than end-use ones, as do more expensive technologies with environmental applications (Bento and Wilson, 2016).

The second methodological approach applies models of innovation to historical market data. This technique is more abstract than the observational approach, but can endogenise market characteristics such as technological learning and uncertainty (Grubler et al., 1999). Bento et al. (2018) use a mathematical model to analyse the results from Bento and Wilson (2016) on the duration of formative phases. Their parametric hazard model uses data on technological characteristics and the adoption environment to estimate the event of ending the formative phase, but does not consider the duration of widespread diffusion. Lund (2006) models an S-shaped diffusion process using a logistic curve to find the penetration rate, or rate of diffusion, and the market share. Using data from twelve country-level energy transitions for nuclear, oil, solar and wind, he finds an average time of 35 years for a technology to reach 50% of its market potential. However, this duration depends heavily on Lund's (2006) judgement of a technology's potential. For example, wind and solar power are considered to have the potential to reach 10% and 1% of global energy demand respectively, meaning that the absolute scale of their deployment is far smaller than mature technologies such as oil and nuclear.

The combined evidence from these two methodological schools is summarised in Figure 2.7. It suggests that past transitions have been slow, although the absolute duration depends on the choice of boundaries for the diffusion process. Diverging from this consensus, Sovacool (2016) contends that adoption of new fuels takes only around a decade, based on sector-level transitions in particularly fast-moving economies. However, ex ante differences between the technologies in Sovacool (2016) and previous works may explain the divergence, namely in the complexity of the transitions, the availability of substitutes and knowledge spillovers when the transition occurs in a second-moving 'follower' country (Grubler et al., 2016).

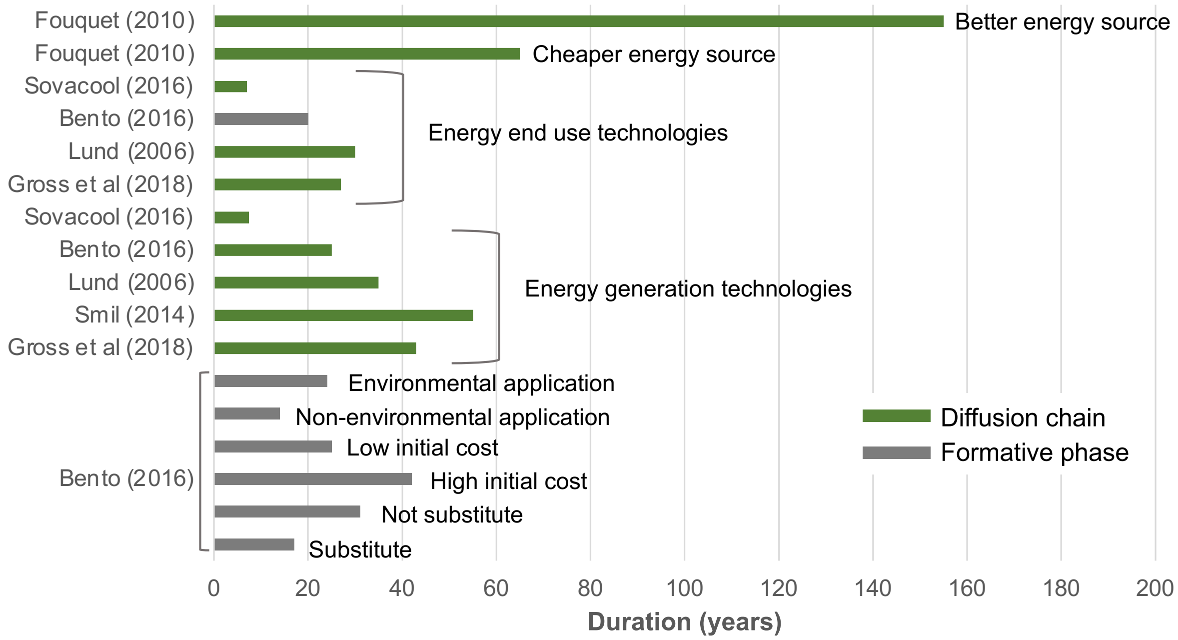

Fig. 2.7 Estimates of the duration of historical technological transitions. Sources in figure.

That the long diffusion period of historical energy transitions applies to today's decarbonisation timeline is disputed. Grubb et al. (2020) argue for S-shaped energy transitions, meaning linear extrapolations of current deployment rates underestimate the future potential. Kern et al. (2016) suggest that future technological diffusion may be quicker due to increasing political will, stronger governance and more interconnection between domestic markets. Lovins et al. (2018) argue that wind and solar can beat large scale technologies like nuclear on construction speed, addition rate and required project lead time. However, the underwhelming success of Germany's *Energiewende* programme to increase wind generation suggests that political will cannot overcome physical constraints of deployment (Smil, 2016).

Physical determinants of technological transitions

The dynamics and duration of technological transition depends on the characteristics of the technology. End-use devices, which are smaller, cheaper and have a larger potential market, can take less than a decade to penetrate a market (Lund, 2006; Sovacool, 2016). Small markets are easier to change (Grubler et al., 2016), and those where technologies are easily substituted can achieve swifter adoption (Bento et al., 2018). However, decarbonisation requires an overhaul of energy generation—a large-scale, costly transition with limited substitutability. The physical constraints on deployment are significant.

Constructing large energy infrastructure and integrating it into existing grid networks presents a significant challenge (Beake and Cole, 2020). While the literature on construction limitations for energy infrastructure is incomplete, there are many reports of the long process between procurement and completion for other types of large engineering projects. Shackman and Climie (2016) describe the process for a replacement bridge across the Forth River in Scotland from siting assessment to construction, ten years later. Similar work has shown equally protracted processes for overground and underground rail extensions (East and Mitchell, 1999; Lloyd-Davies and Rowark, 2017), flood damage to roads and bridges (Affleck and Gibbon, 2016) and tunnels (Fenwick et al., 2012). These examples demonstrate what Flyvbjerg (2014) calls the 'iron law of megaprojects': they are over budget, over time, over and over again. The same law will limit the rate of diffusion of large-scale energy technologies.

Even for technologies that have achieved commercialisation such as wind turbines, there is little evidence the required scale-up will be realisable (Smil, 2016). Of eight renewable technologies necessary for a clean energy transition, only solar and bioenergy power generation are progressing swiftly enough to contribute significantly to climate targets (International Energy Agency, 2020). Wind power, along with other mature technologies including hydropower and geothermal, is not on track to meet renewable energy targets.

Wilson et al. (2020) suggests that a more granular transition based on smaller-scale technologies could accelerate deployment and reduce lock-in and social opposition. Smaller units also require more frequent replacements, increasing the rate of advancements and updates (Sweerts et al., 2020). Lovins et al. (2003) show that less infrastructure means distributed resources can reduce system planning, construction and the operational burden of utilities. Capitalising on lower costs as well as smaller size, distributed energy technologies can also reduce financial risks with shorter lead times, portability and lower fuel price volatility (Lovins et al., 2018). However, replacing 'lumpy' technologies with granular ones could reduce coordination and security and increase transaction costs, pollution and material waste.

Political and economic determinants of technological transitions

The rate of diffusion of a new energy technology depends on the political and economic context of the transitioning market, which differs across countries and time. LaBelle and Goldthau (2014) define three factors which jointly determine the success of an energy regime change: the political fit, industry fit and social fit. The political fit of a technology describes the degree of commitment from the political sphere, evidenced by strong political backing or subsidies for a particular energy technology. Throughout both innovation and commercialisation, policy plays a large role in determining the rate of change. Government research funding increases the rate of 'new ideas', measured by patents filed, but needs to be followed up by additional funding to achieve commercial viability (Goldstein et al., 2020). Even once commercial viability is reached, government support is often needed to stimulate domestic demand and achieve integration into key markets such as energy supply (Fouquet, 2016).

The industry fit describes the nationally embedded companies and institutions that can accelerate a transition by facilitating R&D and financing (LaBelle and Goldthau, 2014). Industrial research, often funded by government, enhances the market's ability to learn from experience, research or collaboration and can accelerate change (Tang, 2018). Learning spillovers mean that follower countries can skip the long innovation phase of technological diffusion, and progress relatively swiftly to commercialisation (Grubler et al., 2016). These effects can be compounded by a comparative lack of lock-in to older technologies in developing or late-industrialised countries, leading to a particularly swift transition (Perkins and Neumayer, 2005). However, pre-existing industry can also be a critical determinant in successful change. The process of commercialisation itself, reliant as it is on scaleable production, can be accelerated if a country already has strong technological capabilities to achieve industrial competitiveness (Bergek et al., 2008). On the other hand, 'second-mover' countries can piggyback on first-movers' capabilities to achieve significantly quicker transitions (Sovacool, 2016). The price of the product is key to commercial motivation, and low prices can reduce pressure for technological transitions (Fouquet, 2016).

The social fit of an energy transition describes whether the technology meets the interests and preferences of society (LaBelle and Goldthau, 2014). This is generally measured through opinion polls, and affects the political fit of a technology. In some cases, certain social groups can be pivotal to a transition's success. The 'not in my back yard', or NIMBY, phenomenon describes local opposition that can stall new energy projects, even when wider public support is high (van der Horst, 2007). Renewable energy projects tend to suffer from NIMBYism due to concerns over noise and visual impacts, harm to wildlife and distrust of developer incentives (Smith and Klick, 2007). NIMBYism can also be motivated by safety concerns. Wittneben (2012) cites NIMBYism as the motivation for the shift away from nuclear energy after the Fukushima incident in 2011. In contrast, Ramana (2011) argues that opposition stems from a deep, historic stigmatisation of nuclear power. In either case, social opposition after Fukushima led to the shutdown of many nuclear stations across the world (Hayashi and Hughes, 2013). This example illustrates the importance of social fit to the continued success of an energy transition.

Summary: Literature provides methods for estimating transition duration

The literature on the duration of technological transitions is well-developed. Various methodological approaches have been tried and tested, yielding a diversity of duration estimates. This is useful in two ways. First, the methods described above provide guidance for developing a broader approach to both social and technological transitions. Second, various estimates of technological transition duration already exist and can be used to compare and corroborate future studies. Research into the physical, social and political determinants of transitions provides the context necessary to translate these historical observations into predictions for the future. Together, the quantitative and qualitative research on technological transition duration provides a solid foundation for further study into low carbon transitions.

2.2.3 Social transitions for net zero

Social transitions are large-scale disruptive changes in societal systems (Loorbach et al., 2017). They integrate behavioural and structural change to influence norms and values (O'Rourke and Lollo, 2015). In the context of climate mitigation, social transitions can refer to wide-scale diffusion of demand-side adjustments in energy use, consumption and travel.

Social transitions could affect emissions at a global scale. While there is a persistent focus on marginal changes that achieve little meaningful mitigation, such as printing on both sides of a sheet of paper, a broader focus on the social and cultural contexts of behaviour yields potential for meaningful emissions reduction (Capstick et al., 2014). Welch and Southerton (2019) argue that an integrated global transition to sustainable consumption would help achieve climate targets. Such a transition would require changes in corporate and government practices (O'Rourke and Lollo, 2015), to make the wider societal context more conducive to change (Carmichael, 2019). Specific examples include a shift to vegetarian diets, foregoing air travel or purchasing smaller cars (Carmichael, 2019). The prevailing political view is that behavioural adjustments are seen by voters as sacrifices. However, institutional contexts are key to determining personal decisions, and increasing public engagement widens the scope of potential mitigation options (Rajan, 2006).

The potential for mitigation through behaviour change is significant; the residential and transport sectors each contribute 20% of UK emissions (BEIS, 2020a). Behaviour change can also reduce the cost of mitigation: Roberts et al. (2021) show that it can reduce the cost of rapid decarbonisation by 10-20%. However, changing behaviour is complex. This section considers theories of social transition, the specific behaviours that could reduce emissions and the various factors which could affect a widespread social transition to low carbon lifestyles.

Theories of social transition

The dynamics of social change are addressed in the fields of psychology, sociology, economics and sustainability. There are many theories of social and behavioural change across these disciplines. This review is limited to concepts which have been commonly applied to societal transitions for decarbonisation. Five of the most common models of social transition are summarised in Table 2.5, and expanded upon below. They are classified into three branches based on their scope: individual behaviour changes, societal and norm changes, and sociotechnical transition theories.

Table 2.5 Theoretical models of behaviour change commonly used in environmental studies.

Model	Description	Example applications
Theory of planned behaviour	Predicts behaviours based on an individual's intentions, which are in turn influenced by subjective norms, attitudes and perceived control over the behaviour (Ajzen, 1991).	Consumption (Jiang et al., 2019); e-waste (Echegaray and Hansstein, 2017); transport (Muñoz et al., 2016); energy use (Allen and Marquart-Pyatt, 2018).
Transtheoretical model	Identifies six stages that an individual goes through before a new behaviour becomes automatic: precontemplation, contemplation, preparation, action, maintenance and termination (Prochaska et al., 2015).	General low carbon behaviours (Energy Research Partnership, 2021); cycling (Forward, 2014); impact of films and media (Howell, 2014).
Value-belief-norm theory	Environmental behaviours are determined by a conjunction of values, beliefs, and personal norms that impel individuals to act in ways that support the goals of a social movement (Stern et al., 1999)	Household energy consumption (Steg et al., 2005); tourism (Sharma and Gupta, 2020); willingness to sacrifice items (Stern et al., 1999)
COM-B model	Behaviour (B) is jointly determined by the capability (C), opportunity (O) and motivation (M) to change (Michie et al., 2011).	General low carbon behaviours (Energy Research Partnership, 2021); commonly used for health applications.
ABC framework	Behaviour (B) arises from an interaction between personal attitudes (A) and contextual (C) factors. Behaviours map attitudes closely when contextual factors are neutral; they diverge when the context is strongly for or against a certain behaviour (Stern, 2000).	Curbside recycling (Guagnano et al., 1995).

The predominant model of individual behaviour change is the theory of planned behaviour. Simply put, it predicts that behaviours depend on what we think and feel, what we perceive others to think and feel (social pressure), and our capacity to act. The theory of planned behaviour is illustrated in Figure 2.8. This theory was not developed in the sustainability literature, but has been widely applied to pro-environmental behaviours. Despite this prevalence, Yuriev et al. (2020) find amongst empirical studies utilising the theory of planned behaviour, only around half provided quantitative analysis of its predictive power, and the results varied between explaining 6% and 81% of behavioural variation.

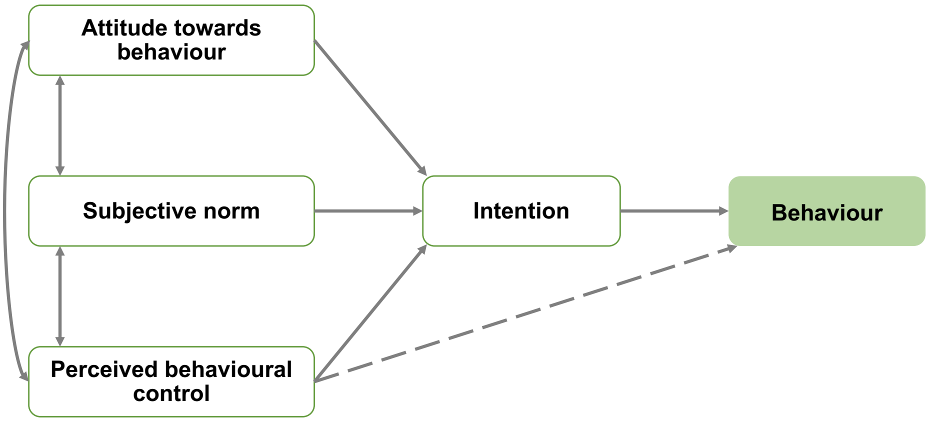

Fig. 2.8 The theory of planned behaviour. Adapted from Ajzen (1991).

While the theory of planned behaviour aims to predict actions, the transtheoretical model describes the processes of behaviour *change* (Prochaska et al., 2015). The theory identifies ten processes of change. Because it was developed for health-related behaviours, several of these processes are largely irrelevant for environmental behaviours. However, a number have been applied to climate-related behaviours, including consciousness raising, self-identity and reinforcement management (Whitmarsh et al., 2021).

The second category of social transition models considers the dynamics of broad societal norm changes. Widespread social change is achieved by changing values and norms, which can create social pressure for individuals to adopt pro-environmental behaviours. The remaining theories presented in Table 2.5 place a larger emphasis on social context and norms to motivate individual behaviours. The value-belief-norm framework applies norm-activation theories of altruism to environmental problems (Stern et al., 1999). It is built on the concept that self-expectations, or personal norms, create feelings of self obligation and direct individuals towards low carbon behaviours (Schwartz, 1977). The COM-B and ABC models both aim to provide a more integrated approach to individual behaviours, but have not yet been widely adopted in environmental behaviour studies (Whitmarsh et al., 2021).

The third category explicitly addresses interactions between behaviour and its social and technological context. The significant role of technology in climate transitions means social change is often considered in concert with technological transition. Geels (2011) describes low carbon transitions as a process of sociotechnical regime change with feedback loops between the socio-cultural context, policy, technologies, users and markets. The regime change model fits into a larger, multi-level landscape that describes the systemic change needed for sustainable transitions (Geels et al., 2017). Sociotechnical approaches use a multi-level perspective to evaluate the mechanisms of systemic change (Lawhon and Murphy, 2012), and integrate ethics to consider the welfare implications of regime shifts (Jenkins et al., 2018). The interconnected forces captured in the sociotechnical transition model can interact to accelerate or slow social change (Loorbach et al., 2017). Under this model, governments can influence emissions through broad, interconnected policies that affect energy demand and climate impacts (Geels et al., 2017).

Determinants of social transitions

Achieving social change means understanding and tapping into the dynamics of individual decision-making. In turn, these dynamics must be considered in their social and cultural context. Low carbon behaviours depend on demographic characteristics such as attitudes and personal norms, but are also influenced by economic, physical and social infrastructure (Wang et al., 2021). However, cultural values and economic development also play a large role in determining how individuals relate to the climate challenge. Jakučionytė-Skodienė and Liobikienė (2021) find a significant relationship between economic development, the perception of personal responsibility and climate behaviours in European countries. Climate concern tends to be highest in cultures with particularly high uncertainty avoidance, such as Spain and Greece (Jakučionytė-Skodienė and Liobikienė, 2021). Organisational culture can also play a part in societal transition. Janda and Parag (2013) show that ‘middle out’ change can propagate through society from the influence of professionals and practitioners in climate-intensive industries. Despite this, the influence of the workplace is largely ignored in the literature on environmental behaviour change (Yuriev et al., 2020).

The government can influence behaviour using demand-side climate policies. Young and Middlemiss (2012) classify policies to affect behaviour change into three categories: empowering individuals, empowering communities and changing the wider context to change actions of individuals. Changing energy-use behaviour to achieve demand-side mitigation will rely on a mix of all three types of policy (Sarrica et al., 2016). Interventions to disrupt behaviour must address the many interconnected ways in which the public engage with energy systems (Chilvers et al., 2021). Financial incentives can, of course, affect individual behaviours (Dietz et al., 2009). However, other strategies can also be used to affect societal trends. Otto et al. (2020) argue that behavioural transitions can be accelerated by ‘social tipping interventions’, which capitalise on rising social concern to activate exponential transfers of behaviours, norms, technological adoption and structural reorganisation.

Communication and the framing of climate change can have a major impact on behaviour. Homar and Kne (2021) show that emphasising potential losses due to climate damage can induce behavioural intention by capitalising on the cognitive bias of loss aversion. Loss aversion also means that contextualising climate change in relation to 'big risks' such as atmospheric tipping points can increase public concern (Barrett and Dannenberg, 2014). Using a more positive framing, Jennings et al. (2020) show that highlighting society-wide cobenefits, such as improvements in public health or job creation, can increase engagement. However, doubt that individuals can achieve meaningful change can reduce the impetus to change behaviour (Bostrom et al., 2019).

Technology and behaviours are interconnected, and technological functionality can affect the success of a behavioural transition. Dietz et al. (2009) estimated that households could reduce emissions by around 20% with little or no reduction in welfare, largely through the adoption of new technologies or changes in how they use existing ones. However, the success of an intervention depends on its complexity: technologies that require constant interaction can have limited or even negative impacts (Adua, 2020). Education about technology use may be able to improve outcomes for complex interventions. van den Broek (2019) suggests addressing energy literacy gaps by explaining how behaviours and financial cobenefits can reduce energy demand. Nonetheless, Adua (2020) shows that interventions that require a one-off decision or action should be prioritised over equivalent interactive ones.

Summary: Social transitions have promise but are not well understood

Behavioural change has the potential to accelerate mitigation, despite the complexities of changing public beliefs and norms. Theories of social transition exist, but their application to future transitions has so far been limited. In particular, there is little evidence about how quickly such transformations could occur, and whether policies could accelerate behavioural change. Historical analyses of societal and climatic transformations have made some progress towards estimating the timescales of change in ancient societies (Caseldine and Turney, 2010; Clarke et al., 2016). This review did not uncover any research on the timescale of societal change in the contemporary context. Compared to the vast literature on historical energy transitions, social transitions are relatively under-studied.

2.2.4 Research gap: Comparing technological and social transitions

Accelerating technological diffusion is a key priority of climate policy. Theoretically, this is within reach: markets just need to initiate the gloried 'exponential potential' of technological transitions (Section 2.2.1). However, historical evidence belies the concept of exponential diffusion and indicates that large-scale energy transitions can take several decades (Section 2.2.2). Small scale generation technologies have the potential to increase diffusion rates and accelerate decarbonisation, as do effective end-use technologies. However, the required scale and pace of decarbonisation demands a more varied toolkit.

Yet policies which utilise behaviour change to accelerate action are rare. There are numerous theories of behavioural transitions and a wealth of evidence on the influence of social norms, culture and technology (Section 2.2.3). Moreover, many studies directly consider the potential for governments to support low carbon behaviour change, establish infrastructure for climate-minded decisions, and even initiate tipping points in societal transitions. But this academic literature has yet to translate into a broader policy menu at domestic or international levels: the UK Climate Change Committee's *Net Zero* proposal sources only 9% of mitigation from behaviour change (Stark and Thompson, 2019); the International Energy Agency propose 8% of global emissions reductions stem from behaviour change (Bouckaert et al., 2021).

The reticence of governments to support climate behaviour changes may be partly attributable to the relative dearth of evidence about the dynamics and duration of social transitions. While the technological literature yields a reasonably consistent prognosis of slow technological change (albeit not a prognosis that policymakers want to hear), no convincing argument about the duration of behavioural transitions exists. This is perhaps due to the amorphous nature of behaviours and norms, and the challenge of quantifying or delineating large-scale social transitions. But similar challenges have been overcome for technological transitions; the methods used in the technological literature seem a useful starting point for studying social transitions.

To conclude, delivering net zero can only be achieved with a combination of technological and social transitions. In some sectors, such as energy supply, technology will provide most of the necessary emissions savings. In others, like agriculture, behaviours have an essential role. So far, government policy has focused on the potential for technological solutions to provide urgent climate action. The academic literature has answered with many detailed analyses of historical transitions, which emphasise the probability that the diffusion of large-scale energy solutions like wind, solar and CCS will be slow. Policymakers will require a broader climate toolkit going forward. This review has highlighted two specific research gaps in the transition literature. First, methods to estimate the duration of social transitions. Second, comparisons of historical technological and social transitions, which may yield insights for accelerating the delivery of today's climate targets. These research gaps are summarised in the second research question and addressed in Chapter 4.

2.3 Disruption as a lens for climate policy

Achieving net zero will require the deep decarbonisation of modern society. Mitigation efforts, both technological and social, will be disruptive: the changes will affect markets, infrastructure, organisations and behaviours. The extent of that disruption depends on the scale and rate of decarbonisation.

This section reviews the growing literature that discusses the role of disruption in decarbonisation. Section 2.3.1 defines disruption formally and reviews the theory in relation to the net zero transition. Disruption in decarbonisation is reviewed in Section 2.3.2; Section 2.3.3 considers the government's disruptive role. The research gap is identified in Section 2.3.4.

2.3.1 Theories of disruption

The study of disruption stems from Christensen's theory of disruptive innovation, which describes how new processes or practices exploit niches in the business sector (Bower and Christensen, 1995). The original theory largely centred on market disruptions generated by technological developments, and how managers should capitalise on these innovations to attract new customer segments. In this respect, disruption is closely related to Schumpeter's classic theory of creative destruction (Schumpeter, 1943).

Disruption has become an important tool for conceptualising low carbon changes in energy systems. However, Christensen's theory has been criticised as too narrow for this purpose (Geels, 2018; Kramer and Haigh, 2009; Wilson, 2018). McDowall (2018) argues that Christensen's original theory cannot be directly applied to energy and decarbonisation, because the disruptions have not arisen to exploit new markets or attract new customers but rather as a result of policy intervention. Moreover, the breadth of proposed energy transitions means that the niche view of disruptive innovation is insufficient in a modern context. Energy and climate researchers have therefore broadened this original concept to consider systemic, policy-driven changes (McDowall, 2018).

Defining disruption

Definitions of disruption are varied (Wilson and Tyfield, 2018). Johnstone et al. (2020) argue that the term itself suffers from 'definitional challenges', particularly in relation to energy systems. As a general approach, Burt (2007) defines disruption as throwing into disorder the current state, generating consequences that persist over time. He distinguishes disruption from discontinuity by arguing the latter breaks with past experience to herald a new order. Kramer (2018, p. 247) too adopts a general approach, deferring to the dictionary definitions of innovation as “the change of something established by the introduction of new methods, ideas or products” and disruption as any “serious alteration or destruction of structure”. Under this definition, disruption is notably less benign.

In relation to energy and climate transitions, Ketsopoulou et al. (2021) define disruption as any significant deviation from past trends that occurs in a relatively short time frame. They contrast disruption with continuity-based change, in which shifts occur in line with past trends. Johnstone et al. (2020) theorise that energy disruption is characterised by systemic change with socio-technical interactions, which can be anticipated or already underway. Discontinuities, which are unpredictable and can lead to fundamental change to the current state of order, may have adverse social and political effects in the net zero transition (Hanna and Gross, 2020).

The literature on disruption for net zero focuses largely on energy transitions. While this undoubtedly reflects the importance of energy for emissions—both generation and use—it also highlights the focus on technological pathways for net zero. Nonetheless, the theories and concepts developed in the energy systems literature and reviewed here can be applied to a range of sectors, technologies, behaviours and beliefs. The remainder of this review, and indeed the thesis, defines disruption as any swift deviation from current trends. It is a broad classification because the research presented in this thesis considers a wide set of strategies for urgent mitigation.

Summary: Disruption is a useful tool for climate policy analysis

The theory of disruption arose in management studies, but has been fruitfully applied to the low carbon transition. The field is new, and as yet ill-defined, but it provides a promising avenue for considering the non-marginal changes necessary for swift, deep transitions. Especially given the failure of economic theory to achieve urgent change, disruption studies could provide a valuable framework for future climate policy.

2.3.2 Disruption in the low carbon transition

Studies which assess low carbon disruptions are relatively uncommon, given the extent of research effort into climate transitions. Hanna and Gross (2020) review a wide sample of energy models and scenarios to assess how disruption and continuity are represented in energy system forecasting. Of 763 relevant studies, only 30 explicitly assessed disruption. Nonetheless, disruption has gained research traction in recent years as a valuable conceptual tool for analysing energy systems transitions (Johnstone and Kivimaa, 2018). Various frameworks for assessing disruption have been proposed.

Linking innovation and disruption, Kramer (2018) proposes that all decarbonisation scenarios lie somewhere on the dual axes of innovation and disruption. His definition of disruption as an alteration or destruction of structure means that innovation is preferable. But while disruption is undesirable, it is also unavoidable. Kramer (2018) identifies three levels of disruption: light disruption based on favourable climate sensitivity; economic disruption in the form of preventative checks on growth; and environmental disruption where climate impacts impose positive checks which restrain human activities involuntarily. These levels also correspond to different types of innovation, from technical to behavioural, as illustrated in Figure 2.9.

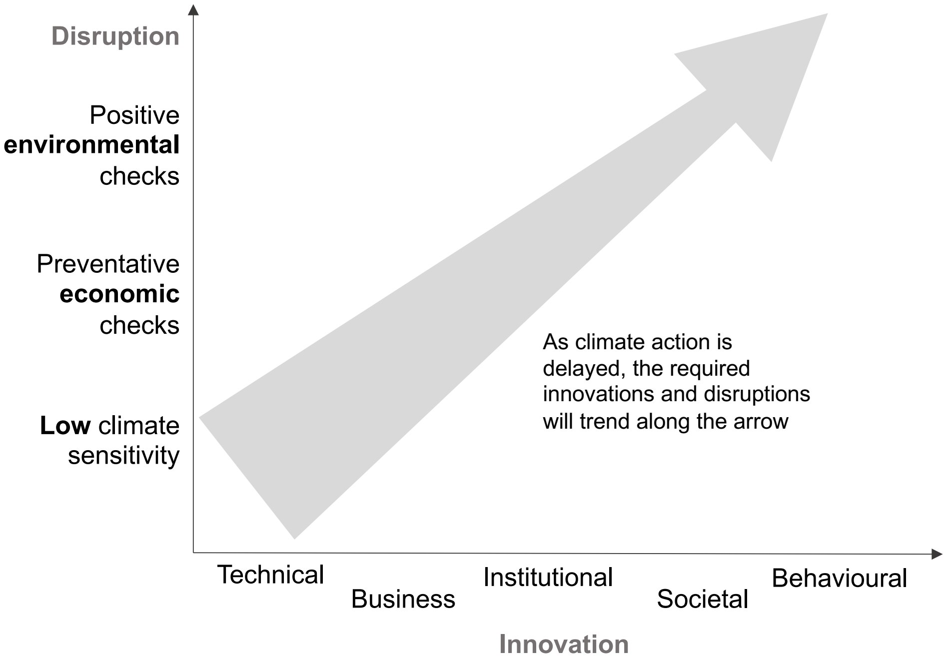

Fig. 2.9 The dual axes of innovation and disruption which span the net zero scenario space. Adapted from Kramer (2018).

The majority of the energy systems literature takes a more positive approach to disruption. Wilson and Tyfield (2018) identify three core streams arising in recent disruption research. The first applies Christensen-esque disruption analysis to the potential for new low carbon goods and services to disrupt markets and communities. The second applies a socio-technical perspective to energy transitions, largely rejecting innovation-driven disruption. Finally, a broad approach to disruption considers external drivers, the role of politics and policy and the conceptual tradeoffs between disruption and continuity. The three themes are increasing in both research scope and the potential scale of disruption they consider.

The third research stream seems to offer the most comprehensive approach to climate transitions. Taking a whole-systems perspective, Ketsopoulou et al. (2021) formalise different approaches to disruption into two axes of change. The first describes the nature of the change on an axis of *disruption—continuity*. This maps differences between changes in line with previous trends and which leave the system architecture unchanged, and those in which the whole system is transformed or even replaced. The second axis describes the source of the change between *emergent—purposive*. Emergent change is uncoordinated, arising from a complex system of individual drivers. Purposive change is orchestrated, often by policy, to achieve a stated goal. All potential disruptions can be mapped between these axes, and will likely change as different forces, actors, decisions and policies are adopted (Ketsopoulou et al., 2021).

A key theme in the energy disruption literature is the dynamic and complex relationships between social, behavioural, political and technical systems. Johnstone et al. (2020) identifies four dimensions of disruption: technology, ownership and actors, markets and business models, and regulation. They argue that, though related, disruptions in each of these dimensions are distinct. Considering them separately offers a more empirical framework for disruption studies (Johnstone et al., 2020). In contrast, Geels (2018) contends that these interdependent and co-evolving functions demand a multi-level perspective that captures ‘whole system’ change.

The literature on disruption in low carbon transitions is growing, but remains highly conceptual. It seems a useful tool for evaluating the system-level changes required for a net zero transition. But the amorphous nature of disruption concepts—and indeed the disputed definition—impedes its empirical and analytical value. The following section reviews case studies of low carbon disruptions in several sectors which, due to their narrower perspective, can offer more focused analysis.

Sector-level case studies

Sector-specific studies offer insight into the specific dynamics and outcomes of disruptive decarbonisation. Four case studies are reviewed in depth. The studies provide an overview of several different methodologies, namely surveys, scenario analysis and theoretical frameworks, and highlight some of the shortcomings of current analytical techniques in disruption analysis. The four sectors each play a significant role in decarbonisation. All the studies here assess UK markets, partly reflecting the dominance of UK-based researchers in the emerging disruption literature. However, the policy implications are widely applicable (Ketsopoulou et al., 2021).

Surveys of energy experts and policymakers are used to assess the potential for disruption in energy and heat (Lowes and Woodman, 2020; Winskel and Kattirtzi, 2020). Winskel and Kattirtzi (2020) gauged sentiment on the future of the UK energy sector amongst academics, regulators, consultants and industry experts. They asked for experts’ opinions on likely transitions in energy systems governance, security and flexibility, innovations, supply market concentration and policy priorities. Their findings are mixed, and to some extent contradict the popular 'smart and local' narrative of energy transitions. Overall, energy experts see little chance of a sweeping energy revolution. Instead, the system is likely to remain largely centralised, with incumbent firms retaining dominance and infrastructure being repurposed rather than replaced (Winskel and Kattirtzi, 2020). However, digital and distribution innovation will facilitate increasing localisation, motivated by growing political will, particularly at a local level.

Lowes and Woodman (2020) surveyed policymakers for their opinions on heat decarbonisation. Their results provide an interesting contrast to Winskel and Kattirtzi (2020). Policymakers see little upside to heat decarbonisation. The possibility of deep disruption to consumers, compounded by technological uncertainty, means that policymakers do not feel equipped to assess the transition using the usual 'trilemma' approach which balances security, sustainability and equity in energy systems.

Brand et al. (2020) and Killip and Owen (2020) assess the disruption of transport and construction to identify barriers to change. A detailed scenario analysis of UK transport policy shows that a ban on internal combustion vehicles imposed in 2040 is not consistent with a 1.5°C warming pathway (Brand et al., 2020). Moreover, this relatively distant target—and the accordingly slow change—means that many of the main actors face little disruption, including the oil and gas industry and the local governments who will eventually be called upon to develop charging infrastructure (Brand et al., 2020). A more ambitious timeline and a greater emphasis on demand reduction could achieve the transport sector's decarbonisation, but would require more disruption, and sooner.

Decarbonisation in buildings will largely be achieved by retrofitting the existing stock. Killip and Owen (2020) use an innovation-skills-institutions framework to assess the persistent design-performance gap in retrofitting activities, and the potential for disruptive improvements to the industry. A review of literature on best practices in retrofitting versus renovation identifies elements that will be disrupted (integrated design; co-ordination; retraining workers) and those that will experience continuity (mature technologies; building regulations; project flexibility).

These case studies illustrate the different approaches to disruption necessary in different industries. They also highlight that sectors face a variety of barriers to disruption, from infrastructural lock-in to skills shortages and powerful incumbents. Ketsopoulou et al. (2021) map the four sectors reviewed here to their dual-axis disruption framework, described above. The results are shown in Figure 2.10. Despite their different approaches, these studies all highlight the necessity of deliberately disruptive policies to reach net zero by 2050.

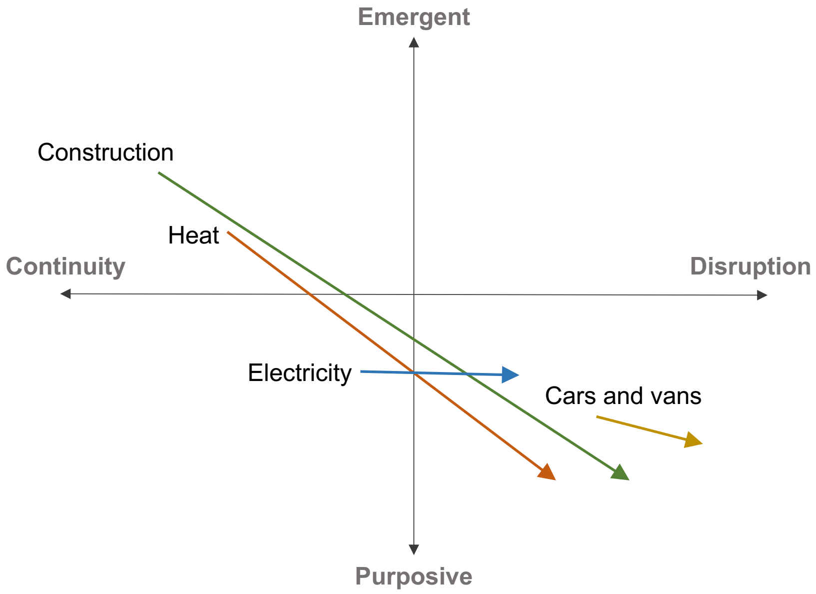

Fig. 2.10 Four case studies of disruption mapped onto the disruption framework proposed by Ketsopoulou et al. (2021). Arrows indicate the likely progression of the transitions over the coming decades.

Summary: Disruption studies needs practical tools to evaluate climate policies

Deeper understanding of sectoral disruption is needed to achieve the purposive change required for successful decarbonisation. At the same time, the multitude of approaches, methodologies and even definitions limits the comparability of these sector-level case studies. How can we say whether the disruption to energy markets or the change to construction will be greater? Practicable tools are needed for evaluating and comparing disruption across different climate strategies in order to identify where urgent change is possible.

2.3.3 The role of government in low carbon disruptions

There is a growing interest in understanding the role of policy in energy system disruptions (Ketsopoulou et al., 2021). In government, disruption is related to policy innovativeness. This concept describes the adoption of an instrument or programme that 'tips' a government into a new policy regime (Schaffrin et al., 2014). A successful net zero transition is likely to combine innovative policy with coordinated and intentional change, which Ketsopoulou et al. (2021) refer to as purposive disruption. However, sudden and unanticipated policy changes could create disorder and increase disruption to undesirable levels (Fulton et al., 2020).

Returning to Christensen's original theory of innovative disruption, McDowall (2018) proposes that the concept of 'low end footholds' can be helpful for climate policymaking. Low end footholds exist when there is an opportunity for a disruptive market entrant to undercut incumbents. Policymakers could use these footholds to disrupt incumbent companies, activities or systems—the challenge is how to direct disruptions towards low carbon outcomes (McDowall, 2018). Johnstone et al. (2020) argue that disruption need not mean incumbents are overthrown. The renewable revolution in the UK has so far been led by incumbents—the 'big six'—in contrast with other European countries, which have seen an increasingly diverse energy supply market. However, Johnstone et al. (2020) note that understanding how policy affects the ownership, rate, direction and acceptance of disruption should be a core research priority for the net zero transition.

Government-led disruption is not always welcome. Wilson (2018) assessed the appetite for policy to support disruptive low carbon innovation amongst innovators and researchers, finding unresolved tensions between the need for funding, collaboration and strategy and the risks of 'picking winners'. Lowes and Woodman (2020) illustrate that policymakers themselves are unsure of the role of policy in disruptive change. This was exacerbated by the uncertainties inherent in system-level disruption.

Summary: Governments can identify and support positive disruptions

An urgent low carbon transition demands deep disruption. An *effective* transition requires purposive disruption, guided by government policy. Governments tend to dislike disrupting their constituents' lives, but it will be unavoidable in the coming decades. Overcoming this aversion, and the opposition from incumbents, will be necessary to achieve swift decarbonisation.

2.3.4 Research gap: Quantitative tools for policy disruption analysis

Disruptions are going to be an essential part of the net zero transition. Whether desired or not, we are likely to see disruption in many corners of the economy and our own lives. Four such corners were reviewed here (Section 2.3.2); all will likely require policy to initiate and support the necessary changes (Section 2.3.3). Disruption studies offer a useful lens for policy analysis in the climate debate, which steps outside the conventional box of climate economics to consider the social and technological practicality of accelerating decarbonisation.

This section reviewed the nascent field of disruption studies for decarbonisation. Theories of disruption have been adapted from Schumpeterian ideas of creative destruction in business innovations (Section 2.3.1), and offer promise as a tool in climate policy analysis. The literature is relatively young and, like transitions studies, does not yet provide a consistent framework for analysing and comparing different climate policies. In particular, this review did not uncover any studies that quantify and compare the disruption of climate policies across various sectors.

Every year of inaction intensifies the mitigation necessary in the remaining period to 2050. It also very likely increases the disruption. What this means for the UK's chances of achieving net zero—and achieving it by 2050—is a question not yet answered by the budding literature on low carbon disruption. This research gap is broad and ambitious, but provides an opportunity for both quantitative and qualitative analyses to yield insights on the risks and returns of various climate strategies. The third research question addresses this gap, and Chapter 5 presents the research.

2.4 Research questions

This thesis combines methods and insights from engineering and economics to consider opportunities to accelerate the delivery of climate targets. In particular, it will answer the question posed in Section 1.5: *How can policy accelerate the delivery of climate mitigation?* The overarching question is addressed in three stages. First, identifying the political and social barriers which are currently hindering meaningful climate action, and asking how they might be overcome. Second, considering what lessons history can provide about the potential for technological and social transitions to accelerate net zero. Finally, assessing whether the current approach to climate action puts the UK on a path to achieving climate targets, and identifying opportunities for urgent action. These steps are addressed in research Chapters 3 to 5. Specifically, this thesis aims to answer three specific research questions, summarised in the box at the end of this section.

RQ1: How do political institutions and public beliefs affect the urgency of climate policy?

The literature on climate economics has so far been dominated by somewhat esoteric discussions of theory (Section 2.1.1), quantification (Section 2.1.2), and carbon pricing (Section 2.1.3). Given the significant influence of economists in policymaking, this has resulted in climate policy that focuses on small adjustments to the status quo. The social cost of carbon and marginal abatement cost are metrics that give rise to policies which are efficient 'in the margin': carbon taxes and emissions targets. Yet we are no longer in a marginal world. Large climate impacts are now inevitable, and the risks of non-linear catastrophic events are growing. Urgent climate action requires structural changes occurring at an unprecedented rate. Different tools are necessary.

Some research has considered the barriers to the conventional approach: myopic politicians, influential but unconvinced voters, and a proclivity for supply-side policy (Section 2.1.4). This research does not, however, conclusively demonstrate why these factors have stood in the way of meaningful climate action for three decades. Nor does it provide broad, practicable suggestions for ameliorating them. The first research section in this thesis aims to address this research gap by considering the role of political institutions and public beliefs in developing climate policy, and what economic tools can be deployed to ameliorate the barriers to urgent action. RQ1 is answered in Chapter 3.

RQ2: What can history tell us about the speed of technological and social transitions?

The low carbon transition will be unlike any coordinated development in modern history. Nonetheless, past transitions can provide guidance for the future of decarbonisation. This task is already underway for technological transitions. Theories of technological development, innovation and diffusion (Section 2.2.1) provided a springboard for applied studies of past transitions, which yielded insights about the duration and determinants of technological transitions (Section 2.2.2). Social transitions are less well studied. While theories of behavioural and social changes exist, they provide little guidance for quantitative analysis of the duration and dynamics of societal change (Section 2.2.3). The second research question stems from this observation. Numerous studies consider what lessons history has for technological transitions, but few consider the promise of social transitions. The research to answer this question uses past transitions, both technological and social, to answer RQ2. It is presented in Chapter 4. The logical next step is to apply these lessons to the coming low carbon transition. This is the task of the third research question.

RQ3: What do current climate strategies imply for the United Kingdom's timeline to net zero by 2050?

Disruption provides a useful lens for assessing climate policy. In particular, the achievable timescale of mitigation depends on the nature and ambition of the proposed policies. High ambition policies require large disruptions to markets or activities. They have the greatest abatement potential, but will also take the longest time, as physical and social infrastructure is developed. Therefore, disruption offers a useful tool to link climate policies with climate timelines. Section 2.3 reviewed the literature on disruption as a tool for transition analysis. Theories and definitions vary (Section 2.3.1); the low carbon literature has yet to settle on a unified approach (Section 2.3.2). Nonetheless, the relationships between disruption, policy and decarbonisation are clear (Section 2.3.3). What is less clear are the implications of disruption on the duration of low carbon transitions. This research gap gives rise the to the final research question of this thesis, RQ3.

Thesis structure

This thesis addresses the specific research questions given above. Relevant literature has been reviewed in Chapter 2. This chapter also identified several gaps in the literature and outlined the three research questions. Chapters 3 to 5 present the research undertaken to answer these questions. Each research chapter includes a brief introduction that relates the work to the context and literature reviewed in Chapters 1 and 2. The research chapters then introduce the methods and materials, present results and discuss the implications for urgent climate action. Each chapter ends with a summary of findings.

Finally, Chapter 6 discusses the overarching implications of the research results. It draws together the results from the preceding chapters to answer RQ0 and the three specific research questions. It then discusses the wider implications of this work and areas for further study. References are provided, followed by supporting information for Chapters 4 and 5 given in Appendices A and B respectively.

The three research questions addressed in this thesis are summarised below. The overall structure is summarised in Figure 2.11.

Research questions

RQ0. How can policy accelerate the delivery of climate mitigation?

RQ1. How do political institutions and public beliefs affect the urgency of climate policy?

RQ2. What can history tell us about the speed of technological and social transitions?

RQ3. What do current climate strategies imply for the United Kingdom's timeline to net zero by 2050?

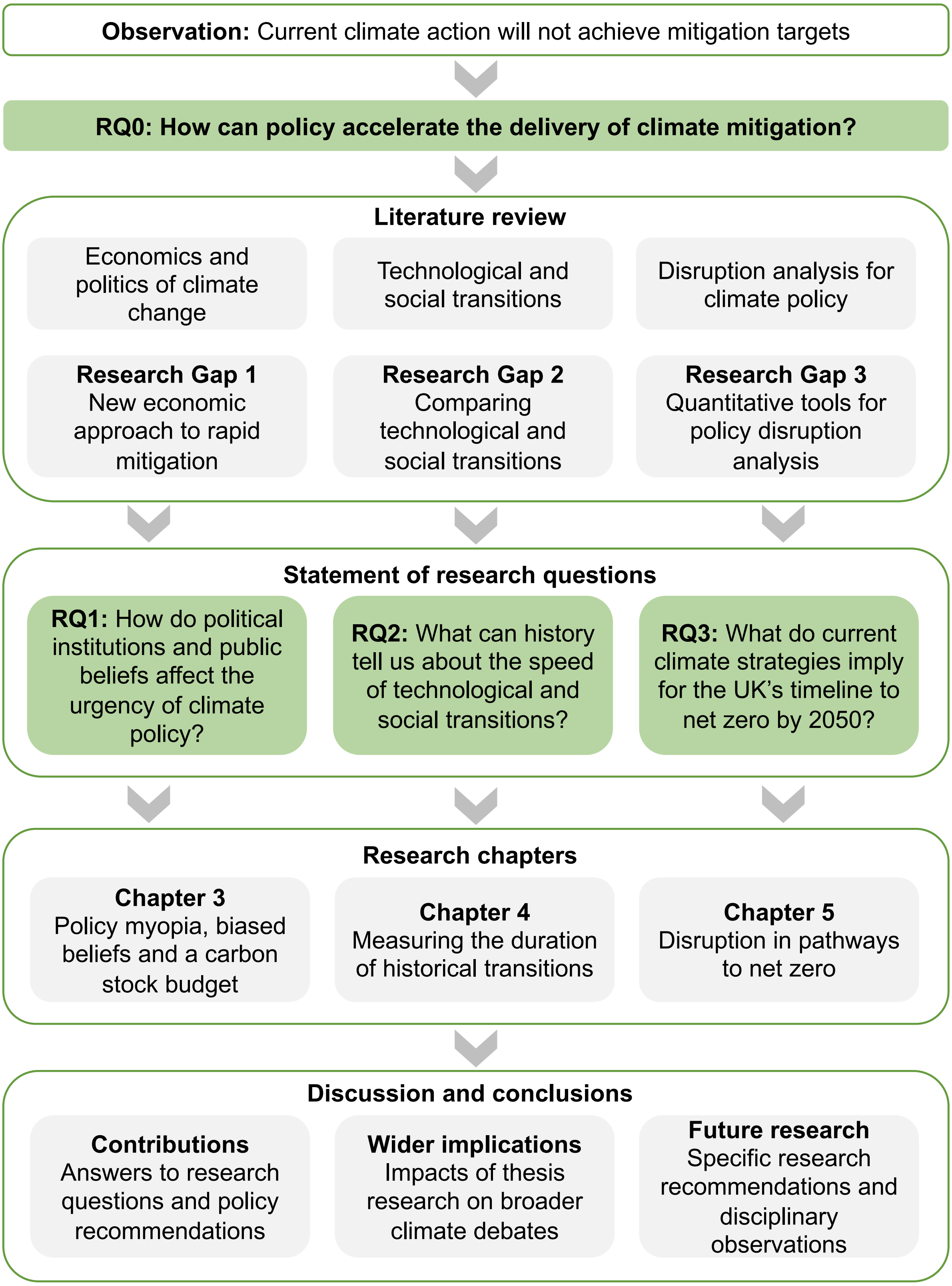

Fig. 2.11 The structure of this thesis.

Chapter 3

Politics, beliefs and urgent climate policy

The research in this chapter addresses *Research Question 1*:

How do political institutions and public beliefs affect the urgency of climate policy?

Climate policy suffers from a time-based incentive inconsistency. Politicians, businesses and individuals in the present bear the costs of climate policy, but the benefits—or rather, the avoided damages—are not felt until years or even decades later. Section 2.1.4 reviewed the political economy barriers to urgent climate policy. These include incentives to freeride on neighbours and future generations, the inherent uncertainties of climate damages, and many vested interests. Together these factors have led to a short-term bias in climate politics, which this study refers to as climate policy myopia.

In theory, democratically elected politicians act out their constituents' wishes and pursue socially-sanctioned polices. However, this system is vulnerable to biased public beliefs. Myopic policy is reduced when voters hold policymakers to account by only electing officials who meet performance standards (Ferejohn, 1986). This strategy fails if the public incorrectly perceives the risk of myopia and sets excessively lenient standards. Biases occur when people hold systematically inaccurate beliefs, so the median belief does not agree with the truth (or expert opinion). This thesis argues that public beliefs over the threat of climate change and the urgency of mitigation are downwardly biased. Moreover, it proposes that this bias occurs because individuals' climate beliefs are rationally irrational.

Rational irrationality implies that people have preferences over beliefs, specifically over their deviation from rational expectations (Caplan, 2007). The extent of their bias—or the quantity of irrationality consumed—depends on their preferences and the private cost of holding irrational beliefs. Preferences are grounded in psychology, while private costs depend on the context of people's decisions. Particularly in politics, where the likelihood that an individual's vote will be pivotal to the election is minuscule, voter irrationality becomes a classic collective action problem where individually rational decisions beget large political failures (Caplan, 2001, 2009).

To achieve urgent climate policy, the perception of climate risk needs to change. A potential mechanism to correct rationally irrational beliefs is reframing climate change as a stock problem, rather than a flow problem. Currently, climate policy and political discourse largely focus on annual emissions—carbon flows. Yet the most meaningful physical indicator of climate damages is the atmospheric carbon stock: the total amount of greenhouse gases stored in the atmosphere (Allen et al., 2009). Carbon stocks are usually measured in gigatonnes of CO_2 ($GtCO_2$). Adopting a binding target over the stock of carbon, known as a carbon stock budget, would provide an effective political commitment mechanism and a highly accessible concept for individuals well-versed in their own financial budgeting. It could help overcome biased beliefs and limit policy myopia.

The concept of a carbon stock budget is not novel. In fact, it was enshrined in the first major climate treaty, which aimed to achieve "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992, p. 4). The scientific case for carbon stock budgets is well-established (Allen et al., 2009; Millar et al., 2017). Yet carbon stock budgets rarely feature in public discourse of mitigation policy. When they do, they take second fiddle to net zero emissions targets. Correcting the discrepancy between expert discourse and public rhetoric on carbon targets is the core tenet of this research.

This chapter presents a political and behavioural argument for a carbon stock budget. Section 3.1 draws together three strands of literature and establishes the relevance of policy myopia and biased beliefs to climate policy. The value of a carbon stock budget is demonstrated using a simple climate-economy model, described in Section 3.2. The model assesses the effects of different policies on an economy that faces both gradual and abrupt climate damages. The implementation of a carbon stock budget is modelled in policy environments defined by myopia and biased beliefs. The model's results are given in Section 3.3. This section also explores two issues that could fuel myopia even in the context of a carbon stock budget, namely the cost of delaying a budget and the impact of imposing an unduly strict budget. Section 3.4 discusses the best approach to implementing a carbon stock budget and evaluates the assumptions of the model. Findings are summarised in Section 3.5.

3.1 Theories and evidence

This chapter proposes that a global carbon stock budget is a useful tool to alleviate climate policy myopia and biased beliefs. There are three cornerstones to this argument: that current climate policy is myopic, voters' beliefs are biased, and that a carbon stock budget could ameliorate shortsighted climate policy.

3.1.1 Policy myopia

Policy myopia occurs when voters and political institutions allow elected officials to distort policies towards short-term outcomes. In public investments, this means a low long- to short-term spending ratio (Aidt and Dutta, 2007). In climate policy, myopia can be understood as a high long- to short-term mitigation ratio. In other words, myopic climate policy avoids expensive or politically challenging policies to reduce emissions now, resulting in a high future mitigation burden.

Is climate policy myopic?

Myopic climate policy trades off current and future mitigation. Given that 2°C warming will very likely bring droughts, extreme weather and higher risk of tipping points (Hoegh-Guldberg et al., 2018), the strongest evidence of this tradeoff is the lackluster implementation of national climate agendas. Over 70% of global emissions are now covered by net zero pledges, but these commitments are not yet supported by near term measures to create change (Bouckaert et al., 2021). Currently implemented national policies will leave global emissions 22GtCO_2 higher by 2030 than the level needed to limit warming to 2°C (Roelfsema et al., 2020). Even if all of today's domestic net zero targets are achieved, global emissions will be more than 20GtCO_2 in 2050 (Bouckaert et al., 2021).

Future ambition is vastly outpacing today's realised mitigation. The remaining pathways to the Paris target implicitly require large future emissions cuts, risking economic wellbeing, food security and biodiversity (UNEP, 2020). Some policies explicitly bet on future mitigation to achieve climate targets, like the widespread reliance on negative emissions technologies to achieve net zero emissions by 2050 (Rogelj et al., 2019, see Chapter 5). The promise of future advances means that politicians feel exempt from making tradeoffs today (McLaren et al., 2019). However, dependence on speculative technologies elevates the risk of future damages if these innovations fail.

3.1.2 Rational irrationality and biased beliefs

The relevance of rational irrationality to climate policy lies in voters' beliefs over the risk of climate change and the urgency of mitigation. These beliefs affect their personal decisions over climate-intensive activities and how they vote on climate issues. In particular, if voters believe that climate mitigation is less urgent than it really is, then support for climate policies, and the candidates who propose them, will be lower than optimal.

Biased beliefs are only one of the many factors that contribute to policy myopia (see Section 2.1.4 for a full review). Powerful groups with an interest in maintaining the status quo can influence policy (Aidt, 1998; Prieur and Zou, 2018; Tol, 2017). Party politics may shift priorities into the short-term (Gersbach, 2004). Nonetheless, public beliefs are crucial. By affecting voters' preferences, beliefs over the optimal climate policy contribute the likelihood of reelection for politicians. Vested interests and party politics can only be countered if the general support is sufficiently strong. Biased climate beliefs leave politicians little incentive to pursue urgent mitigation.

Does rational irrationality imply biased climate beliefs?

Assessing whether rational irrationality implies biased beliefs about the urgency of climate mitigation requires establishing three conditions.

1. It is *socially irrational* to believe mitigation is not urgent;
2. It is *individually preferable* to believe mitigation is not urgent; and
3. The *private costs* of believing mitigation is not urgent are negligible.

First, is it irrational to think mitigation is not urgent? There is a near complete consensus amongst scientists that recent global warming trends are caused by human activities (Carlton et al., 2015; Cook et al., 2016). Moreover, a wealth of evidence demonstrates the potential severity of climate damages (Hoegh-Guldberg et al., 2018), which could occur within decades. Together, this suggests that such a belief is indeed irrational.

Second, would people prefer to believe that climate mitigation is not urgent? Insights from psychology and behavioural economics are relevant here. Like for politicians, if proclimate beliefs would induce frequent and costly decisions while providing few short-term benefits, myopic loss aversion may induce a preference for a 'head in the sand' approach (Thaler et al., 1997). Adopting proclimate behaviour when others do not might seem unfair (Kahneman et al., 1986; van den Assem et al., 2012). In some contexts, there may even be a social cost of holding proclimate beliefs that clash with those of friends or coworkers (Kahan et al., 2012).

Third, what are the private costs of believing that mitigation is not urgent? Crucially, the private cost of holding a belief is marginal—not *what would happen if everyone thought this way?* but rather *what happens if I think this way?* In this case, the collective cost is severe long run damages. However, because climate change is a global problem, an individual's actions have a near zero impact (notwithstanding the benefits of collective action). Like in the ballot box, the chances of being the pivotal emitter are effectively nil. So the private cost of this belief is zero and individuals are free to consume irrationality to their bliss point (Caplan, 2007).

Are public beliefs over the urgency of climate change biased?

Now consider the evidence that public beliefs about the urgency of climate action are biased. Beliefs over climate change can broadly be categorised into three main categories: that climate changed is caused or accelerated by human activities; that climate change is a problem; and that urgent climate action is necessary.

There is some evidence that public belief in anthropogenic climate change is biased; in a 2010 study in the US, 57% of the public agreed that warming was human-induced, versus 81% of energy scientists and 70% of policymakers surveyed (Bolsen et al., 2015). More recent surveys suggest most people believe humans are at least partly responsible for climate change (YouGov, 2019). Regardless of attribution, people seem to acknowledge that climate change is a global challenge. In a survey covering 50 countries, 64% of respondents agreed that climate change was a global emergency (Flynn et al., 2021). 93% of European citizens believe climate change is a serious problem (European Commission, 2019).

While public beliefs over the existence of climate change seem relatively consistent with scientists', this research concerns beliefs over the *urgency* of climate change. For this, the relevant beliefs are those concerning the relative importance of climate change amongst policy challenges, i.e., its issue salience.

To establish bias, a baseline is necessary. This study assumes that experts—climate scientists—have the most informed, and thus most unbiased, beliefs over the urgency of climate action. There are few studies that ask scientists about their policy recommendations, perhaps due to a belief that policy advocacy would inhibit their objectivity (e.g., Lackey, 2007). However, Rosenberg et al. (2010) found in a 2005 survey that 91.3% of climate scientists disagreed with the idea that scientific uncertainty meant there was 'no need for immediate policy decisions' (even more than the share who agreed that humans were accelerating climate change!). Since 2005, the scientific consensus on climate change has only grown: recent studies suggest between 97% and 100% of climate scientists believe in human-induced climate change (Cook et al., 2016; Powell, 2019). Assuming that scientists' views on the necessity of immediate policy decisions have increased in line with these beliefs, or at least have not declined, then the unbiased baseline is that climate action is urgent.

Now turning to public beliefs over the importance of immediate climate action. This study considers the share of people who believe that climate change is the most important issue facing the country. There is significant variance amongst surveys. Crawley et al. (2020) find that only 7% of the UK public rank climate change the highest amongst eight issues including crime, healthcare and immigration. 53% ranked it among the bottom two. In the US, the share who think climate change is the most important issues is 2%[1] (Gallup, 2021).

Surveys which are less explicit about policy tradeoffs see less drastic results. Around 30% of Britons rank climate change among the top three issues facing the country in January 2020 (YouGov, 2021). 52% of Americans agree that climate change should be a 'top priority' (Funk and Kennedy, 2021). Globally, 54% of respondents to the World Values Survey agreed that protecting the environment should be prioritised over economic growth (Haerpfer et al., 2020). However, to elect farsighted politicians people need to believe that urgent climate action is the highest policy priority—and vote accordingly. Comparing public beliefs to scientists' consensus on the necessity of climate action, established as early as 2005, suggests that public beliefs over the urgency of climate action are indeed biased.

Beliefs over the issue salience of climate change are important because they hint at the opportunity cost of urgent climate policy: the idea that, if a government were to take meaningful action, other agendas would be sacrificed. Urgent climate action would mean less spending on other issues, or higher taxes. So while 61% of people in the UK believe the government is not doing enough to combat climate change, only 32% would accept higher taxes to fund more ambitious policy (Crawley et al., 2020). Globally, even among those who believe that climate change is an emergency, only 59% want urgent, comprehensive action (Flynn et al., 2021). Without acceptance that something—new roads, low taxes, air travel—must be sacrificed in order to avoid climate damages, myopic policymakers will continue to prevail.

3.1.3 A carbon stock budget

A carbon stock budget is a long-term limit on cumulative greenhouse gas emissions, which can be allocated across borders and time. In the climate literature, such constraints are often termed simply 'carbon budgets'. However, this phrase has become somewhat muddled by the United Kingdom's so-called 'carbon budgets' that set five-yearly emissions targets (Climate Change Committee, 2020b). To avoid confusion and emphasise the constraint over long-term cumulative emissions, this thesis uses the term carbon stock budget.

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[1] Note that this survey was undertaken in March 2021, during the Covid-19 pandemic, which significantly affected public perceptions of policy issues (YouGov, 2021)

How would a carbon stock budget help?

A carbon budget can act as a long-run commitment mechanism for politicians, to combat their myopic tendencies. Setting a legally binding budget, with meaningful penalties if it is exceeded, would create incentives for adopting forward-looking policies which reduce the mitigation burden in future years. Selecting a long-term carbon stock target may seem an alarming prospect given the myriad uncertainties of climate change. Indeed, Fitzpatrick and Kelly (2017) argue that adjusting the size of the budget would increase the benefits from technological development by allowing learning-by-doing. However, flexibility creates ambiguity over the appropriate size of the budget and can reduce the impetus for urgent action. Constant revisions of budget estimates reinforce policymakers' views that it will always be "five minutes to midnight" (Geden, 2018, p. 382). Setting a firm target for carbon accumulation would emphasise long-run risks to both policymakers and the public.

A carbon stock budget could influence voter beliefs by highlighting the opportunity cost of emissions. 'Spending' the budget today means carbon austerity in the future. A carbon stock budget is an easily communicated concept that appeals to the common practice of household budgeting. Bernauer and McGrath (2016) argue that reframing climate action will elicit no additional support because the public are already pretreated by the abundance of evidence and opinions on traditional and social media. However, messaging based on carbon stock budgets is an accessible way to redefine climate risks that could overcome pretreatment.

Concreting the public perception of risks will ameliorate rationally irrational biases about the urgency of mitigation. While it remains true that the likelihood of being the pivotal emitter is small, if individuals recognise the potentially life altering impacts of climate damages, the perceived private cost of climate denial will increase. Belief in the low urgency of mitigation will no longer be rational—not even rationally irrational. Changing beliefs over the private costs of climate change is key to motivating public support for urgent climate action. In turn, broader support increases incentives for policymakers to implement farsighted policies.

Why is a carbon stock budget better than an emissions target?

Climate targets take many forms. The most common are emissions targets—over 100 countries have pledged or intend to pledge to reach net zero (van Soest et al., 2021). However, net zero targets provide a weaker policy commitment than carbon stock budgets.

A carbon stock budget aims to stabilise total carbon stocks, rather than annual contributions. This is important because temperatures are determined by cumulative emissions (Matthews et al., 2009). A net zero target limits emissions in the target year, meaning carbon stocks will stabilise only after this point. However, different pathways to net zero emissions give rise to very different levels of carbon stock stabilisation, as illustrated in the top panel of Figure 3.1. Slow or linear decarbonisation is allowable under net zero targets but yields high carbon stocks. These pathways elevate climate risks. The bottom panel of Figure 3.1 illustrates the effect of an enforced carbon stock budget. Slow or linear decarbonisation results in emissions being curtailed rapidly and precipitously, causing major societal disruption and imposing drastic social harm. A carbon stock budget creates far stronger incentives for near term mitigation than a net zero target.

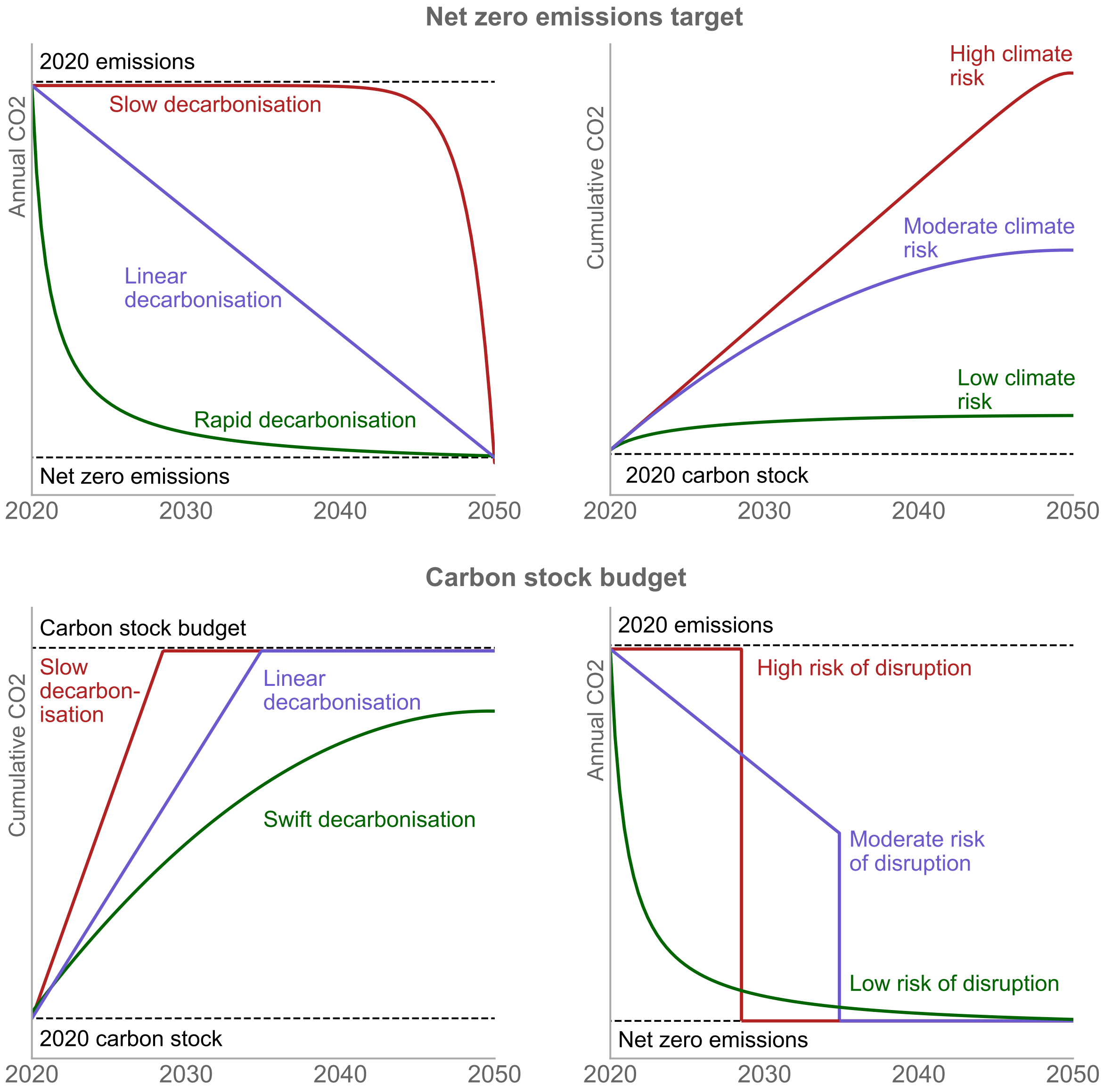


Fig. 3.1 Potential emissions and carbon stock pathways under two alternative climate commitment mechanisms.

A persuasive literature explores the risk reduction potential of carbon stock budgets (e.g., Allen et al., 2009; Meinshausen et al., 2009; Millar et al., 2017). This work considers the value of carbon stock budgets in the context of policy myopia and biased beliefs; a detailed review of the science of carbon stock budget is out of its scope. To summarise, extensive research has shown that limiting the total accumulation of carbon would provide a clearer environmental signal than constraining annual emissions.

Alternative commitment mechanisms include temperature targets and green investment commitments. Temperature targets do not provide sufficient actionable guidance to be a useful climate commitment mechanism, due to the time delay (Samset et al., 2020) and uncertainty (IPCC, 2018) in the relationship between emissions and temperature changes. Indeed, net zero targets grew out of a desire to turn the Paris Agreement's aim to limit warming to well below 2°C into an actionable target. Green investment commitments are eminently actionable. They may well be part of the solution: many governments include research funding targets as part of their climate strategies (e.g., HM Government, 2020). However, investment targets are a means to an end, and cannot replace a scientific long-run commitment mechanism.

3.2 Quantitative methodology

The argument presented in this chapter is predominantly theoretical. It ties together theories of policy myopia and rational irrationality to explain some of the systemic barriers to climate policy. Both effects could be ameliorated by popularising the concept of a carbon stock budget. A budget can act as a commitment mechanism and heuristic tool, combating political and behavioural inertia.

The quantitative method presented here supports the conceptual argument. An adapted Hotelling model is used to evaluate the impacts of a carbon stock budget. Hotelling models consider the optimal extraction of finite resources (Hotelling, 1931) and have been used to assess constraints on carbon accumulation (e.g., Chakravorty et al., 2006; Kollenbach, 2015a). This model is simple; its methodology is not representative of the myriad complexities of climate change, nor particularly novel. Instead, this model illustrates the benefits of a carbon stock budget in the presence of myopic policy.

This section first describe the model qualitatively, aiming for clarity. It then introduces a mathematical description of the model, details of extension and the solution method. Assumptions are examined in Section 3.4.2.

3.2.1 Model overview

This economy uses capital, energy and labour to produce output. Production exhibits diminishing marginal returns, and aggregate output is determined by the total factor productivity (TFP) of the economy. It assumes a stable labour force with constant productivity. This means the unchanging impact of labour can be ignored, and the model focuses on the role of capital and energy.

Output can either be consumed or invested in next year's capital stock. Capital depreciates as assets become obsolete or less productive. Production generates emissions that contribute to the stock of carbon, so the stock is the sum of all past emissions. The economy is subject to gradual and abrupt climate damages.

The accumulation of atmospheric carbon gradually diminishes social welfare. These damages are already being observed, in the form of higher average temperatures, changing weather patterns and rising sea levels (Hoegh-Guldberg et al., 2018). In the model, gradual damages reduce welfare, but do not affect production. Damages from emissions are felt in the year in which they are emitted. Letting γ be a constant parameter governing the relationship between carbon stock and socioeconomic impacts, then gradual climate damages at time t are given by:

$$\text{Gradual damages}(t) = \gamma\big[\text{Carbon stock}(t) + \text{Emissions(t)}\big]^2$$

A second mechanism of climate damages incurs much harsher consequences. When carbon accumulation exceeds a threshold, a new climate regime is initiated that reduces aggregate productivity. Significant shifts in climate dynamics could occur through several highly interconnected mechanisms including the collapse of the Greenland ice sheet or changes in the frequency of El Niño events (Kriegler et al., 2009). Resulting impacts would accumulate over decades but are irreversible and will affect production processes, for example through reduced complexity of international supply chains or deteriorating health of the labour force. In the model, exceeding the carbon threshold permanently reduces TFP by 60% over a decade, comparable to returning to the productivity of the 1940s (U.S. Bureau of Labor Statistics, 2019). The carbon threshold is assumed to be deterministic.

Social welfare is measured using a utility function that depends on consumption and gradual climate damages. Future utility is discounted by factor $\beta = 0.99$, meaning that a consumer would be indifferent between receiving £100 next year and £99 today. Discounting occurs due to the possibility of an exogenous shock to the macroeconomy or underlying growth process, such as a global pandemic or technological revolution (Weitzman, 1998).

Three climate policy scenarios are compared, referred to as gradualism, budgeting and switching. In each of these scenarios, policymakers aim to maximise total social welfare over the period to 2100, subject to different political economy constraints. Gradualism accounts for continuous damages to social welfare but not the threshold risk to productivity. Policymakers balance benefits of production against gradual emissions damages, but are unaware of or indifferent to threshold risks. This scenario might arise if policymakers face incentives to continue supporting high emissions industries, or if climate scepticism permeates public beliefs to the extent that mitigation becomes politically impossible. Policy myopia and voter bias dominate climate decisions. Inevitably, gradualism results in the economy overshooting the carbon threshold. The resulting damages convince policymakers of climate risks; after overshoot, this economy adapts to the post-threshold climate dynamics.

In the budgeting scenario, policymakers foresee threshold damages and implement a carbon stock budget. This scenario represents a society which has overcome policy myopia: politicians choose the optimal policy in the face of high threshold damages, and have sufficient voter support to achieve the necessary mitigation. The carbon stock budget creates energy scarcity and restricts production in the long run, but prevents threshold damages. The core policy question is how best to 'spend' available emissions over time. It is assumed that the policymaker can identify the carbon threshold and sets the budget at a level that *just* avoids threshold damages.

In the switching scenario, the government initially takes a gradualist approach to climate policy then adopts carbon stock budget after 15 years. The switch may occur when an event, such as a major weather disaster, increases public belief in the threat of climate change and reduces institutional and political barriers to a carbon stock budget. The switch may also come about after a slow accumulation of support for climate action or a breakthrough in international negotiations. After switching, the policymaker reverts to a carbon stock budget with the same ceiling as in the budgeting scenario.

3.2.2 Mathematical description of the climate-economy model

This section provides further detail on the model described qualitatively above. The economy uses capital, K_t, energy, E_t, and labour, L_t, to produce a composite output good, Y_t, that satisfies all consumption requirements. Output is produced according to an increasing, concave production function, $F(A_t, K_t, E_t, L_t)$, where A_t is TFP. Production follows a Cobb-Douglas function with constant returns to scale, and capital and energy share given by α:

$$F(A_t, K_t, E_t, L_t) = A_t K_t^{\alpha} E_t^{\alpha} L_t^{1-2\alpha} \qquad \alpha = 0.3$$

The stock of labour is assumed to be constant, experiencing negligible population growth and no increase in productivity. This is a strong assumption, but one that allows for easier examination of the effect of energy-intensive capital use. L_t is normalised to unity, meaning the effective production function is:

$$F_{eff}(A_t, K_t, E_t) = A_t K_t^{\alpha} E_t^{\alpha} \qquad \alpha = 0.3$$

Output can either be consumed, C_t, or invested in the next period's capital stock, K_{t+1}. Each period, the existing capital stock depreciates by a fraction δ. The evolution of capital stocks is given by:

$$K_{t+1} = Y_t - C_t + (1 - \delta)K_t$$

Capital and energy shares

The capital and energy shares of the economy are both $\alpha = 0.3$. Roughly, this translates into an assumption that 30% of GDP arises from capital use—machinery, information technologies and so on—and 30% arises from energy use. The remainder is derived from labour. More specifically, the capital share reflects the share of national income distributed as capital income: the profits, interest and capital gains which are paid to capital owners as compensation for their assets (Bengtsson and Welenström, 2018). Using this statistic to measure inputs' relative importance in aggregate production relies on the assumption that compensation reflects marginal productivity.

The typical stylised model with Cobb-Douglas production assumes about a third of output arises from capital (Mankiw et al., 1992; Solow, 1957). Labour is assumed to provide the remaining two thirds. However, recent evidence suggests labour shares are declining across the rich world, particularly in the United States (OECD et al., 2015). Most models do not explicitly include energy as a production input.

Determining the production share of energy is difficult because it is so integrated into modern society as to be indistinguishable from other inputs. A typical estimation method would be to take the share of national income derived from the energy sector. This would lead to a share of around 3% in the UK and USA (BEIS, 2020a; US Bureau of Economic Analysis, 2021). However, this figure is unlikely to reflect the marginal productivity of energy. Energy is integral for economic growth: the relationship between energy consumption and national production is well established (Chontanawat et al., 2008; Kraft and Kraft, 1978). Safa (2017) estimates that almost half of global GDP is derived from energy. Almost all capital and a large share of labour would be useless without it. The income energy share underestimates its productive value.

This model economy uses energy to 'power' production using capital and labour. The assumption that capital and energy contribute equally to the production process is admittedly somewhat ad hoc. However, for a stylised model focusing on the energy-emissions relationship, it is appropriate. One effect of this assumption is that the constraint on emissions and therefore energy places significant restrictions on aggregate production. The importance of energy in production (Safa, 2017) justifies the 30% energy share assumption.

Climate damages

This economy has a single energy source that produces one unit of emissions for each unit of energy, so production effectively takes emissions as an input. Emissions contribute to the stock of carbon. Letting S_t be the stock at the start of period t, the evolution of carbon is given by $S_{t+1} = S_t + E_t$. Some studies of the exhaustibility of atmospheric carbon assume that a portion of carbon stock is eliminated each period, through reabsorption via oceans or forests. (e.g., Chakravorty et al., 2006; Kollenbach, 2015a; Withagen, 1994). However, equilibrium is reached after centuries, not decades (Archer et al., 2009). This analysis focuses on the 80 years to 2100 which is the most consequential for climate policy, so does not include an atmospheric regeneration rate in the model.

Carbon stocks are used to proxy temperature changes. It is assumed that the accumulation of carbon stock results in gradual, continuous climate damages, and high-impact threshold damages.

Gradual damages are based on the carbon stock, and decrease societal welfare each period. Damages from each period's emissions are incurred in the period in which they are emitted. The direct damage from carbon stock accumulation is given by:

$$D(S_t, E_t) = \gamma(S_t + E_t)^2$$

where γ is a constant parameter. Given the evolution of carbon stock, this can be written $D(S_{t+1}) = \gamma S_{t+1}^2$.

The value of γ (given in Table 3.1) is such that gradual damages affect emissions behaviour, but do not override incentives to produce output and generate consumption. The economic literature varies hugely in the assumed impact of large, gradual changes in climate conditions. In DICE-2007, a 12°C temperature increase lowers welfare-adjusted consumption by 26% (Nordhaus, 2007), while Weitzman (2012) proposes a reduction of 99% for the same temperature change based on human adaptability to heat stress.

When carbon accumulation exceeds a threshold, a new climate regime is initiated. The large-scale events constituting threshold damages are likely to take many years, but are irreversible. Weitzman (2012, p. 236) describes the approach of imposing an immediate cost for an long-term but irreversible change as "the sky [being] allowed to artificially fall at once". Threshold damages in this model are imposed over a decade, consistent with the approach in Lontzek et al. (2015).

Changing climate dynamics affects TFP, which falls by 60% over a period of ten years after the threshold is breached. This means that the same combination of capital and energy would produce 40% of what it did before the threshold was breached. It is undoubtedly a strong assumption. However, evidence that catastrophic climate damages could to lead to mass migration, conflict, food shortages and health crises (Froese and Schilling, 2019; McMichael et al., 2012; Richards et al., 2021) justifies the assumption of dramatic and long-lasting economic damages. Let $\bar{S}$ denote the carbon threshold. Then the sequence of TFPs over time is given by:

$$A_t = \begin{cases} \{1, 1, ..., 1\} & S_t < \bar{S} \\ \{0.94, 0.88, ..., 0.46, 0.4, ..., 0.4\} & S_t \geq \bar{S} \end{cases}$$

Pre-threshold (initial) TFP is referred to as $A_I(t)$ and post-threshold (damage) TFP as $A_D(t)$.

Welfare and utility

In-year welfare is measured using a two-part utility function composed of standard consumption-based log utility, $u(C_t) = ln(C_t)$, and continuous climate damages, $D(S_{t+1})$ given above. Next year's utility is slightly less valuable than today's, by a factor of $\beta = 0.99$, equivalent to a utility discount rate of 1%. The small but non-zero discount rate reflects the uncertainty related to catastrophic events (Weitzman, 1998) and the choice of 1% for this risk component is consistent with the choice made in the Green Book (HM Treasury, 2018). The assumed rate of societal pure time preference is zero; the model does not directly discount the utility of future generations (Ramsey, 1928).

Policy scenarios

This economy is controlled by a theoretical 'social planner', a benevolent dictator who selects capital and emissions each period. Carbon policies impose constraints on the social planner's possible choices. The policy affects the choice of emissions, and overall growth and welfare through output, consumption and utility. The political economy constraints imposed by the three scenarios are:

1. In the gradualism scenario, the threshold damage function is a hidden constraint, and the social planner acts as if it does not exist. The social planner's problem is as given below, but policymakers do not respond to the threat of threshold damages.

2. Under budgeting, the social planner's problem has an additional budget constraint that eliminates the threat of threshold damages, namely $S_t < S_{max}$ for all $t > 0$.

3. In a switching economy, threshold damages are initially hidden, then become visible due to scientific advance or political breakthrough. As a response, the social planner implements a carbon stock constraint at time t_{sw}. If the threshold is crossed before the switching date, the economy cannot recover and TFP falls. The social planner faces the budget constraint $S_t < S_{max}$ for all $t > t_{sw}$.

Social planner's problem

The aim of the social planner is to maximise total social welfare (V) of this economy over the planning horizon, subject to the evolution of capital and carbon stocks and the carbon damages. The full social planner's problem for a planning period $[0,T]$ with initial capital and carbon stock (K_0, S_0) is given by:

$$V(K_0,S_0) = \max_{\{K_t,S_t\}} \sum_{t=0}^{t=T} \beta^t \left[u(C_t) - D(S_{t+1}) \right]$$

Subject to physical and political economy constraints given by:

$$\begin{array}{ll}
\text{Evolution of capital:} & K_{t+1} = A_t K_t^{\alpha} E_t^{\alpha} - C_t + (1-\delta)K_t \\
\text{Evolution of carbon stock:} & S_{t+1} = S_t + E_t \\
\text{Non-negativity constraints:} & K_t, S_t, C_t, E_t \geq 0 \quad \forall \quad t \\
\text{Threshold damages:} & A_t = \begin{cases} A_I(t) & \text{when} \quad S_t < \bar{S} \\ A_D(t) & \text{when} \quad S_t \geq \bar{S} \end{cases} \\
\text{Budgeting scenario:} & S_t < S_{max} \quad \forall \quad t \geq 0 \\
\text{Switching scenario:} & S_t < S_{max} \quad \forall \quad t > t_{sw}
\end{array}$$

Table 3.1 summarises the parameter values used in the analysis.

Table 3.1 Parameter values used in the accompanying analysis.

Parameter	Definition	Value
β	Discount factor	0.99
α	Production elasticities of capital and emissions	0.3
δ	Depreciation of capital stock	0.05
γ	Parameter on gradual damages	5×10^{-6}
$\bar{S}$	Carbon threshold	200
$S_{\max}$	Carbon stock budget	200
K_0	Initial capital stock	2
S_0	Initial carbon stock	0

Green investment

Renewable energy is very likely to play a significant role in decarbonising the economy. This section briefly describes how green energy technologies would affect the simple model. Consider an economy which can invest in either productive or green capital. Productive capital increases output. Green capital reduces future emissions intensity of energy, for example by replacing fossil fuels with renewable electricity. This then increases the potential to use energy in the future when the carbon constraint is binding. The choice between productive and green capital then induces a tradeoff: output today or output tomorrow?

Both gradualist and budgeting economies would invest in green capital. Even gradual damages are sufficient to make green investment optimal. However, a carbon stock budget provides a stronger incentive—a budgeting economy could drastically increase their welfare by investing in the ability to generate output once the budget is exhausted. Indeed, other studies which have a renewable option—a so-called 'backstop technology'—find that investment reduces or eliminates the effect of the carbon ceiling (Kollenbach, 2015b, 2017; Lafforgue et al., 2008).

However, deployment of green technologies faces significant constraints. Historical evidence suggests deployment is likely to be slow (Fouquet, 2010; Gross et al., 2018; Smil, 2014) due to innovation delays (Bento and Wilson, 2016), engineering constraints (Beake and Cole, 2020) and public resistance (Poumadère et al., 2011). Some efforts have been made to model these constraints in studies similar to this one (Amigues et al., 1998; Boucekkine et al., 2013). However, Kollenbach (2015b; 2017) and Lafforgue et al. (2008) rely on deployment rates which are currently infeasible. This study's simple model does not consider green investment because evidence of slow technological change suggests that most decarbonisation will need to occur in the absence of transformative new technologies.

3.2.3 Solution method

Backward induction dynamic programming is used to solve for the optimal pathways in each policy scenario. Dynamic programming is a recursive optimisation method that assesses each decision independently of all other periods or choices (Ljungqvist and Sargent, 2012). It is a form of reinforcement learning, a branch of machine learning commonly used in shortest-path optimisation problems (the model presented here is a very simple application of this powerful tool). Dynamic programming can be widely applied to a number of economic problems.

An economic problem is defined by its state variables, which completely characterise the economy at each point in time. The model then aims to achieve its objective (for example, maximising utility) by selecting the optimal level of the choice variables, which in turn determine next period's state variables. In this model, *this period's* capital and carbon stock are the state variables. The social planner decides *next period's* capital and carbon stocks (the choice variables) based on the state variables. Consumption and emissions are jointly determined by the state and choice variables.

For brevity, this explanation proceeds assuming a single choice and state variable; K_{t+1} and K_t respectively (climate damages are ignored for simplicity). The solution to a one-dimensional dynamic programming problem is a policy function, $g(K_t)$, which yields the best choice of K_{t+1} for each possible value of K_t. In order to find $g(K_t)$, it is necessary to define a value function, $V(K_t)$, which allocates a value to every possible state. If the functional form of $V(\cdot)$ was known, then the policy function could be found by solving the following equation for each possible K_t:

$$\max_{K_{t+1}}\{u(C_t)+\beta V(K_{t+1})\}$$

However, the form of $V(\cdot)$ is unknown. Dynamic programming provides a way to jointly solve for the value function, $V(K_t)$, and policy function, $g(K_t)$, which are linked by the *Bellman equation*:

$$V(K_t)=\max_{K_{t+1}}\{u(C_t)+\beta V(g(K_t))\}$$

Where $g(K_t)=K_{t+1}$. Backward induction methods start from an end-of-life assumption and recursively solve the Bellman equation to evaluate the value and policy functions in each period. In other words, there is a different value and policy function for each period, depending on how close that period is to the end-of-life period, T. For this analysis, it is assumed that there is no value of holding capital or carbon stocks in T. The horizon is sufficiently beyond this model's 80-year planning period such that end-of-life behaviour does not affect results.

The end-of-life assumption means that the value of holding capital at time T is zero, i.e., $V_T(K_{t+1}) = 0$. Then the value of function at $T-1$ is

$$V_{T-1}(K_t) = \max_{K_{t+1}}\{u(C_t)\}$$

The general equation for backward induction is:

$$V_{t-1}(K_t) = \max_{K_{t+1}}\{u(C_t) + \beta V_t(K_{t+1})\}$$

Backward induction then solves for the value and policy function at each period by recursively iterating on this general equation. Once $V(\cdot)$ is known, it is then trivial to consider the optimal path of an economy from an initial assumption over capital stocks, by making the optimal consumption choice (according to the policy function) based on the capital stocks each period.

In this model there are two state and choice variables, and climate damages must be considered in the value function. The Bellman equation takes the form:

$$V(K_t, S_t) = \max_{K_{t+1}, S_{t+1}}\{u(C_t) - D(S_{t+1}) + \beta V(K_{t+1}, S_{t+1})\}$$

Where K_{t+1} and S_{t+1} are given by policy functions $g_1(K_t, S_t)$ and $g_2(K_t, S_t)$. Other analyses (e.g., Chakravorty et al., 2006; Kollenbach, 2015b) solve Hotelling models analytically. However, the dynamic programming method employed here tends to be less vulnerable to human error, particularly with more than one state and choice variables.

3.3 Results

The model introduced in the previous section explores the benefits of a carbon stock budget. This section presents the model's results before discussing their significance in the context of policy myopia and rational irrationality.

The projected economic pathways are given in Figure 3.2. As expected, a policy of gradualism yields higher annual emissions, enabling higher output and swifter capital accumulation. Optimal emissions decline even before threshold damages occur due to accumulation of gradual damages. Despite this trend, the gradualist economy exceeds the threshold after 28 years. TFP declines over the following decade. Capital becomes less productive so it is optimal to hold less of it, meaning lower output and optimal emissions. The choppy path of emissions after carbon overshoot reflects the economy's response to the continual productivity damage. The same adjustments are present in all other variables, but their relative scale means they are difficult to see for capital and carbon stock, Figures 3.2(a) and (b). Following the decade-long TFP transition, the economy re-optimises capital and emissions before stabilising in about year 50. Utility drops off dramatically, caused by both threshold effects and the continued accumulation of gradual climate damages.

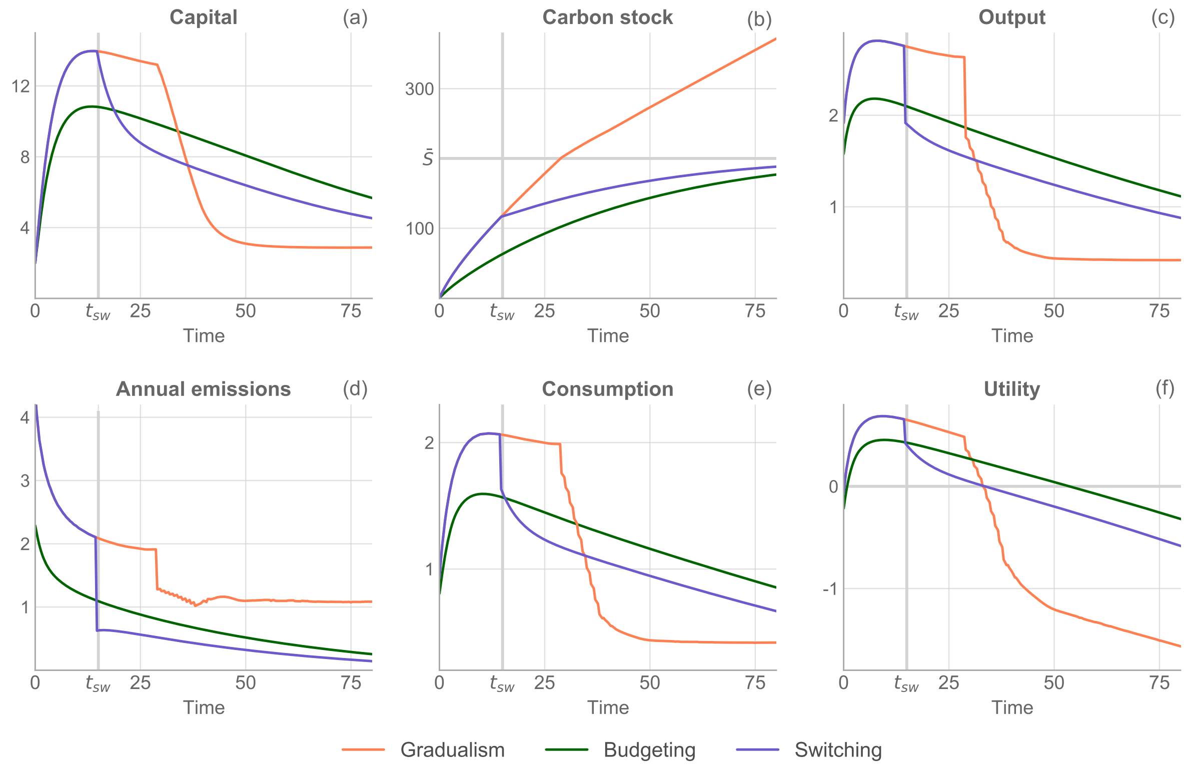


Fig. 3.2 The projected pathways for economic and physical variables over 80 years. The switching economy adjusts their policy at $t_{sw} = 15$. The initial values for capital and carbon stock are 2 and 0 respectively and set the carbon threshold ($\bar{S}$) and carbon stock budget ($S_{\max}$) at 200. Note that the model takes arbitrary units—important is that $\bar{S}$ and $S_{\max}$ are significantly lower than the unconstrained carbon stock in 2100, which is $S_{2100} = 371$ for a gradualist economy.

Implementing a carbon stock budget imposes an additional scarcity constraint over emissions. The budgeting economy therefore has lower emissions than in the gradualist economy and they decrease over time as the budget is exhausted. This constrains the economy as a whole. Output is decreasing, meaning capital stocks and consumption face a slow decline. The utility of the budgeting economy is initially lower than the gradualist and switching economies, but higher in the long run for two reasons. First, this society avoids the threshold damages that limit capital productivity, output and consumption. Second, carbon accumulation is slower so gradual damages are lower.

The economy that switches from gradualism to a carbon stock budget at time t_{sw} has higher emissions than the budgeting economy before the switch, and correspondingly higher output, consumption and utility. However, after adopting a carbon stock budget the economy is worse off because high initial emissions means more abatement is required in $t > t_{sw}$. Delaying a carbon stock budget increases its stringency when it is eventually implemented.

3.3.1 The cost of myopia

Myopia prevails in a gradualist economy. Its cost is measured by the difference in cumulative discounted utility, i.e., social welfare, until 2100 between the gradualist and budgeting economies. A carbon stock budget increases social welfare by 2.5% with respect to gradualism for the economy illustrated in Figure 3.2. This effect is small due to discounting of future utility. In 2100, nominal utility in a budgeting economy is five times that of a gradualist economy, and output is 40% higher.

Now consider the cost of delaying a carbon stock budget, as in the switching scenario. Figure 3.3 shows the difference between welfare in a budgeting economy and in an economy which switches policy after a sequence of delays. A larger welfare difference means that the carbon stock budget is more beneficial. The fundamental and unsurprising result is that the benefit of a carbon stock budget decreases the longer it is delayed. Perhaps more interestingly, the difference between welfare in the budgeting and switching economies is never negative, meaning that the initial welfare boost never outweighs the additional stringency of the stock constraint. Depending on the size of the carbon stock budget, unconstrained emissions prior to the policy switch may exceed the threshold, after which point a carbon stock budget becomes impossible and the welfare difference stabilises. The sharp spikes in Figure 3.3 arise when the switch occurs just before overshoot. At this point, the required mitigation is such that emissions must immediately fall to near zero, so a carbon stock constraint is more painful than threshold damages. As the climate threshold increases, cost of delaying the carbon stock budget declines. This is primarily because a less stringent budget means the remaining emissions after switching are higher, giving the economy more slack to emit after adopting a carbon stock budget. Discounting also has a minor effect.

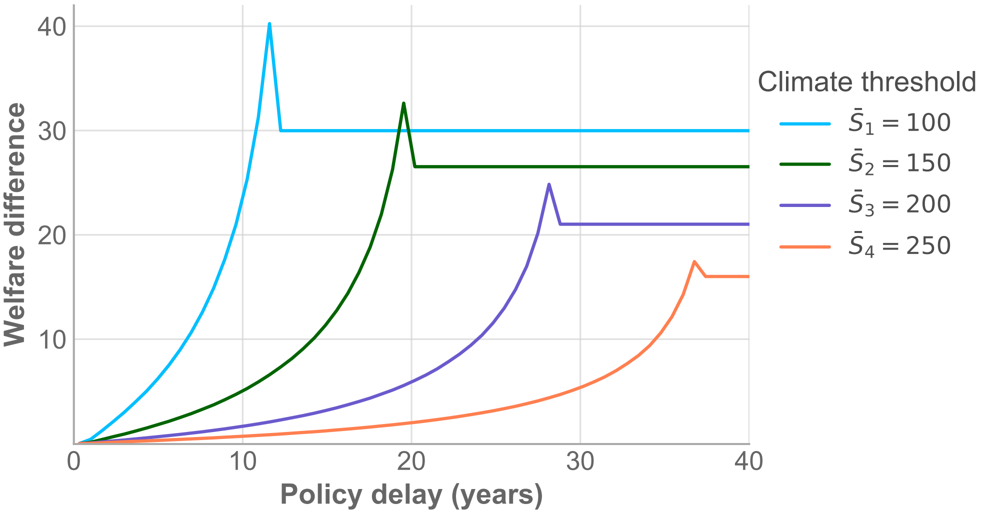


Fig. 3.3 The cost of delaying a carbon stock budget, given by the difference between the total social welfare of a budgeting economy, and the total social welfare of an economy which starts with gradualist policy and changes to a carbon stock budget after some delay.

Delaying mitigation will make it more difficult to achieve future climate targets. This is even more true for carbon stock budgets than for emissions targets, because every year of unconstrained emissions reduces the available budget. However, these results show that, even if myopia and biased beliefs slow the adoption of urgent policy, a carbon stock budget is welfare-improving. With the exception of the short period just before overshooting the threshold, it is better to switch and constrain than to continue emitting and incur threshold damages.

3.3.2 The cost of immediate action

Continued myopia is costly. However, immediate action can also be costly if a rash decision over the size of a carbon stock budget means the constraint is overly stringent. This model assumes that policymakers have perfect information over deterministic threshold damages, so set a carbon stock budget that just avoids the threshold but does not waste any pre-threshold emissions. In reality, policymakers do not know the carbon threshold, which is itself stochastic, so might ‘get the budget wrong’. Particularly in the presence of voters who are already sceptical of urgent mitigation, the risk of getting the budget wrong could exacerbate policy myopia: too lenient a budget means severe climate impacts, while imposing an overly stringent budget unnecessarily stifles the economy and reduces a politician’s chances at reelection. The cost of overestimating the available carbon stock budget is clearly high, as the economy experiences both limited emissions and threshold damages. This section assesses the impact of setting the budget too low.

Figure 3.4 gives the difference in welfare between a budgeting economy in which the budget, $S_{\max}$, takes a range of values, and a gradualist economy subject to threshold damages at $\bar{S}$. A positive welfare difference means a carbon stock budget makes the economy better off. Figure 3.4 shows it is better to apply a carbon stock budget policy even when $S_{\max}$ is significantly lower than the carbon threshold, due to the large welfare cost of overshooting the threshold. A carbon stock budget is welfare-reducing only when the allocated budget is less than half the actual climate threshold. The gradient of the curves decreases at higher thresholds because the gradualist economy has more time to accumulate output, consumption and welfare before the carbon threshold is breached.

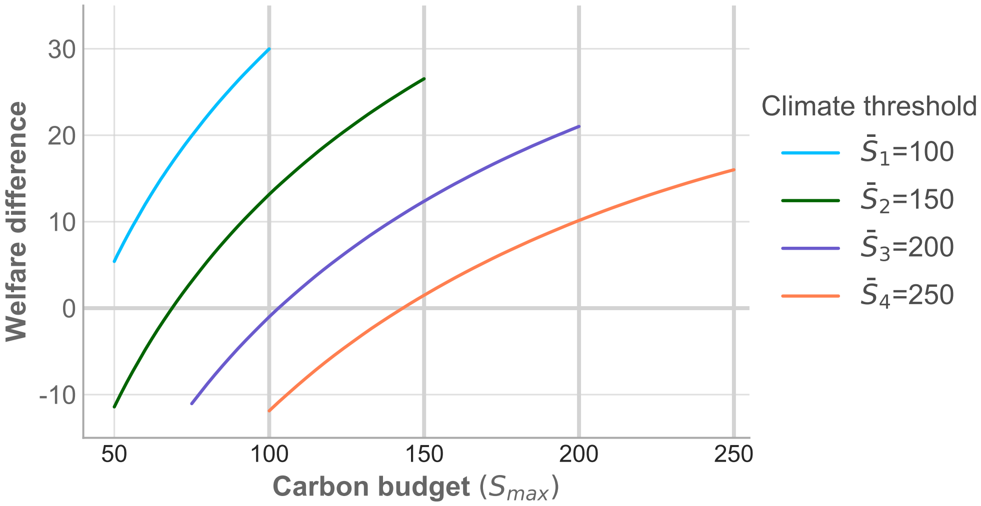


Fig. 3.4 The cost of getting the budget wrong, given by the difference between the total social welfare of an economy under a budging economy with budget size $S_{\max}$, and that of a gradualist economy subject to threshold damages at $\bar{S}$.

Being wrong about the threshold makes the economy worse off, but not as badly off as ignoring it entirely. Even an overly stringent carbon stock budget yields social welfare higher than in an unconstrained economy that overshoots the carbon threshold. While this simple model makes abstractions, its results shows that concern about getting the budget exactly right should not be allowed to slow climate policy—and that, when policymakers need to select policies with imperfect information about threshold risks, it is better to err on the side of caution.

3.4 Discussion

This section considers the challenges of implementing a carbon stock budget, and assesses the limitations of this research.

3.4.1 Implementing a carbon stock budget

A carbon stock budget is a political commitment mechanism that can also align public beliefs with scientists' understanding. Negotiating a carbon stock budget undoubtedly presents challenges, but the resulting political and societal shifts will lessen the barriers to mitigation and motivate swift decarbonisation.

International coordination

The environmental benefits of a carbon stock budget would be maximised if it were multilateral. A global budget would eliminate the carbon leakage that occurs when production and the resulting emissions shift across borders to avoid regional climate constraints. The patchy track record of international climate treaties suggests international coordination will be challenging. Creating a sense of urgency is critical, both amongst policy negotiators and the public. Speedy negotiations will be supported by a shift in public opinion towards more urgent mitigation (Howe et al., 2015), accelerated by budget-based climate messaging.

A major barrier to timely multilateralism is achieving consensus on the equitable distribution of a carbon stock budget. The United Nations (1992) states that developed nations have a responsibility to ensure equitable climate management. At the same time, treaties need to be sufficiently appealing to all countries—developed and developing—to cover a meaningful share of global emissions (Barrett, 2005).

International treaties can be designed to overcome such barriers. Participation in a global carbon stock budget would be necessarily voluntary (there is no global enforcement authority), but responsibility could be allocated in such a way as to induce compliance. Developing countries have contributed less to today's carbon stock and lack the resources for a swift transitions, so could be allocated a disproportionate share of the budget. Developed countries—many of whom have signalled their rosy climate intentions with net zero pledges—could be induced to cooperate by the promise of international coordination. Quotas could be transferable between countries, both to increase their political acceptability and ensure abatement occurs where it can be achieved most cheaply (Baumol and Oates, 1971).

Allowing climate treaties more 'bite' would help a carbon stock budget overcome policy myopia. This could mean creating mechanisms to sanction countries who overshoot their agreed target. It could also mean imposing uniform tariffs on non-participating countries, proposed by Nordhaus (2015) as a way to eliminate free riding in international climate negotiations. Enforcement mechanisms can accelerate decarbonisation. They must be deployed with care so as not to undermine improvements to living standards in developing economies.

The role of climate science in climate policy

Climate scientists can support the implementation of a carbon stock budget by collectively presenting a 'best guess' for the global budget. Ambiguous policy recommendations can facilitate myopia if politicians use doubt to avoid creating binding commitments (Geden, 2018). While climate uncertainty is undeniable, providing a single recommendation on the level of the carbon stock budget would concentrate political effort and public support.

Some argue for allowing budget adjustments in response to technological progress (Fitzpatrick and Kelly, 2017). However, any gains are eliminated if flexibility renders a budget toothless in terms of mitigation ambition. When implementing a budget—and doing it swiftly—is more important than getting it right, as this analysis shows, a consistent recommendation from scientists will accelerate the adoption of a carbon stock budget.

Framing carbon stock budgets as a precautionary policy to prevent large threshold damages provides another opportunity for scientists and science communicators to support urgent mitigation. This thesis argues for the optimality of a carbon stock budget in the presence of threshold risks, which could precipitate significant, irreversible climate damages (Hoegh-Guldberg et al., 2018). The risk of abrupt climate catastrophe can prompt timely mitigation in theoretical models (Karp and Tsur, 2011). Threshold risk framing has also been shown to strengthen cooperation in an experimental setting (Barrett and Dannenberg, 2014). However, threshold risks are rarely discussed in domestic policymaking. Describing carbon stock budgets as a signal for an abrupt and catastrophic threshold could emphasise their importance to politicians and the public.

Heuristic value of a climate budget

A carbon stock budget will motivate consequential climate action, some of which will be disruptive to markets and lives. Here the heuristic value of carbon stock budgets is important: messaging based on carbon stocks is an accessible way to redefine climate risks. A carbon stock budget appeals to the common practice of household budgeting by emphasising the risks of 'overspending' our atmospheric resources. It highlights the opportunity cost of emissions—spending the budget today means carbon austerity in the future. A target based on carbon stocks rather than annual emissions can concrete the impact of individuals' choices, by allowing them to tally their impact against the remaining per capita budget.

Moreover, public perceptions of threshold risks could incentivise rational climate beliefs. The potential for abrupt damages has been shown to increase the propensity to act in the interests of the greater good (Barrett and Dannenberg, 2014). If individuals recognise the potentially life altering impacts of climate tipping points, the perceived private cost of climate denial will increase. Returning to the theory of rational irrationality, they will then hold less biased beliefs over the urgency of mitigation and be more likely to support proclimate politicians and adopt emissions-reducing lifestyle changes. Public support is key to farsighted policies, and climate communicators should focus on threshold risks and carbon stock budgets.

3.4.2 Limitations

The model presented in Section 3.2.2 deliberately abstracts from a number of climate complexities to present a simple illustration of the impacts of damage thresholds and carbon stock budgets. Here the assumptions over climate dynamics and uncertainty are explored.

Climate dynamics and extreme damages

The model assumes that damages result directly from changes in the carbon stock. More complex economic models of climate change, including the widely-used DICE model (Nordhaus, 2017), have a climate module to estimate temperature changes from carbon stocks. Temperature then dictates socioeconomic damages. For simplicity, this model uses carbon stocks to proxy the temperature change which affects societal welfare, an assumption supported by current scientific understanding (Matthews et al., 2009). However, the relationship between stocks and warming changes at very high cumulative emissions (Herrington and Zickfeld, 2014) and possibly when annual emissions are very low (Sanderson, 2020). This means the use of stocks to proxy temperatures may break down at the extremes, but remains valid for the majority of emissions levels in this study.

DICE has received criticism for its optimistic assumptions about extreme climate change. In DICE, damages are determined by the relationships between emissions and temperature and between temperature and socioeconomic damages. Simultaneous changes in these relationships yield severe damages but individual changes do not, meaning that catastrophic risk rarely translates into catastrophic outcomes (Ackerman et al., 2010). Another approach to extreme damages is introducing non-linearities into the damage function (Lenton and Ciscar, 2013). Abrupt threshold damages can outweigh the impact of continuous damages (Gjerde et al., 1999) and imply that limiting total emissions is optimal (Tsur and Zemel, 1996). While most studies consider damage directly in the welfare function, abrupt damages to capital stocks have lasting impacts on growth (Kopp et al., 2012). In this thesis, gradual damages do not affect production because they are anticipated by firms who can adjust capital and supply chains. Abrupt damages are unexpected (unless, as in the budgeting economy, they are recognised and avoided), so impose costs directly on unsuspecting producers.

Uncertainty

Much of climate science is inherently uncertain, and a significant literature explores the implications of uncertainty on estimates of climate damages (e.g., Ikefuji et al., 2020; Lemoine and Rudik, 2017; Weitzman, 2009a). This model assumes deterministic damages, admittedly a significant abstraction but one that does not materially change the results. There are two major sources of uncertainty in this model.

First, the effect of threshold damages on society is highly uncertain. This uncertainty will not affect results if the potential severity of damages means the decision to impose a carbon stock budget is unchanged, even when risks are uncertain. With sufficiently severe threshold damages, a carbon stock budget remains optimal. Current evidence predicts that impacts of continued warming would be significant (Hoegh-Guldberg et al., 2018), suggesting that this condition is satisfied. Moreover, uncertain catastrophic risks have been shown to increase cooperation on urgent climate action (Barrett, 2013; Barrett and Dannenberg, 2014), a result that strengthens the optimality of a carbon stock budget. The gradualist economy does not foresee threshold damages so uncertainty would not affect their decisions.

Second, the relationship between carbon accumulation and threshold damages is uncertain. Tsur and Zemel (1996) show that an uncertain threshold means carbon concentration converges in an interval between the optimal threshold without uncertainty and the level at which stabilisation becomes unduly harmful to future generations. In effect, this model's policymaker identifies this interval and selects a budget within its bounds. Previous studies have shown show that a stochastic threshold prompts more stringent climate policies (Lemoine and Traeger, 2016; van der Ploeg, 2014), indicating that uncertainty would induce a stricter carbon stock budget, reducing the welfare gains from limiting emissions but still avoiding threshold damages.

3.5 Summary of findings

Climate action is curbed by political shortsightedness and biased public beliefs. This chapter tied together theories of policy myopia and rational rationality to consider political barriers to urgent climate policy. It considered why politicians seem unable to support ambitious climate rhetoric with meaningful action. It also addressed the effect of biased climate beliefs on voter behaviour, and how that could impact political incentives.

A simple economic model under assumptions of both gradual and abrupt damages was presented. Its results showed that a carbon stock budget increases long-run nominal output by 40% compared to a policy focusing on gradual damages, despite restrictions on economic activity. Given the added impact of high threshold damages, a budgeting economy is five times better off than its myopic counterpart in nominal terms by 2100. Moreover, this welfare advantage is robust to errors in selecting the magnitude of the budget. The welfare impacts of a budget become negative only when the allocated budget is less than half of the carbon stock remaining before the threshold at which catastrophic damage occurs. This shows that an overly stringent carbon stock budget is better than no budget at all.

To conclude, this chapter illustrates that the reluctance to pursue consequential abatement today is increasing tomorrow's mitigation burden. This can be ameliorated by setting a target to limit total future greenhouse gas emissions, known as a carbon stock budget. The climate science literature has established that limiting the accumulation of carbon stocks would reduce peak warming and lessen the risk of abrupt climate catastrophes. This thesis contributes a political argument to this consensus: a carbon stock budget would also act as a commitment mechanism to limit myopia, and offers the relatable concept of budgeting as a heuristic tool to increase voter support for more urgent climate policy.

Chapter 4

Measuring historical social and technological transitions

The research in this chapter addresses *Research Question 2*:

What can history tell us about the speed of technological and social transitions?

Large-scale energy transitions typically occur on the scale of decades (Gross et al., 2018; Smil, 2014, see Section 2.2.2 for a full review). The abundance of research on historical energy transitions reflects the emphasis on low carbon technologies for achieving current climate targets. Most global carbon forecasts rely on swift uptake of new technologies, notably negative emissions options, to offset the bulk of remaining emissions by 2050 (Anderson, 2015). Many proposed technologies have not yet reached commercialisation.

Even achieving the necessary scale of mature technologies is an unprecedented challenge. In order to meet a 2°C temperature target, the International Energy Agency (2020) predicts that the share of low carbon generation from wind and solar needs to rise from 37% currently to 86% by 2040, despite the share increasing just 2% between 2000 and 2019. The slow diffusion of energy technologies suggests this will be challenging, even with robust and ambitious government support. Achieving net zero targets with only technological deployment is unlikely. This chapter considers whether social transitions can deliver emissions reductions by 2050.

The potential for social change to achieve meaningful emissions reductions is currently overshadowed by optimism about technologically-driven mitigation. This is partly due to a dearth of evidence about the duration of social transitions. This chapter will address this knowledge gap by comparing five energy technology transitions and seven social transitions in the last century. Detailed timelines are developed for each transition, yielding insights into the technical, political and social drivers of change. This research combines qualitative developments of transitions with time-series data for diffusion at both a global and local scale. In contrast, previous studies rely on a review of other academic reports to present a simplified timeline, and do not compare global and national commercialisation rates. The detailed chronologies are used to develop two generalised frameworks for social and technological change, and identify common features of each transition category. Finally, the durations of technological and social transitions are compared.

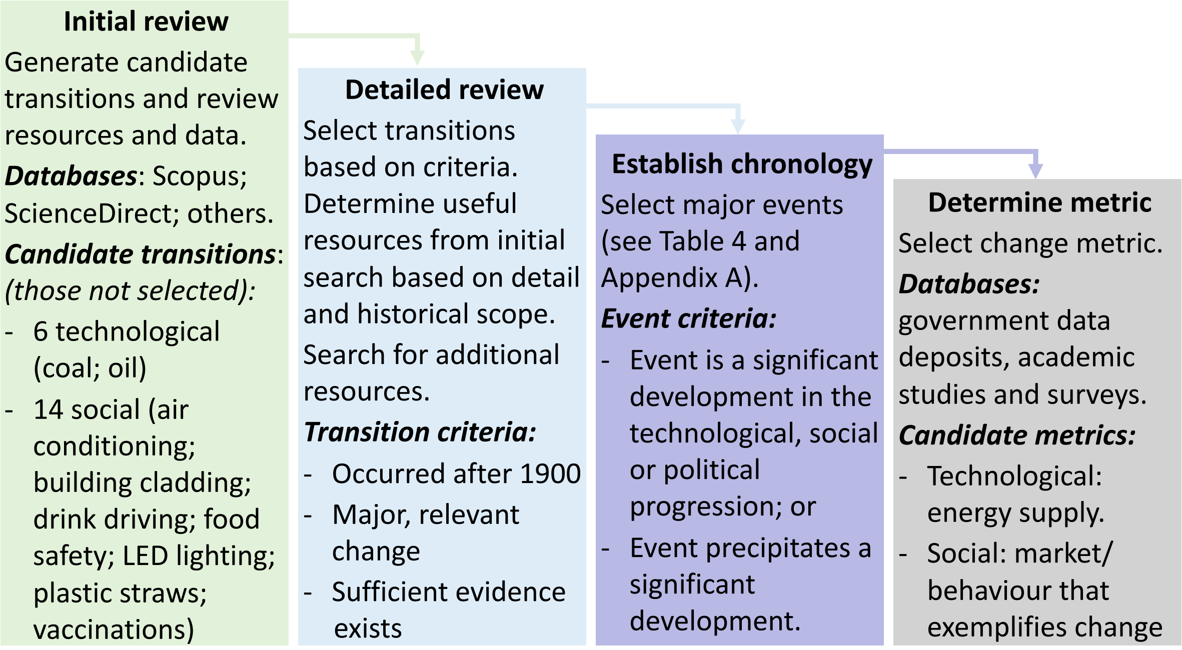
The rest of this chapter is as follows. Section 4.1 describes the methodology applied to the technological and social transitions to establish the timelines and frameworks. Evidence and data are also detailed in Section 4.1. Section 4.2 presents the results, giving the timelines of the historical transitions, presenting transition frameworks and drawing out key findings. Lessons for the future are discussed in Section 4.3. Section 4.4 summarises the findings.

4.1 Methods and materials

Technological transitions refer to the process leading to widespread adoption of a new technology to meet societal needs, catalysed by supply-side innovation (Geels, 2002). Technological transitions are usually driven by improvements to quality from better and different services, or increased profits through efficiency (Fouquet, 2010). Social transitions describe the gradual, continuous process of structural change that yields a societal state of higher quality or complexity (Roggema et al., 2012). This chapter is concerned with social transitions that change behaviours and that arise due to concern over the impact on welfare or health of an action or inaction, which shifts public beliefs and preferences. While a social transition may precipitate the diffusion of a new technology, this study reviews transitions that are catalysed by demand-side pressures rather than supply-side innovation. For example, the growth of hydrochlorofluorocarbons (HCFCs) in the 1990s was a response to concern over the effect of previously-used chlorofluorocarbons (CFCs) on the ozone, rather than any commercial or technical advantage of HCFCs.

4.1.1 Qualitative and quantitative review of historical transitions

The review of technological and social transitions draws on contemporary resources and ex post evaluations. The research process for the review is illustrated in Figure 4.1.



Initial review

Generate candidate transitions and review resources and data.

Databases: Scopus; ScienceDirect; others.

Candidate transitions: *(those not selected):*

- 6 technological (coal; oil)
- 14 social (air conditioning; building cladding; drink driving; food safety; LED lighting; plastic straws; vaccinations)

Detailed review

Select transitions based on criteria. Determine useful resources from initial search based on detail and historical scope.

Search for additional resources.

Transition criteria:

- Occurred after 1900
- Major, relevant change
- Sufficient evidence exists

Establish chronology

Select major events (see Table 4 and Appendix A).

Event criteria:

- Event is a significant development in the technological, social or political progression; or
- Event precipitates a significant development.

Determine metric

Select change metric.

Databases: government data deposits, academic studies and surveys.

Candidate metrics:

- Technological: energy supply.
- Social: market/ behaviour that exemplifies change

Fig. 4.1 The evidence review undertaken to establish the chronology of events for transitions.

Sample selection

The first stage of the research process yielded a set of candidate transitions (unsuccessful candidates are given in Figure 4.1). Technological candidates were drawn from the literature of large-scale energy transitions, primarily Smil (2014) and Gross et al. (2018). The literature on climate-relevant historical social transitions is incomplete, so candidates were compiled based on their similarity to proposed future transitions. For example, smoking provides insight for changes in societal expectations of ‘good behaviour’—possibly charting a similar path to future transitions in flying or meat eating.

From the candidates, transitions are selected based on three criteria. First, the review is limited to those transitions occurring since 1900 CE. While some existing studies on energy transitions cover transitions as early as 700 CE to assess the first mover advantage across evolving contexts (e.g., Fouquet, 2010), this study follows Gross et al. (2018) in assuming that transitions involving the electricity grid-—all occurring since 1900—provide the most relevant insights for future decarbonisation. For social transitions, increasingly interconnected social networks means that changes before 1900 are unlikely to reflect the patterns of coordination and persuasion that define norm change in the 21st century (Dellavigna and Gentzkow, 2010). This criteria therefore selects historical transitions for which the market and society are most similar to present conditions.

Second, this review concerns transitions which involved major market or behavioural change comparable to those being suggested as necessary for a low carbon economy. For technological transitions, this narrowed the pool to energy technologies, which disrupt a large essential market and are likely to play a large role in 21st century decarbonisation. For social transitions, the sample is limited to cases in which pre-transition behaviour was significantly lower than optimal, and for which changes were made for the ‘greater good’ rather than self-interest.

Third, transitions are selected for which there was sufficient evidence to build a detailed timeline and measure technological or behavioural adoption. Where possible transitions for which there is existing research on the transition duration are chosen, allowing for corroboration and contrasting of results. This condition was easily met for technological transitions, due to the abundance of energy-related data and research. Evidence was more sparse for social transitions, and an original list of 14 candidates was narrowed to seven based on the availability of data. No existing studies which systematically estimate the duration of social transitions were uncovered.

Historical transitions

This chapter reviews twelve transitions, summarised in Table 4.1, ten of which have progressed sufficiently to allow detailed review of their chronologies and adoption. Two transitions, carbon capture and storage (CCS) and electric vehicles, are in the early stages of transitions and will be considered separately in this analysis. Each timeline is separated into global technological or social developments, and national policy developments. The selected countries were leaders in the transition, or experienced an exceptional rate of change. All four energy transitions are also studied in Gross et al. (2018), and wind and solar are reviewed by Smil (2014). The final step in the review was to determine metrics that measure the progression of the transitions. These metrics are given in Table 4.1.

Table 4.1 The historical transitions assessed in this research.

Transition	**Geography**	**Change metric**
Technological transitions		
Nuclear energy	France	Supply (TWh and proportion of total)
Solar power	Germany	Supply (TWh and proportion of total)
Wind energy	Denmark	Supply (TWh and proportion of total)
Combined-cycle gas turbines	United Kingdom	Supply (TWh and proportion of total)
CCS (early stage)	United Kingdom	Capture rate ($MtCO_2$/year)
Social transitions		
Asbestos	United Kingdom	Consumption (thousand tonnes)
Ozone depleting substances	United States	Production (thousand tonnes)
Smoking	United Kingdom	Proportion of adults that smoke (%)
Seat belt wearing	Australia	Rate of seat belt wearing (%)
Central-city congestion	London, UK	Traffic counts (number of cars)
Leaded petrol	United States	Proportion of petrol containing lead (%)
Electric vehicles (early stage)	Norway	EV market share of passenger cars (%)

TWh = terawatt hour. CCS = carbon capture and storage. $MtCO_2$ = megatonnes of carbon dioxide.

Market supply data for technological transitions

This study measures the deployment of technology using market supply. This differs from Gross et al. (2018), who measure progress with installed capacity. However, supply provides a more comparable and relevant metric, particularly for wind and solar, which typically supply energy equivalent to less than a quarter of their capacity (BP, 2019). As in Smil (2014), this study also reports supply as a proportion of the global or national electricity supply, in order to provide a comparison of the scale of deployment in each jurisdiction.

This chapter relies heavily on the *Statistical Review of World Energy* (BP, 2019) for energy supply data. The *Review* provides country-level and international generation data from 1965 for nuclear, solar and wind energy. For nuclear, there was some commercial generation from 1959, however the generation capacity was very small, at 233 megawatts electric (MWe) (World Nuclear Association, 2020b). Generation data from 1965 is therefore accepted for nuclear. For CCGT in the UK, generation data are provided by BEIS (2019a). Data on global supply from natural gas do not disaggregate into generation in CCGT or other technologies. While it is likely that the majority of natural gas generation uses CCGT due to its superior efficiency (Vatopoulos et al., 2012), some open-cycle gas turbine plants remain in operation and contribute a significant portion to gas generation, so comparing to just gas generation would yield misleading conclusions about the deployment of CCGT. However, CCGT has been the preferred technology for gas generation since the early 1990s (International Energy Agency, 2008). To estimate CCGT generation, this study considers all gas plants commissioned after 1993 (drawn from Global Energy Observatory et al. (2018)) and assumes that 90% of these plants use CCGT technology. This allows for estimation of the global supply from CCGT and enables comparison of the UK's rapid deployment to global CCGT growth.

Technologies' generation is calculated as a proportion of total electricity generation. For solar and wind, total generation data is drawn from BP (2019). However, these data are reported from 1985, so do not cover the first two decades of nuclear generation in France. Instead, The World Bank (2020) *World Development Indicator* is used, which provides nuclear generation as a proportion of total electricity supply from 1960 in France, and 1970 worldwide. Comparing The World Bank (2020) data to calculations from 1985 using the BP (2019) *Statistical Review*, the maximum discrepancy was 2.5%, and only seven years had a difference of more than 1%. For British CCGT, the proportion of total electricity generation was calculated using BEIS (2019a) historical data on total generation. The proportion of world electricity generated using CCGT is based on the estimation of global CCGT supply and BP (2019), finding a 2018 value of 17.7%. This is consistent with The World Bank (2020), which estimates 22.3% is generated using natural gas, and the International Energy Agency (2008) conclusion that CCGT is the dominant generation technology.

The final technological transition is CCS. This transition is still in the early stages, and the review did not uncover any data for utilisation rates of CCS plants, which measure how much of the reported capture capacity is realised. Indeed, it appears that 'capacity' and 'utilisation rate' are often confounded. For example, the Global CCS Institute (2019) reported that Shute Creek in the USA, in operation since 1986, has a 7MtCO_2/year capacity, but had cumulatively captured only 100MtCO_2—equivalent to an effective capacity of only 3MtCO_2/year and a utilisation rate of 43%.

To measure CCS deployment, this analysis uses the installed capacity and makes an assumption about how much of this capacity is utilised. It assumes a 50% utilisation rate, meaning that a CCS plant stores carbon equivalent to half its annual capacity. This rate is determined by the load factor and capture rate of the CCS plant. The load factor affects the sequestration availability. Brouwer et al. (2013) estimate the load factors of gas and coal plants fitted with CCS at between 40% and 80%. For comparison, the average load factor for wind and solar over the last ten years have been 12% and 23% respectively (calculations based on BP (2019)). The capture rate gives the proportion of CO_2 passing through the CCS plant which is sequestered. Current plants generally achieve 85-90% capture rate (Budinis et al., 2018).

Behaviour change data for social transitions

Unlike for energy transitions, there is no singular metric or global collection of data for behaviour change. This study therefore selects different metrics for each transition, and reports relevant data on a local and, where possible, global scale. Metrics are chosen that most accurately represent the choice in question. For transitions that rely on organisational decision-making rather than individual choices, or where the individual's decision is fully captured in the market, indicators of market size or share capture progress. This is the case for asbestos, ozone depleting substances, congestion, leaded petrol and electric vehicles. For smoking and seat belt use, market data such as national cigarette consumption or seat belt production do not accurately measure the prevalence of behaviour. Behavioural decisions are obscured by aggregating to a market level; for example, this study asks whether individuals wear a seat belt, rather than whether seat belts are installed. Existing studies generally rely on data obtained through surveys for smoking rates, where self-reported consumption data are reliable (Blank et al., 2016), and using road-side observation for seat belt wearing, where people typically over-report their behaviour in surveys (Zambon et al., 2008). This study follows this precedent.

Data for social transitions were relatively sparse, and sources rarely covered the whole time frame of interest. For smoking and seat belts, the majority of the studies reported only a few years of data. Where two surveys occur in the same year, the average value is taken. Data sources are merged for asbestos, ozone depleting substances, and leaded petrol. For central-city congestion, no data were available for traffic counts before 2000. However, given that the congestion zone was implemented in 2003, this was sufficient to illustrate the effect of the policy. For electric vehicles, change is measured by the proportion of the vehicle fleet that is electric. This proportion is calculated based on the size of the EV fleet in Norway and the EU (European Alternative Fuels Observatory, 2019a), and the vehicle fleet in Norway (Statistics Norway, 2019) and the EU (European Automobile Manufacturers Association, 2018).

Evidence and data processing

The data and detailed evidence used in developing and measuring progress of the transitions are given in Table 4.2. Chronologies with each event referenced individually are provided in Appendix A.

Table 4.2 The references used to build historical timelines for each of the transitions.

Transition	Data sources	Timeline sources
Nuclear energy	BP (2019); The World Bank (2020)	World Nuclear Association (2020a); World Nuclear Association (2020b); World Nuclear Association (2020d); Hayashi and Hughes (2013)
Solar power	BP (2019)	Green (2005); Sabas (2016); Jacobsson et al. (2004); Brown and Hendry (2009); Frondel et al. (2010); Pfeiffer (2010); Leiren and Reimer (2018)
Wind energy	BP (2019)	Jones and Bouamane (2011); IRENA and GWEC (2013); UN ESCAP (2012)
Combined-cycle gas turbines	BEIS (2019a); Global Energy Observatory et al. (2018)	Watson (1997); Kern (2012); Watson (2004); of Lords (2018); Eckhardt (2013); Colpier and Cornland (2002); Winskel (2002); BEIS (2019a); U.S. Chemical Safety and Hzard Investigations Board (2010); International Energy Agency (2008)
Carbon capture and storage	IEA (2016); Global CCS Institute (2019); Global Carbon Project (2020)	Rochelle (2009); IEA (2016); MIT (2016); Herzog et al. (1997); IPCC (2005); Kerr et al. (2009); Department of Energy and Climate Change (2012); Kern et al. (2016); Global CCS Institute (2019); BEIS (2018); Stark and Thompson (2019); Drax Group (2019)
Asbestos	USGS (2018); Virta (2006)	Bartrip (2004); Oracle Asbestos (2020); Allen et al. (2017)
Ozone depleting substances	UNEP (2015); Hoffman (1987)	Solomon (1999); Morrisette (1989); Molina and Rowland (1974); Haas et al. (1993); Environmental Protection Agency (2020)
Smoking	Wald and Nicolaides-Bouman (1991); Office for National Statistics (2018); NHS Digital (2018); Office for National Statistics (2019b); The World Bank (2020)	Proctor (2012); ASH (2017); Doll and Hill (1954); World Health Organization (2003)
Seat belt wearing	Milne (1985); Diamantopoulou et al. (1996); Pederson and Mahon (1983); O'Hara et al. (1987); Arup (1988); Reark Research (1989); Carter (1979); Pennay (2006)	Ronan (1979); Kashyap et al. (2017); Government Activities and Transportation Subcommittee (1988); Eastman (1981); Milne (1985); Volvo Car USA (2009)

Table 4.2 continued from previous page

Central-city congestion	Department for Transport (2020a)	Walters (1968); Santos et al. (2008); Leape (2006); Börjesson et al. (2012); Schaller (2010); Oxera Consulting (2018)
Leaded petrol	Newell and Rogers (2003); OECD and UNEP (1999)	Landrigan (2002); Seyferth (2003); OECD and UNEP (1999); Newell and Rogers (2003); Hagner (1999)
Electric vehicles	Statistics Norway (2019); European Automobile Manufacturers Association (2018); European Alternative Fuels Observatory (2019a); European Alternative Fuels Observatory (2019b)	Norwegian Electric Vehicle Association (2020); U.S. Department of Energy (2019); Zeniewski (2017); Ingram (2013); Steinbacher et al. (2018); Hertzke et al. (2018); Nissan (2019); Norwegian Ministry of Transport and Communications (2018)

Includes only the sources which were used directly for the chronologies or the metrics used to measure change.

4.1.2 Transition frameworks

The frameworks of social and technological transitions are based on observations across ten past examples (CCS and electric vehicles are excluded because these are early stage transitions). This study identifies stages in the adoption of the technology or idea, and maps each stage of adoption to technical, social and political advances. While there is some variability across the historical transitions, they are sufficiently uniform to identify key developments and determine where the transition can be accelerated or is vulnerable. The definitions of each stage of the technological and social transition frameworks are given in Table 4.3.

Table 4.3 How each stage of the transitions' progression is judged.

Stage	**How initial year is defined**
Technological transitions	
No supply*	Year that key scientific advance is discovered
Limited non-market supply*	Year of first technology demonstration
Rapid growth	Year of first commercial installation
Maximum deployment rate	Peak of 3-year moving average for year-on-year supply growth rate
Slowing growth	3-year moving average of year-on-year supply growth remains below 20% of peak for 5 or more years
Market saturation	3-year moving average of year-on-year supply growth remains below 1% for 5 or more years
Social transitions	
No change*	Year of first evidence that behaviour is not optimal.
Niche change*	First evidence of behaviour change in early-adopters, or desire for change (where individual change is not possible).
Tipping point	Year of first policy that enforces change, strongly incentivises change or proposes ban.
Saturation	Encouraged behaviours (seat belts): the change achieves 90% of maximum rate. Discouraged behaviours (asbestos, leaded petrol, ozone depletion, congestion, smoking): behaviour falls to 10% of maximum rate.

The stage is measured between the initial year of the given stage, and the initial year of the next stage.
*Geography is global.

The total transition window of this study is larger than in other studies. The transition is assumed to have started (at *no supply*) when the enabling scientific advance is made, rather than the first technical application of that advance, as in Gross et al. (2018). The start of the innovation cycle in Gross et al. (2018) is similar to the *limited non-market supply* period. Moreover, this analysis extends well past commercialisation. Where Gross et al. (2018) review past transitions up until the technology has reached widespread commercialisation (defined as achieving 20% of its maximum installed capacity), this review covers the period until the market growth rate has stabilised. In this respect, the definitions in Table 4.3 are more aligned with Fouquet (2010).

The second difference in this study's technological framework is that market expansion is defined using growth rates. Most studies define the stages of market expansion using a proportion of total market share (Smil, 2014; Sovacool, 2016), or a proportion of the technology's maximum supply (Gross et al., 2018). However, measuring transition progress using market growth relates this research to the S-curve of innovation, which illustrates that the uptake of new technologies slows as all potential adopters accept the new innovation (Brown, 1991).

For energy technologies, slowing supply growth indicates the market is nearing saturation. Moreover, this thesis is interested in energy transitions for climate mitigation, so focuses on supply growth because many carbon projections assume unprecedented (and unproven) growth rates of low carbon technologies (e.g., Global CCS Institute, 2019).

Defining the stages of social transitions is based on important chronological events and rates of behaviour change. Policy is explicitly included in the stages of social transition due to the feedback between social preferences and political decisions. Unlike technology, *saturation* is defined using absolute behaviour change rather than growth rates due to the relative scarcity of consistent data for some of the social transitions.

4.2 Results

A review of the evidence presented in Table 4.2 yields detailed chronologies for twelve technological and social transitions. Together, the timelines tell a story. Common features are identified and standardised frameworks of technological and social transitions are developed. The technological framework maps technical developments and policies to the supply of energy. The social framework maps the changes in societal perception and policy developments to the scale of observed behaviour change. These models enable comparison of the duration of each change, provide a guide for what we might see in future transitions, and identify stages where there is potential to accelerate decarbonisation or where the transition is particularly vulnerable.

Sections 4.2.1 and 4.2.2 present the results for technological and social transitions. Common features in both transitions are discussed in Section 4.2.3 and the special case of hybrid sociotechnical transitions is considered in Section 4.2.2.

4.2.1 Technological transitions

Figure 4.2 presents the timelines for the development of nuclear energy, solar power, wind power and CCGT, alongside quantitative measures of each transition's progression. For brevity, the timelines include only details of the transitional events—those that heralded the beginning of a transition stage defined in Table 4.3. Other important events are marked but not detailed in the timelines; complete timelines are given in Appendix A. Different metrics of change between technological and social transitions makes comparing their progression difficult, so global data are provided for comparison. For all four energy technologies, diffusion in the first mover country, measured by growth rate of capacity, is swifter in the first stages of deployment, likely due to a technological 'head start' compounded by aggressive policy support. However, in the transitions which have reached saturation (nuclear and CCGT), world energy markets were able to maintain a swift growth rate for longer, reflecting a larger capacity to adopt new technologies.

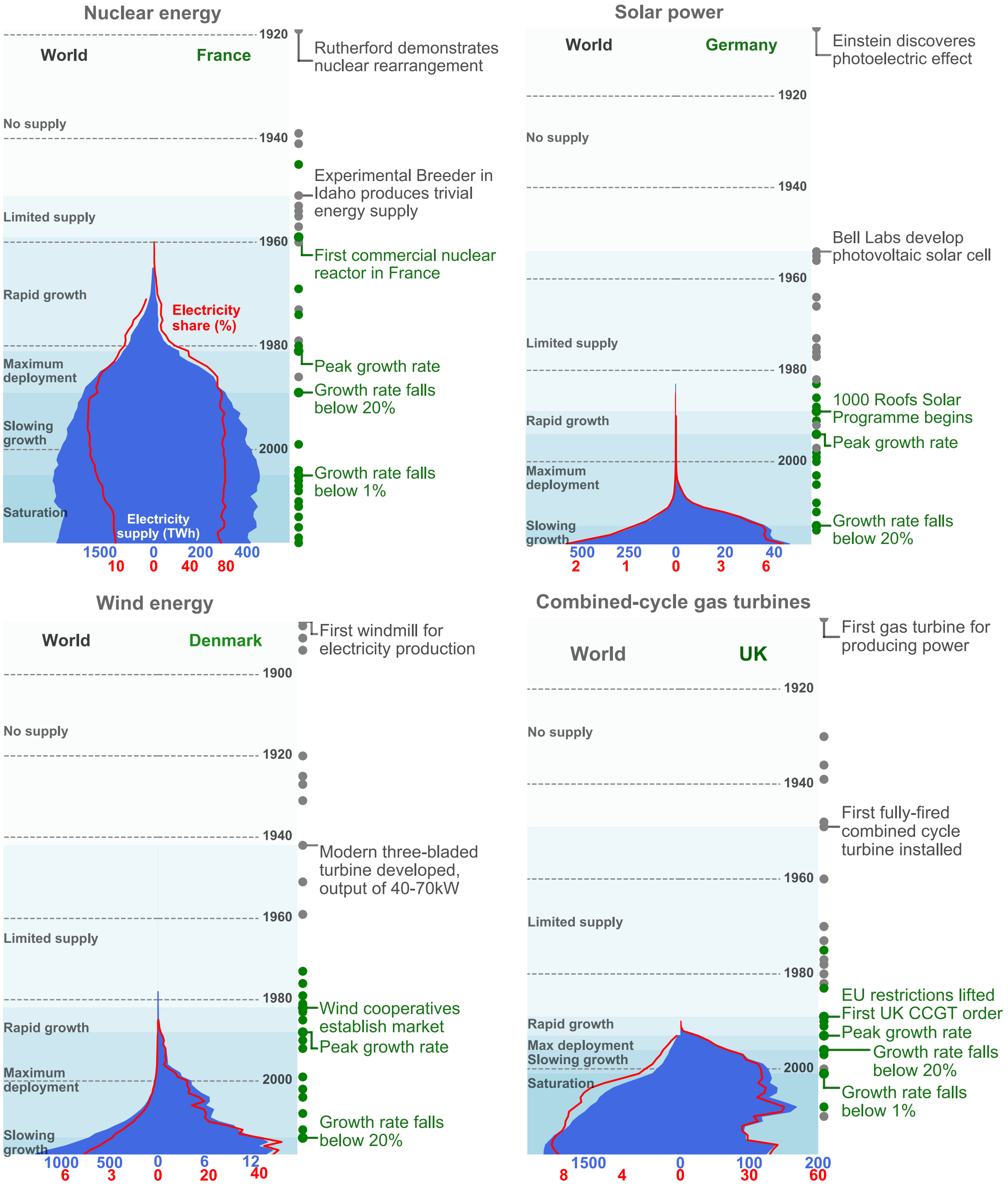


Fig. 4.2 The timelines of historical energy transitions. Global technological developments are in black text, domestic policy developments are in green. Events that begin each transition stage are given in the timelines; other events are noted with grey markers. See Appendix A for more detailed timelines and references.

Technological transition framework

Figure 4.3 presents the technological transition framework. It was developed based on the reviewed transitions. The framework outlines deployment progression, along with factors that contribute to and detract from the speed of transition. It covers the entire chain of innovation and deployment, from the initial technical discoveries to saturation of the market when the technology has reached its maximum market penetration. See Table 4.3 for definitions of the stages of market supply. The technological and policy developments jointly determine market supply.

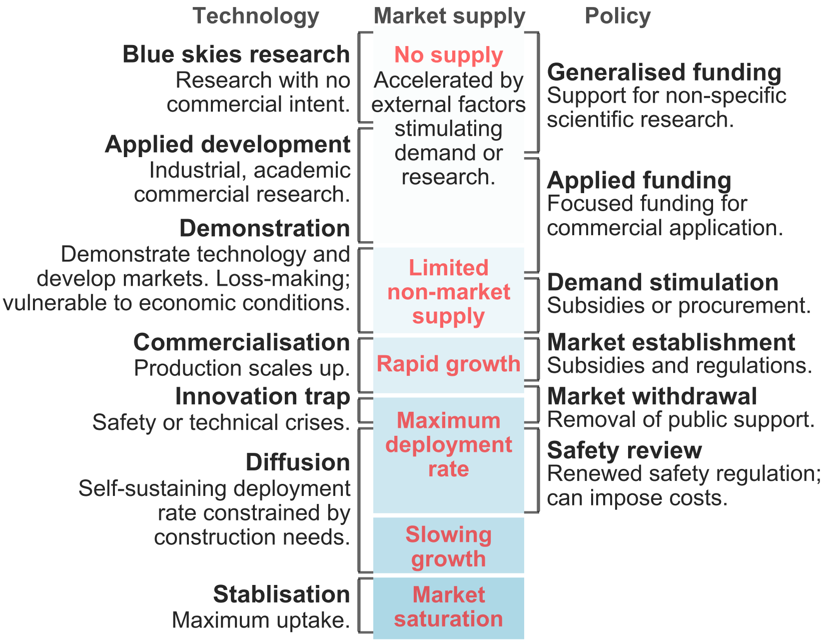


Fig. 4.3 A framework for the timeline of large-scale technological deployment in the energy sector.

External forces can stimulate or slow the progression of a transition. Events that increase the sense of urgency in the transition can accelerate the period to commercialisation. For example, blackouts during the 1960s increased demand for CCGT, which can ramp up quickly. Conversely, macroeconomic crises can distract attention and funding from energy innovation. This is particularly cogent when the market is not yet fully established and still relies heavily on government support, in the *limited non-market supply* and *rapid growth* periods. Similarly, safety crises can result in withdrawal of support from both the general public and government. A stark example of this is the global nuclear power slowdown following the Fukushima disaster of 2011 (Hayashi and Hughes, 2013). Extensive safety regulation in response to crises may slow market development in the interests of public good.

A significant factor in the absolute market change from an energy transition is the maximum deployment rate. This rate is partly determined by the capital intensity of the generation technology: how much financial investment, physical resource and time is required to develop generation infrastructure. Technologies like nuclear and CCGT require large investments, huge efforts of skilled labour, and a significant amount of time to develop generation sites, meaning that generation capacity is built up slowly over time, and government regulation is strict. Section 4.3.3 discusses these constraints in more detail. For distributed technologies such as small-scale solar and wind the capital requirements are lower and plants can be built simultaneously (Wilson et al., 2020). However, small-scale distributed generation may struggle to achieve the necessary economies of scale to enable significant and cost-effective contributions to the energy mix (Pepermans et al., 2005).

It is worth exploring the particular case of nuclear power in France. Figure 4.2 shows a very rapid transition in which a high market supply was achieved in a relatively short period. This extraordinary rate of growth was a feature of France's political landscape at the time (Boyle and Robinson, 1981). The government implemented extremely aggressive nuclear policy based on energy security that completely swamped any commercial incentives. Moreover, policymaking power is highly centralised in France, so there was no consultation with parliament or the public at a policy or project level. The result was that several nuclear plants were commissioned in the 1980s, which came online only five or six years later (World Nuclear Association, 2020b). This is very different to nuclear development in the UK, where consultation can take years. Consent for the first new nuclear site since the 1990s, Hinkley Point C, was requested in 2011, construction began in 2018, and the site is expected to be connected to the grid in 2026 (World Nuclear Association, 2020c). So while the nuclear transition in France was extremely rapid, it is unclear whether it can act as a model for future low carbon transitions in the UK or elsewhere.

Carbon capture and storage

Many commentators propose CCS as an essential component of a low carbon transition. The Climate Change Committee contend that, in order to reach carbon neutrality by 2050, the UK's CCS capability must increase from 0.00036MtCO_2 per year currently to about 180MtCO_2 per year in 2050 (Stark and Thompson, 2019). Whether that is achievable depends on where CCS sits on the technological transition pathway, and how fast it can be deployed. Figure 4.4 shows the technical and political developments of CCS. In the UK, there is only one demonstration bioenergy CCS project, despite almost 20 years of domestic policy. Globally, CCS development has inched into the *limited non-market supply* stage, but is still heavily supported by governments and is vulnerable to macroeconomic downturns.

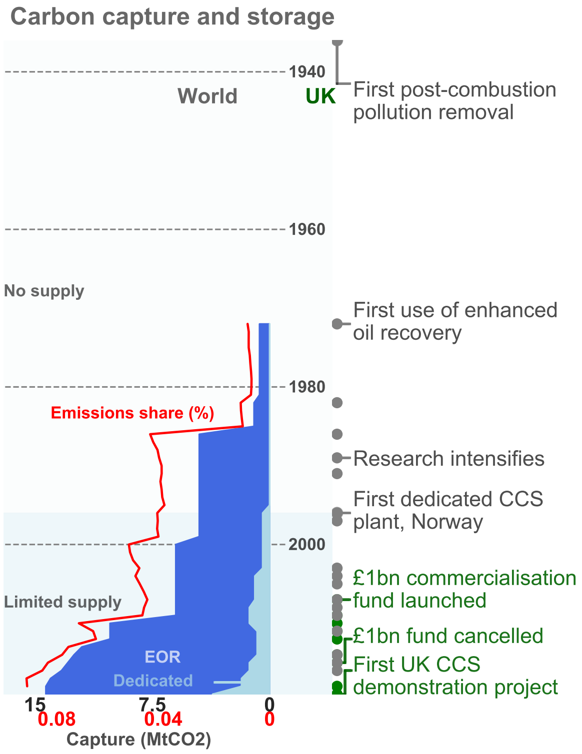


Fig. 4.4 The political and social timeline of carbon capture and storage (CCS). Global technological developments are in black text, UK policy developments are in green. This is an early stage event, so additional detail is provided. The deployment of CCS is shown by the capture of carbon from CCS plants. Only global deployment is shown: the UK has a single CCS demonstration project which began in 2019 with a capture rate of 0.00036MtCO$_2$ per year.

4.2.2 Social transitions

The timelines of the six social transitions are presented in Figures 4.5 and 4.6. Again, the timelines are distilled to only the transitional events. Data are sparse for social transitions, particularly for global behaviour change. However, the evidence is sufficient to illustrate shifts in behaviour, and to develop a social transition framework that enables comparison of transition duration.

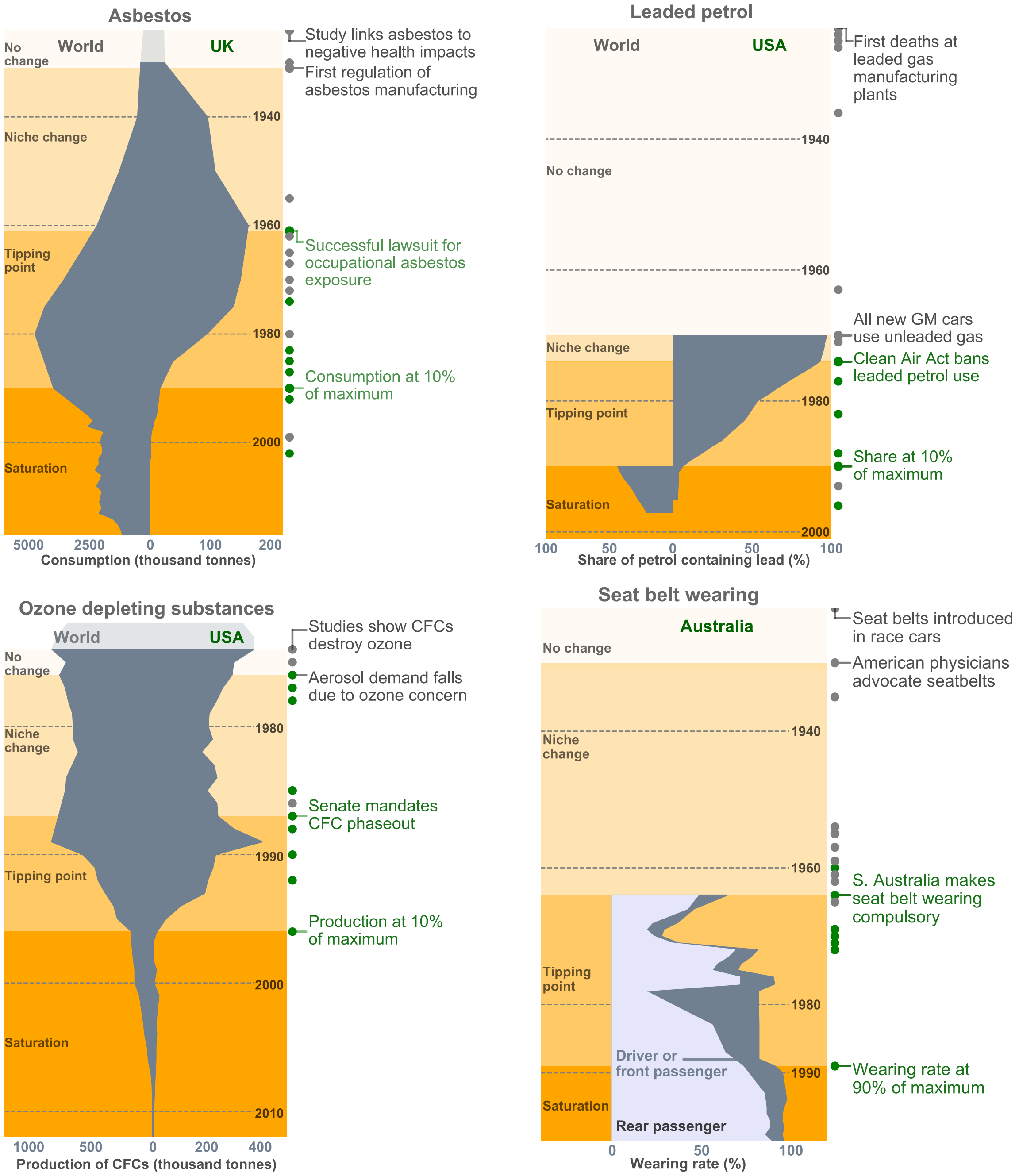


Fig. 4.5 The timelines of the historical social transitions regarding asbestos, leaded petrol, ozone depleting substances and seat belts. Global social developments are given in black, domestic policy development in green. Events that begin each transition stage are given in the timelines; other events are noted with grey markers. See Appendix A for more detailed timelines and references.

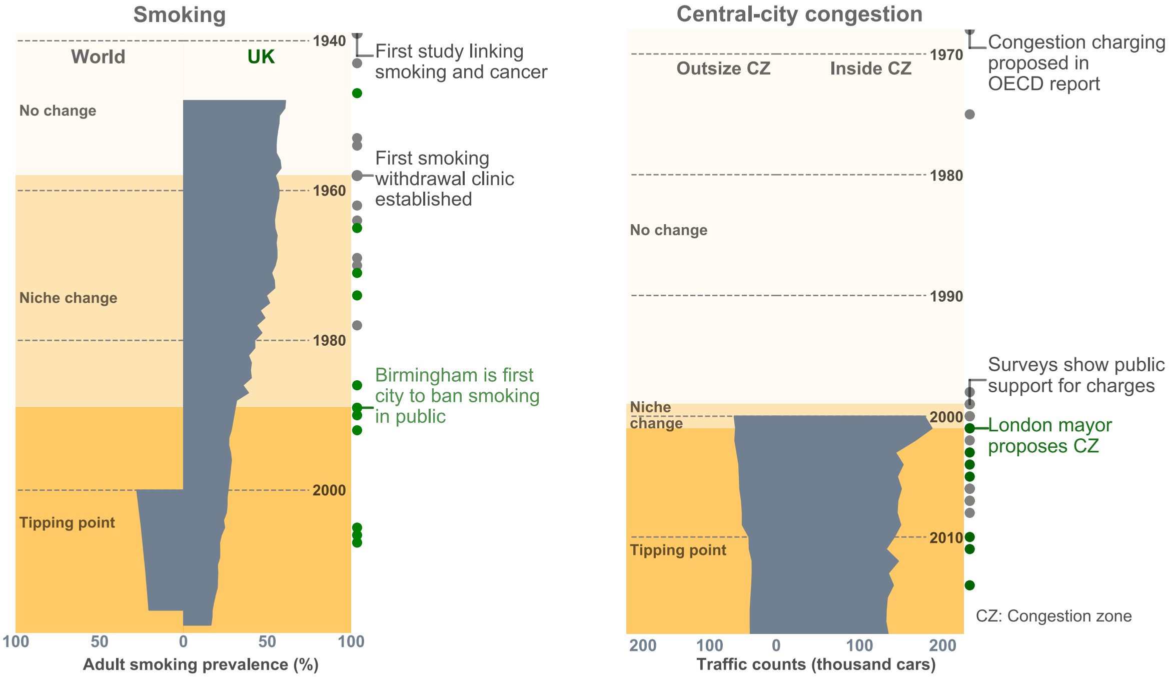


Fig. 4.6 The timelines of historical social transitions regarding traffic congestion charging and smoking.

Social transition framework

Figure 4.7 presents the framework for social transitions, mapping social and political developments to the stages of behaviour change defined in Table 4.3. Governments typically take a less proactive stance in social transitions than in technological ones. They tend to be unwilling to impose strict regulations until some threshold of public acceptance is reached: this was seen in ozone depletion, congestion, seat belt wearing (to some extent—social momentum slowed in the late 1970s), and smoking. Once a policy is put in place, it can precipitate swift change in a population already primed to adjust their behaviour: policy acts as a tipping point. This is particularly evident when transitions ‘capture the public imagination’. For example, ozone depletion was subject to huge citizen participation, in the UK and USA among others (Cook, 1990), that enabled successful international policy cooperation.

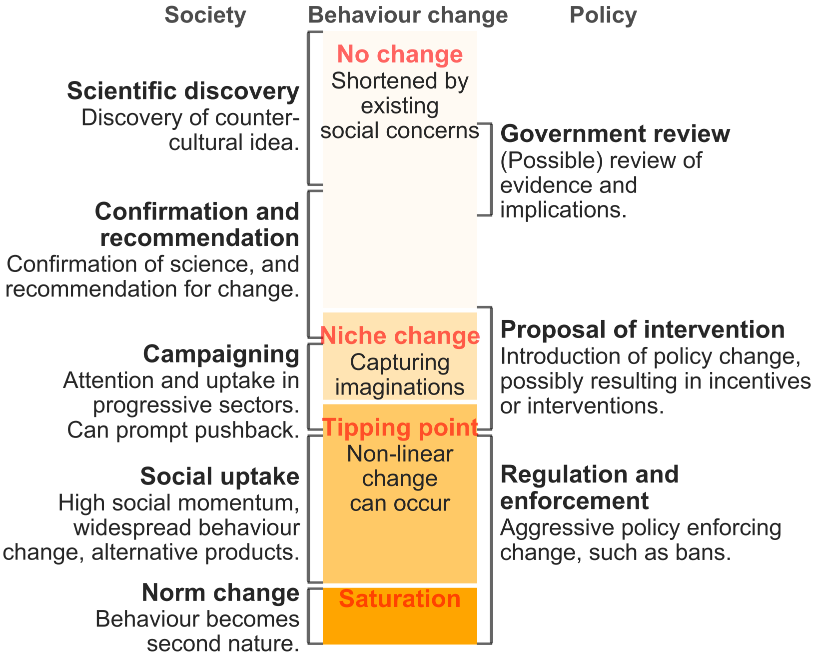


Fig. 4.7 A framework for the timeline of the social and political developments leading to widespread behaviour change.

Hybrid transitions

Some transitions express features of both technological and societal change: the uptake of new energy technologies by individual consumers. Future low carbon transitions are likely to follow a similar trajectory of social momentum and aggressive policy support. A key example of hybrid transitions is electric vehicles (EVs). Figure 4.8 reports the social and political developments in the uptake of electric vehicles in Norway. Clearly, some of this transition is social because success relies on individual consumption decisions. However, the policy developments are more similar to a technological transition. The Norwegian government heavily subsidises EVs through tax breaks, meaning that it is cheaper to own a vehicle powered by electricity than fossil fuels (Norwegian Electric Vehicle Association, 2020). EVs now constitute almost 10% of Norway's car fleet (Statistics Norway, 2019); battery and plug-in hybrid EVs last year were 56% of new car sales (European Alternative Fuels Observatory, 2019b). The market is becoming self-sustaining, and the Norwegian government is withdrawing some incentives.

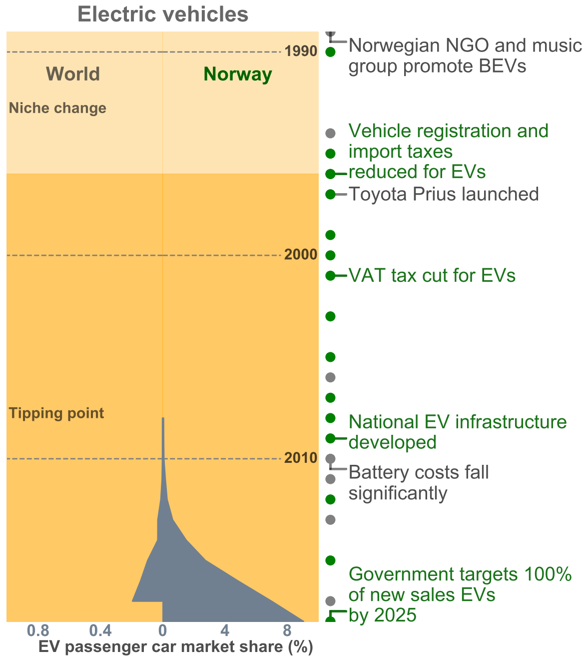


Fig. 4.8 The social and political history of electric vehicles in Norway and the world. This does not show the *no change* period, in order to highlight hybrid social and technical developments occurring in Norway. Detailed timelines and sources are provided in Appendix A.

4.2.3 Common themes

Several common themes emerge from the historical transitions reviewed in this chapter.

Cross-development accelerates change

Both energy and social transitions illustrate the impact of cross-development. If the change is related to another technological or social innovation, preceding or simultaneous, then the diffusion period is shortened. For example, nuclear power technology drew heavily on the World War II pursuit of nuclear weapons, both through research and military funding. CCGT development drew on military advances in jet engine technology. Social examples include ozone degradation and leaded petrol, which tapped into existing concerns about stratospheric degradation and local air pollution respectively. Both for technology and society, having an existing basis from which to build accelerates the transition. For energy transitions, the cause is clear—transferable technologies enable swifter development of marketable products. For social changes, a pre-existing idea appears to reduce the cognitive barriers to behaviour change and the political hurdles to institutional transformation.

Innovation trap

The innovation trap describes difficulties that arise in the rush to bring new products to the market (Kern, 2012). It is closely related to the 'valley of death', which describes the challenge of scaling from innovation to commercialisation (Weyant, 2011). This period, when the technology has been demonstrated and is theoretically market-ready, if not yet profitable, often coincides with a withdrawal of public funding, creating commercial risks and adverse incentives (Hug and Duer, 2009). Energy technologies require public support across all innovation stages from prototype to widespread deployment because of the need for system integration and infrastructure changes (International Energy Agency, 2017). For energy systems, the innovation trap can mean costly issues with new models as generation is scaled up, such as occurred in the UK's swift deployment of CCGT (Kern, 2012), or safety crises such as the nuclear meltdowns at Three Mile Island and Chernobyl (LaBelle and Goldthau, 2014).

An innovation trap is not discussed in the social change literature. However, some evidence for such an effect is visible in the timelines for ozone depletion, seat belt wearing and congestion. The behaviour change for these transitions all display short-term reversals after the start of the transition period, perhaps due to a loss of social momentum.

Vulnerability to macroeconomic conditions

Macroeconomic conditions have a large impact on transitions. Economic downturns tend to slow technology deployment, for two reasons. First, market demand for energy falls, taking prices and profitability along with it. Second, governments cut funding as money is redirected to the wider economy. For technology developers, both effects translate into fewer resources for research and development. For social transitions, economic conditions can have opposing effects. Downturns can redirect efforts away from achieving change, and make governments and individuals wary of additional costs. This is seen for example in congestion charging, when the government repealed the Western extension of the charging zone in 2010, just after the financial crisis. However, economic upturns can also stall progress by stimulating demand for hazardous products. For example, growth in the mid-1980s drove up the production of ozone depleting substances, even as the Vienna Convention called for their prohibition.

4.3 Discussion

A growing number of countries are setting targets to reach net zero emissions by 2050. This section considers whether technological and social transitions can occur swiftly enough to help achieve these net zero targets (Section 4.3.1). This depends on both the delay between conception and uptake and the potential growth of transitions, which historical evidence suggests is largely linear. These factors are discussed in Section 4.3.2. Section 4.3.3 then considers the importance of engineering and construction in technological deployment, and Section 4.3.4 discusses the extraordinary example of social transition prompted by the Covid-19 pandemic. Limitations of this study are reviewed in Section 4.3.5.

4.3.1 Comparing the duration of transitions

Comparing the duration of transitions requires mapping between the social and technological frameworks and the ten historical transitions. The transitions stages were defined in Table 4.3, and draw on both historical events and market supply or behaviour rates. For the latter stages, the growth rates of technological market supply or behaviour rates are used to identify transition points. Figure 4.9 gives the 3-year moving average of market supply growth for the technological transitions. The *slowing growth* stage begins when supply growth falls below 20% of its peak; *market saturation* is marked by the growth rate falling to 1% of its peak. These points are marked in Figure 4.9. Similarly for social transitions, *saturation* is identified when the uptake of the change reaches 90% (or falls to 10% for a ‘negative’ behaviour). This is shown in Figure 4.10. The earlier stages of transitions are identified using qualitative indicators. The events are illustrated on the timelines in Figures 4.2, 4.5 and 4.6. Further details are provided in Appendix A. This analysis yields a duration for each transition, given in Table 4.4.

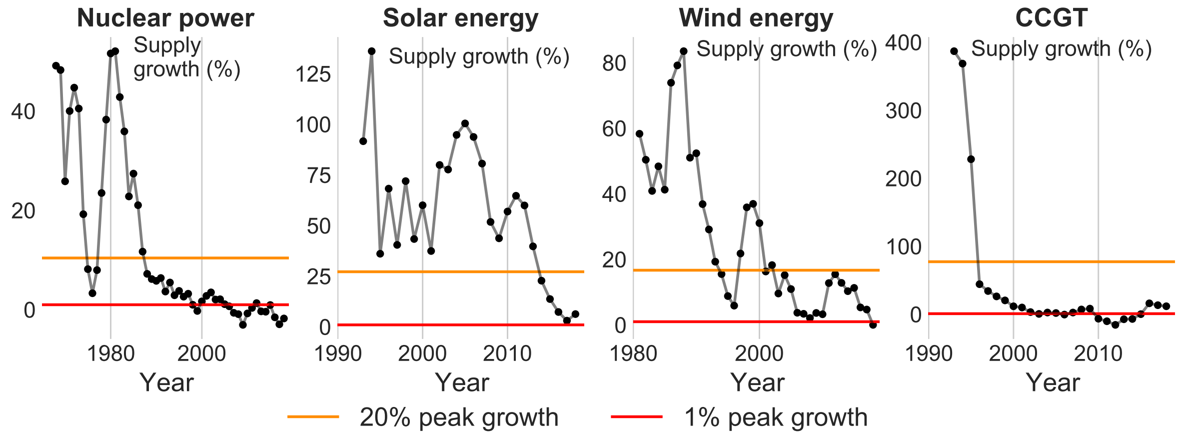


Fig. 4.9 3-year moving average market supply growth rates for the four energy technologies.

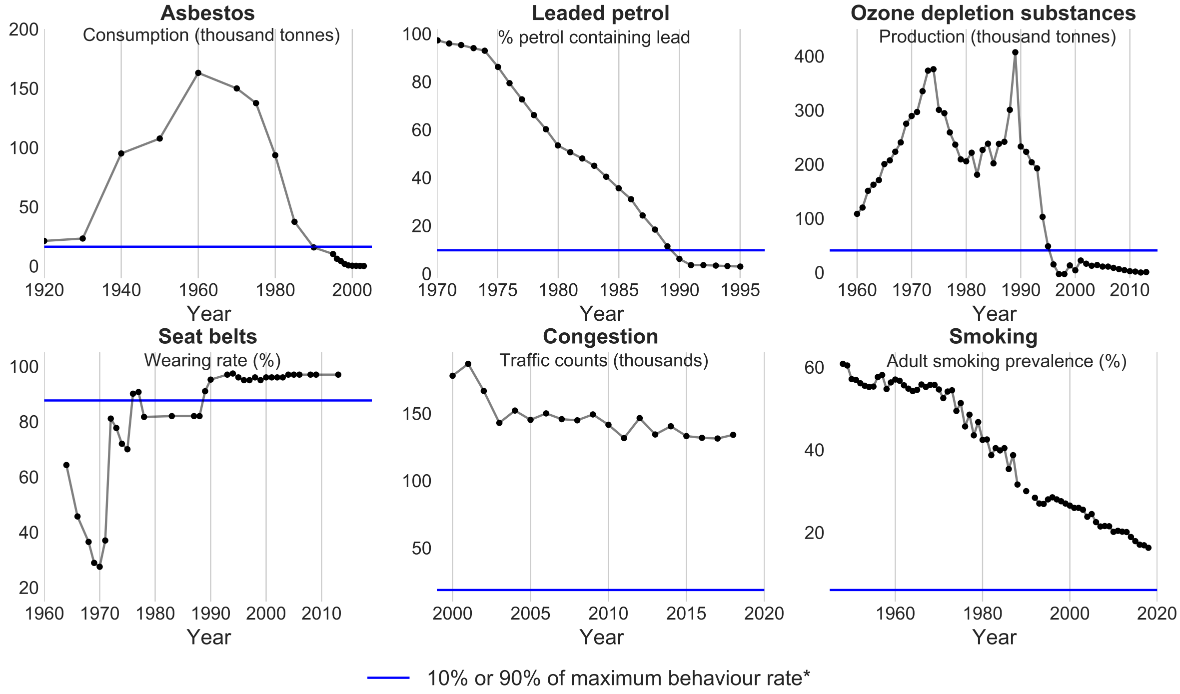


Fig. 4.10 Behaviour rates of the six historical social transitions.

Table 4.4 The duration of each stage of the transitions, in years (dates given in brackets). The events marking the start of each transition stage are defined in Table 4.3 and given in Figures 4.2, 4.5 and 4.6.

Transition			**Transition stages**			
Technological transitions						
	No supply	**Limited supply**	**Rapid growth**	**Max deployment rate**	**Slowing growth**	**Market saturation**
Nuclear	32 (1919-51)	8 (1951-59)	22 (1959-81)	8 (1981-89)	16 (1989-2005)	Stable (2005-)
Solar	49 (1905-54)	35 (1954-89)	5 (1989-94)	20 (1994-2014)	6 (2014-)	Ongoing
Wind	55 (1887-1942)	40 (1942-82)	6 (1982-88)	26 (1988-2014)	6 (2014-)	Ongoing
CCGT	44 (1905-49)	40 (1949-89)	4 (1989-93)	3 (1993-96)	5 (1996-2001)	Stable (2001-)
Social transitions						
			No change	**Niche change**	**Tipping point**	**Saturation**
Asbestos			7 (1924-31)	30 (1931-61)	29 (1961-90)	Stable (1990-)
Leaded petrol			47 (1923-70)	4 (1970-74)	16 (1974-90)	Stable (1990-)
Ozone depletion			2 (1974-76)	11 (1976-87)	9 (1987-96)	Stable (1996-)
Seat belt wearing			9 (1922-30)	34 (1930-64)	25 (1964-89)	Stable (1989-)
Congestion			31 (1968-99)	2 (1999-2001)	19 (2001-)	Ongoing
Smoking			19 (1939-58)	31 (1958-89)	31 (1989-)	Ongoing

Figure 4.11 compares the duration of each stage of the technological and social frameworks for each of the historical transitions. Social transitions typically take less time to go from the initial discovery to saturation. For transitions that have reached saturation, the average duration of the entire transition is 56 years for social, versus 91 years for technological transitions. Comparing the first two periods of each type of transition—the delay between discovery and rapid uptake—social transitions are again swifter, taking on average 38 years compared to 76 for technological transitions.

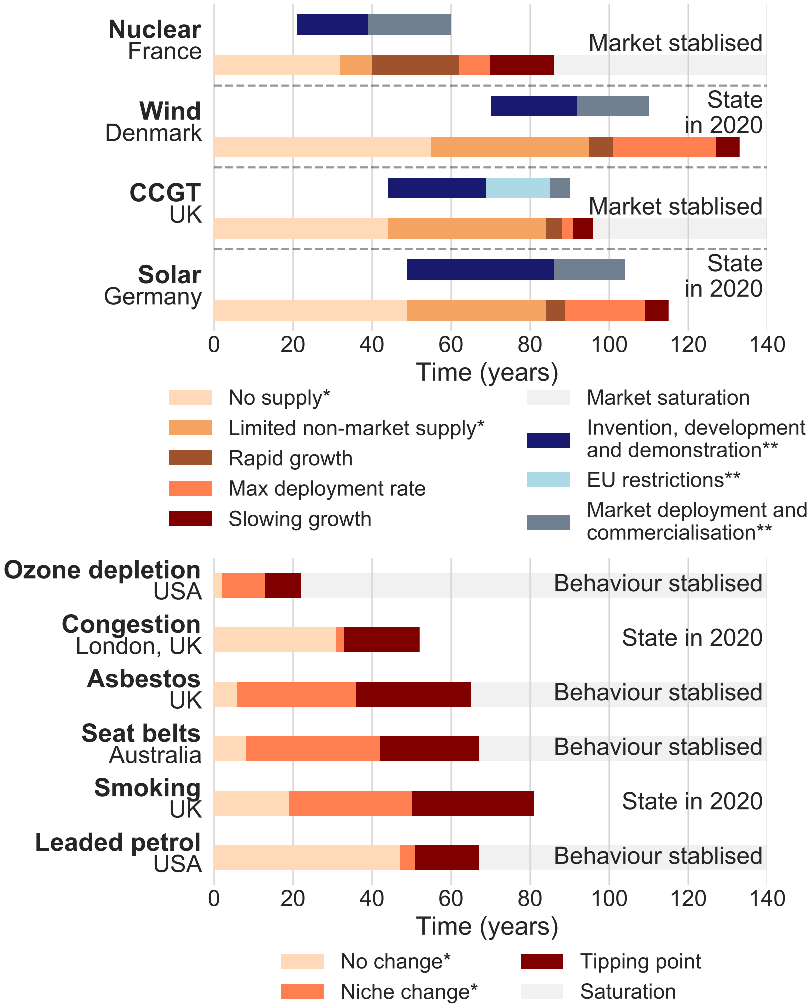


Fig. 4.11 The durations of technological and social transitions assessed in this research. * Technological transition stages *no supply* and *limited non-market supply* and social transition stages *no change* and *niche change* are identified at a global scale, while all other stages apply to national developments. ** The blue and grey bars for the technological transitions give results from Gross et al. (2018). Note that several of the transitions have not reached the final stage.

Figure 4.11 shows a discrepancy between the duration of technological transitions in this research and those from Gross et al. (2018). This study's transition stages include the full and ongoing progression of the market rather than only invention and commercialisation, more similar to Fouquet (2010), who finds an average time to market dominance of 95 years. This study's analysis, similar to Gross et al. (2018) but unlike Fouquet (2010), is undertaken at a national level (Gross et al. (2018) consider the same geographical region as this research), and in mature markets. In particular, these results do not suggest that solar and wind supply are in the *slowing growth* phase at a global scale. However, focusing on mature markets can provide an idea of how the global market might progress.

4.3.2 Z-curves of transition

The speed of transition depends both on the delay between discovery and rapid uptake, and the growth rate of the technology or behaviour once uptake begins. This is related to Brown's (1991) S-curve of diffusion. However, a major drawback of the S-curve model is that the inflection curve can only be identified in hindsight. While a transition is underway, it is unclear for how long adoption will grow and at what point the transition has reached its maximum deployment rate. This ambiguity contributes to the narrative of pseudo-exponential technological diffusion rates that fuels the reliance on large-scale energy transition for achieving net zero (e.g., Grubb et al., 2020).

The observations in this chapter support an alternative transition structure based on linear deployment: a (backwards) Z-curve of technological and social transitions. The delay period, during which the transition achieves no commercial market supply or behaviour change, constitutes the first horizontal section of the Z-curve. Once growth begins, the historical evidence reviewed here shows that—contrary to the S-curve innovation narrative—deployment swiftly settles to a linear rate and remains so for most of the growth period. The technological transitions that have reached saturation, nuclear and CCGT, demonstrate that, even if market deployment is initially exponential, it will soon become linear. This is supported by the analysis of growth rates presented in Figures 4.9 and 4.10. For technological transitions, the growth rate is initially volatile but then settles, either fluctuating around a stable average (such as for solar energy and nuclear power) or quickly moving into the slowing growth stage (such as for CCGT and, to some extent, wind energy). In general, the rapid growth period for new technologies is short relative to the entire transition period, and is followed by a period of linear deployment. For social transitions, the largely linear trends can be easily observed from the behaviour rates. This linear growth period corresponds to the upward-sloping arm of the Z-curve of transition. After the market or behaviour reaches saturation, it swiftly stabilises—giving the second horizontal section of the backwards Z-curve.

Like the S-curves of diffusion and technology, a stylised Z-curve can link transition stages to technological or behavioural adoption. Figure 4.12 presents such diagrams for the technological and social transition frameworks developed in this chapter. They are an approximation: particularly for technological transitions, the concepts of *rapid* and *slowing growth* would seem to contradict the idea of linear deployment. However, these theoretical frameworks reflect the observation that *most* transitions are *mostly* linear—and that climate rhetoric, forecasts and policy should reflect these linear constraints.

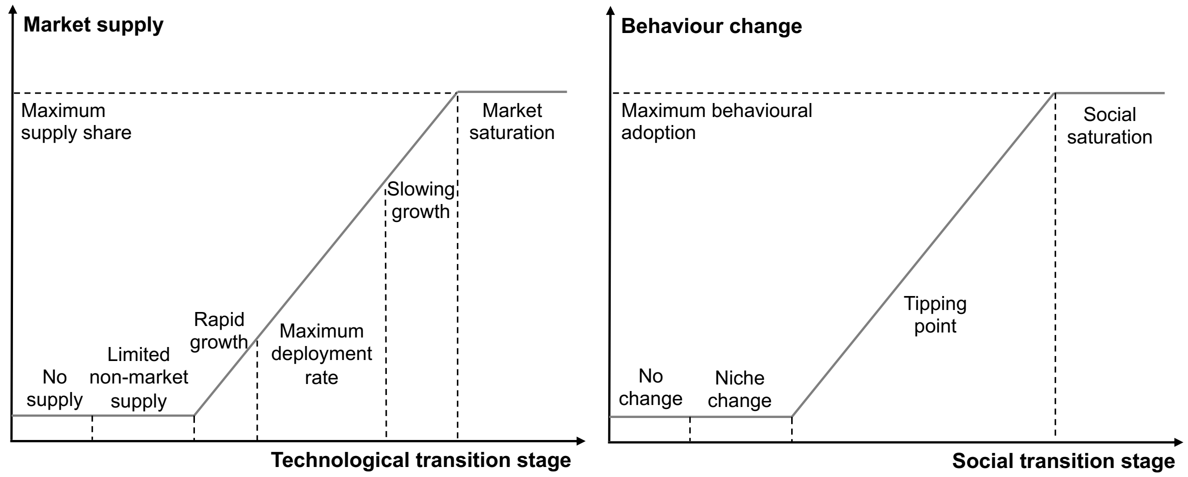


Fig. 4.12 The Z-curves of technological and social transitions, based on the concept of linear growth and the transition frameworks presented in Figures 4.3 and 4.7.

Mapping historical examples to Z-curves of transition

Historical examples can be mapped into theoretical Z-curves to compare the delay and linear growth of transitions. This requires linking the growth period with the maximum supply share or behavioural adoption for each transition, as well as identifying the delay period. The shape and average growth rate drawn from these stylised curves depends on which stages are included in the growth period. Consistent with Figure 4.12, this analysis first considers Z-curves with all growth stages included in the linear arm—*rapid growth*, *maximum deployment* and *slowing growth* for technological transitions, and *tipping point* for social transitions. The implications of alternative growth periods are discussed below.

Figure 4.13 plots stylised Z-curves for eleven transitions at a national and global scale. For technological transitions (above the horizontal axis), the scale of the transition is captured by the proportion of total electricity supplied by that technology in their respective markets. For social transitions (below the horizontal axis), it is measured using change in each relevant behaviour. Transitions without a horizontal portion after the growth period are ongoing.

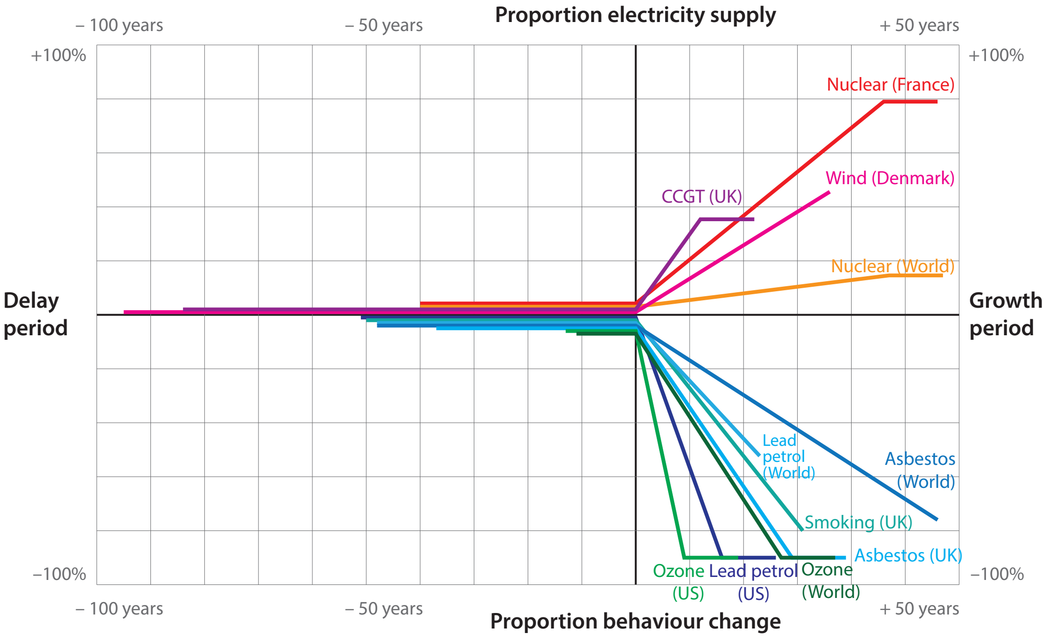


Fig. 4.13 Summary of the progression of transitions, illustrated by the delay period, between initial discovery and rapid uptake (identified by the *rapid growth* or *tipping point* stage), and the growth period which ends at *saturation*.

Figure 4.13 includes transitions which have reached saturation, and which appear to be close to saturation (wind (Denmark); smoking (UK); asbestos (world); leaded petrol (world)). For some, this required defining transition stages at a world scale. World delay periods begin in the same year as national delays. The specific events which indicate the beginning of the growth period are: nuclear–1959, the first commercial installation of a nuclear power station worldwide (World Nuclear Association, 2020a); ozone–1985, the Vienna Convention is adopted by 43 states (Morrisette, 1989); asbestos–1972, Denmark imposes the first partial ban on asbestos products (Allen et al., 2017); leaded petrol–1971, Germany passes the first leaded petrol regulation (Hagner, 1999). The end of the growth period is defined quantitatively in the same way as at a national level. Figure 4.13 omits transitions that are far from saturation (solar, congestion charging) or for which a consistent growth rate is not observed in the data (seat belts). Assessing the scale of adoption and the growth period yields an implied linear growth rate.

The rate at which market deployment or behaviour change stabilises depends on features of the transition itself, as well as contextual factors. Many government interventions, such as demand stimulation policies, or cross-development of technologies or ideas, accelerate the period to widespread market deployment but do not necessarily impact the linear deployment rate. Conversely, a sense of urgency can increase the linear growth rate for both technological and social transitions. For example, ozone depleting substances and leaded petrol were phased out with relative urgency when the detrimental health impacts became widely known (and substitutes became widely available). For CCGT and nuclear, two of the fastest growing technologies, urgency was driven by energy security concerns over blackouts and oil crises. However, the maximum rate of market deployment in technological transitions is limited by the capital intensity of the technology, regardless of the urgency of the transition. This is further discussed in Section 4.3.3.

Delay and growth of transitions

Figure 4.14 maps the growth rate and delay period drawn from the Z-curves in Figure 4.13, key determinants of the duration of transition. Transitions in the upper left quadrant are the swiftest; transitions in the lower right are the slowest. With the exception of nuclear power in France, as discussed in Section 4.2.1, technological transitions are slower to start and slower to grow than social transitions. The average annual growth rate of technological transitions drawn from this graph is 1.6%, versus 4% for social transitions.

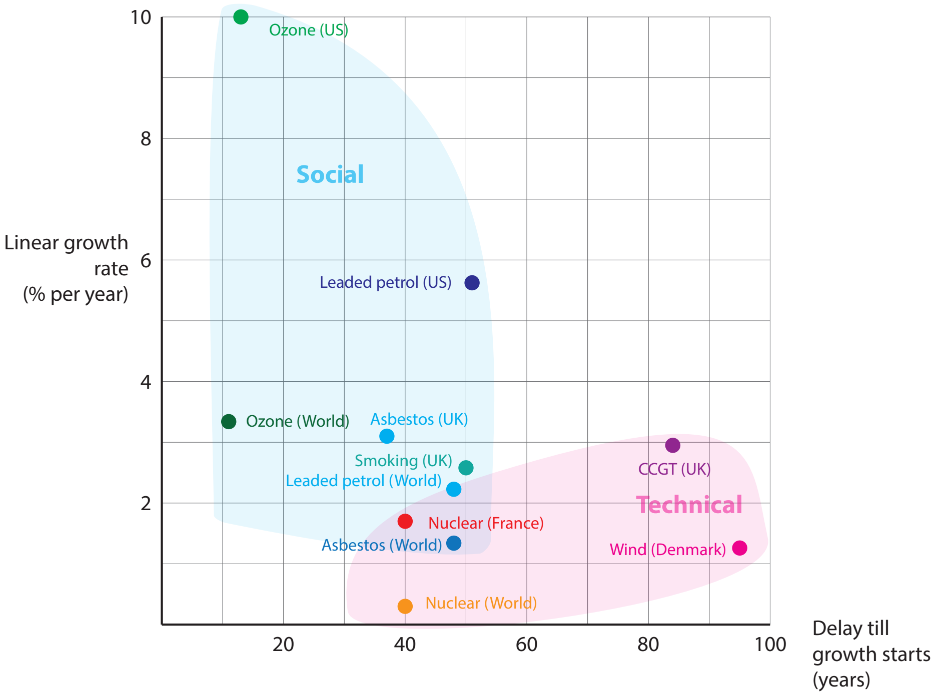


Fig. 4.14 The delay and the implied linear growth rate of social and technological transitions, derived from the growth period and saturation level illustrated in Figure 4.13.

Figure 4.14 supports the conclusions from Section 4.3.1: social transitions typically progress more swiftly than technological transitions. It also goes some way to answering the question of whether we can achieve mitigation faster with social transitions. This analysis does not claim to predict how long climate-related social transitions may take. However, the evidence belies the prevailing belief that social change is too slow and too ineffective to create meaningful mitigation.

Alternative growth periods in Z-curves

The proposed stylised Z-curves of transition includes all growth stages in the linear growth period. Adjusting which stages are included in this period would affect the resulting average growth rate. The following discussion focuses on the implications for technological transitions due to their relatively abundant diffusion data. As a corollary, the transition frameworks developed from the timelines are more granular for technological transitions than social ones, so it is possible to distinguish different transition stages that may be selected for a Z-curve's growth period.

The analysis presented in Figures 4.13 and 4.14 includes all growth transition stages. Consider the effect of limiting the analysis to *rapid growth* and *maximum deployment*. This means the upward-sloping arm of the Z-curve captures only the period during which the technology is scaling up the fastest. The growth period is shorter, but the total scale achieved in that time is smaller—the implied linear growth rate depends on which effect dominates. Table 4.5 compares the implied linear growth rates for the whole growth period with two alternatives.

Table 4.5 The effect of growth period on linear growth rates, derived from the Z-curves of transition.

	All growth stages			**Rapid + max deployment**			**Max deployment**		
Transition	Duration	Scale	Rate	Duration	Scale	Rate	Duration	Scale	Rate
Nuclear (France)	46	79%	1.7	30	75%	2.5	8	37%	4.6
Nuclear (World)	47	15%	0.3	33	15%	0.7	16	12%	0.8
Wind (Denmark)	36	46%	1.3	32	49%	1.5	26	40%	1.5
CCGT (UK)	12	35%	2.9	7	21%	2.9	3	13%	4.3

Scale gives the change in market share that was achieved during the specified growth period. Rate refers to the implied linear growth rate over the given duration, in percentage points per year.

Excluding *slowing growth* increases the implied linear growth rate for nuclear power in France and globally, and for wind in Denmark. Under *rapid growth + maximum deployment*, the implied rate remains unchanged for CCGT in the UK, because less change is achieved in this shorter window. The average linear growth rate increases from 1.6% to almost 2% per year. This effect is more dramatic when the growth period is limited to only *maximum deployment*.

Nuclear and CCGT exhibit very swift growth during this period, consistent with the trends seen in their transition timelines (Figure 4.2). Under *maximum deployment*, the average linear growth rate is 2.8% per year.

Selecting different growth periods affects the implied growth rate. This is an intuitive result given how transition stages are defined. It also reflects the variation in duration estimates amongst related studies which adopt a range of definitions for a technology's diffusion period (see Figure 2.7). However, it seems to contradict the idea that transitions follow linear growth. But the advantage of Z-curves is not that they necessarily map complex diffusion dynamics, but that they remove some of the guesswork from transition analysis and forecasting by assuming that deployment is *mostly* linear *most* of the time. Regardless, selecting alternative growth periods for technological transitions does not affect the conclusion of this analysis. Even with a shorter window that captures only the period of fastest deployment, technological transitions exhibit slower average growth than their social counterparts.

4.3.3 Construction constraints

Once a technology is ready for deployment at scale, a more mundane consideration determines the rate of deployment: the reality of planning, procuring and constructing a large engineering project. There is evidence that the iron law of megaprojects—"over budget, over time, over and over again" (Flyvbjerg, 2014, p. 11)—applies to energy construction. The literature on energy transitions provides little discussion of construction constraints (Beake and Cole (2020) being a notable exception), but conclusions can be drawn from recent trends. For example, the UK's most recent nuclear development, Hinkley Point C, has an anticipated period between initial siting assessment and full operation of 21 years (World Nuclear Association, 2020c), with possible delays and an expected budget overshoot of £2.9 billion (De Beaupuy, 2019). For CCS, a theoretical model of the development of a large demonstration project estimated the likelihood of meeting schedule at 5% given the existing regulatory framework (Carpenter and Braute, 2012). Conversely, some projects display surprising swiftness: offshore wind farms Walney 1 and 2 took less than ten years from initial licensing to grid connection and were 9% under budget (Hervé-Mignucci, 2012; Sovacool et al., 2017). This appears to be an outlier. Based on 51 wind power projects between 2000 and 2015, Sovacool et al. (2017) find that 61% have budget overruns and associated delays, with an average cost escalation of 6.5%.

The existing literature on rates of technological deployment largely considers macro-scale trends. This brief discussion opens an complementary research avenue, focusing on the project-level constraints on the deployment rate of established energy technologies.

4.3.4 Learning from the Covid-19 response

The Covid-19 pandemic that began in early 2020 heralded unprecedented social change. At the time of writing, the long-term effects of the pandemic are uncertain. However, it is evident that Covid-19 is a major challenge for health systems, economies and societies. The pandemic is a public health emergency that requires swift government action and taps into existing fears spread by previous epidemics and Hollywood movies such as *Contagion*. The international response to this public health disaster has been concerted and unilateral, and led to the swiftest social transition since the World Wars.

The near-global slow down of economic activity and travel in the first quarter of 2020 achieved what climate scientists have been recommending for decades (Cohen, 2020). The number of commercial flights fell 75% globally between January and April (Flightradar24, 2020); industrial manufacturing activity in China slowed (Department of Service Statistics and China Federation of Logistics and Purchasing, 2020); commuting fell as more people worked from home (Vallance and Cabinet Office Briefing Rooms, 2020). These changes have climate effects. In China, the economic shut-down is estimated to have reduced CO_2 emissions by 25% in February 2020 (Myllyvirta, 2020), and similar effects have been shown in cities in the United States (Krajick, 2020). In part, these changes have been enforced by government lockdowns. However, the social response was also unprecedented—behaviour changed drastically even before restrictions were put in place. In the UK, travel on underground trains in London fell by more than 80% in the three weeks before the government announced a national lockdown in March (Vallance and Cabinet Office Briefing Rooms, 2020). The swift social changes illustrate individuals' willingness to adjust in the face of an easily-identifiable risk.

As yet, a sense of urgency for climate action is limited to social protests, and has not translated into a large-scale public imperative. The barrier this poses for individual and systemic change has been highlighted by the Covid-19 pandemic which, in contrast, presents an immediate and tangible threat. However, the response also provides hope by showing that widespread, swift political and social transformations are possible in response to a crisis.

4.3.5 Limitations

Difficulties arose in sourcing data and identifying appropriate transitions. For social transitions, data were relatively sparse, particularly for non-market behaviour changes measured with surveys or observation (smoking and seat belt wearing). No world data for seat belts were available. Some of the data were only available for a portion of the period of interest, because the data were collected only after the transition reached a threshold level of public awareness.

As in any analysis, there are risks in extrapolating the results of this analysis to future transitions due to the relatively small number of historical examples, particularly for technological transitions. This study focused on large-scale transitions in the energy sector so the pool of candidates was limited. Compounding this, it examined only transitions occurring after 1900 to ensure a social and political context most similar to today's. While this means a smaller number of transitions, the remaining examples provide stronger and more relevant conclusions. With the small-sample caveat in mind, careful analysis still yielded important features and identified practicable policy recommendations.

4.4 Summary of findings

Twelve historical transitions are compared using qualitative and quantitative analyses. The results show that transitions follow reasonably uniform chronologies, enabling comparison of the time required for each technology or social change to progress through the various stages of transition.

The reviewed social transitions took on average four decades less than the technological transitions to go from initial conception to rapid adoption. Two parameters ultimately determine the duration of a transition: the delay between conception and rapid uptake, and the transition's linear rate of growth. The research in this chapter shows that past social transitions have generally faced shorter delay and had a faster growth rate than their technological counterparts. The innovation delay is four decades longer for technological transitions, which also face slower uptake, with an average annual growth rate of 1.6%, versus 4% for social transitions. The finding that energy transitions swiftly became linear after an initial period of acceleration is illustrated in the stylised Z-curves of transition, and contrasts the accepted wisdom of S-shaped technological diffusion (Brown, 1991; Grubb et al., 2020). This linear constraint is attributable to factors including construction requirements, regulatory processes and social opposition.

The research in this chapter contributes to the literature on the duration of low carbon transitions by extending the analysis to both technological and social transitions. Existing research relates the long timescale of past energy transitions to the challenge of swiftly decarbonising the world economy. By applying established methods of historical review to both technological and social transitions, this research yields lessons for reconciling slow past transitions to the necessarily swift decarbonisation of the 21st century.

Meeting net zero targets will require rapidly reducing carbon emissions. Currently, governments largely focus on technological mitigation potential, and implement strategies to increase the rate of deployment of renewable energy and CCS technologies. This leaves untapped opportunities for mitigation through social transitions. The emissions reductions potential of social change is acknowledged by governments, but considered secondary to technological advance.

While it is vital that new technologies are developed and deployed as quickly as possible, managing climate risk means utilising all abatement possibilities. Widening the climate policy portfolio to include options to support social change would bolster global climate action. Governments' climate efforts should be evenly shared between technological innovation and social change. Only by harnessing both will their climate goals be achieved.

Chapter 5

Technological and behavioural disruption in proposed pathways to net zero

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The research in this chapter addresses *Research Question 3*:

What do current climate strategies imply for the UK's timeline to net zero by 2050?

Delivering net zero emissions requires changing patterns of energy generation, consumption and land use. Mitigation efforts so far have mostly focused on reducing the emissions intensity of energy. Future decarbonisation must look outside the energy sector to disrupt markets, infrastructure, systems and behaviour. This chapter considers the type and scale of disruption in the UK's net zero transition and what that disruption means for the pace of decarbonisation.

Past studies adopt varying definitions of disruption (see Section 2.3.1). Here it is defined as a swift deviation from current trends. There are two types of disruption that are relevant to climate policy: technological and behavioural disruption. Broadly defined, technologies are "methods, systems and devices which are the result of scientific knowledge" (Collins English Dictionary, 2020). Technological disruption affects markets and systems on the supply-side by scaling up new or existing technologies. Behaviour describes choices and actions taken in an individual capacity. Behavioural disruption is any demand-side change to personal decisions or activities.

Technological and behavioural disruption cover all mitigation strategies, but are not mutually exclusive. Many options involve both technological scale-up and individual decisions, such as the deployment of heatpumps in homes. The specific definitions for technological and behavioural disruption adopted in this research are used to quantitatively assess mitigation options. Table 5.1 defines technological and behavioural disruption, along with several other terms used throughout this analysis.

Table 5.1 Definitions of key terms used in the disruption analysis.

Term	Definition
Technological disruption	The percentage change in market share of a new or existing technology. For example, a change in the share of renewable energy in the electricity supply.
Behavioural disruption	The percentage change in the activity share of a particular behaviour or product. For example, a change in the proportion of red meat in diets.
Mitigation option	An intervention aimed at reducing emissions arising in a market or activity.
Proposed scenario	The set of decarbonisation options presented in a given report.
Decarbonisation domain	The list of all decarbonisation options presented in the reviewed reports.
Scale	A quantitative measure of the ambitiousness of a proposed option.
Mitigation potential	The maximum potential abatement available for a mitigation option.
Mitigation ambition	The mitigation achieved by the scale of option proposed by a given scenario.

Mitigation of climate damages is not the only source of policy disruption. Governments' responses to Covid-19 displayed extraordinary appetites for disruption. Unprecedented behaviour change was coupled with some of the swiftest technological advances in medical history. Short-term crises such as Covid-19 provide an illuminating contrast to the 'slow burn' emergency of climate change.

This chapter asks whether the disruption embodied in mitigation is balanced across technological adoption and behaviour change. A new method for quantifying disruption is developed, and applied to decarbonisation strategies for the UK. The analysis is internationally applicable due to the similarity of proposed mitigation pathways in other jurisdictions. The disruption metric is novel and intentionally simple; methodological limitations and assumptions are discussed in Section 5.3.3.

The context of technological and behavioural change in decarbonisation are reviewed in Chapter 2. The remainder of this chapter describes the method and results of the disruption analysis. Section 5.1 sets out the methods and materials used to estimate disruption. Results for several proposed pathways to net zero are presented in Section 5.2. Section 5.3 discusses the patterns of disruption, risk preferences and compares government approaches to climate change and Covid-19. Findings are summarised in 5.4.

5.1 Methods and materials

This study evaluates the balance of disruption in mitigation proposals in three stages. First, a review of several reports that each propose a set of options to reduce emissions (Section 5.1.1). The method determines comparable lists of policy options from the decarbonisation proposals. Second, a novel metric is developed to capture the technological and behavioural disruption embodied in the proposals (Section 5.1.2). Finally, estimation of the mitigation potential of each decarbonisation option (Section 5.1.3). Section 5.1.4 provides example calculations for each stage. The method is summarised in Figure 5.1. Details about mitigation options and scenarios are available in Appendix B. Section 5.3.3 discusses limitations.

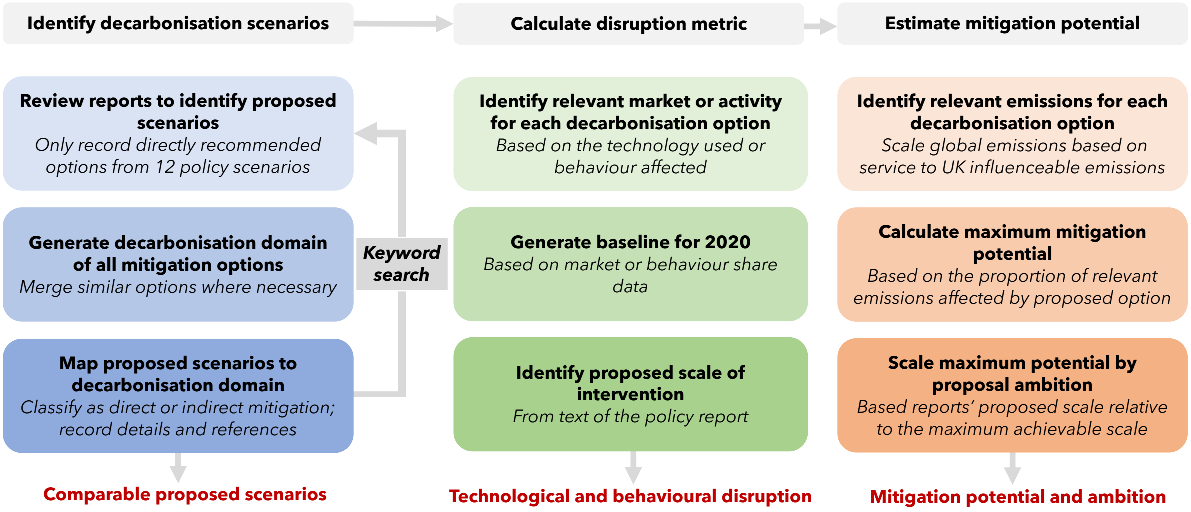

Fig. 5.1 The method used to evaluate the behavioural and technological disruption embodied in decarbonisation proposals.

5.1.1 Decarbonisation scenarios for the UK

Table 5.2 summarises the twelve scenarios assessed in this research, drawn from seven decarbonisation reports. The reviewed sources cover a broad range of perspectives across government agencies (Stark and Thompson, 2019), advocacy groups (Centre for Alternative Technology, 2019; Friends of the Earth, 2018; Greenpeace, 2019), academic researchers (Allwood et al., 2019; Pye et al., 2015) and industry bodies (National Grid ESO, 2020).

Table 5.2 List of decarbonisation scenarios.

Source	Scenario	Scenario ambition
Climate Change Committee (CCC) (Stark and Thompson, 2019)	Further ambition	Significant decarbonisation along with roll out of new technologies reduces emissions in 2050 by 96% compared to 1990.
Centre for Alternative Technology (2019)	Central	Cross-sector and technically feasible scenario reduces emissions by 92% compared to 2020 by 2030.
Friends of the Earth (2018)	Central	Utilises new technologies to achieve net zero emissions by 2045.
Greenpeace (2019)	Central	Socially fair, government-driven strategy based on proven technologies that achieves net zero emissions by 2050.
UK Fires (Allwood et al., 2019)	Central	Improving industrial strategy and reducing energy demand to eliminate emissions by 2050 based on today's technology and incremental improvements.
Deep Decarbonisation Pathways Project (DPP) (Pye et al., 2015)	Decarbonise and expand	Near-term power decarbonisation with strong policy support, widespread electrification and CCS to reduce emissions in 2050 by 86% compared to 2010.
	Multi-vector transformation	Slower electrification and higher reliance on non-electric energy that reduces emissions in 2050 by 90% compared to 2010.
	Reduced demand	Supply-side decarbonisation moderated by demand reductions, motivated by policy across a number of sectors. Achieves 83% emissions reductions in 2050 compared to 2010.
National Grid ESO (2020) (NG)	Steady progression	Slowest credible decarbonisation, hindered by minimal behaviour change and no decarbonisation in heat, which reduces emissions in 2050 by 68% compared to 1990.
	System transformation	Large-scale shift towards hydrogen for heating and supply side flexibility, but low consumer engagement and lower efficiency. Achieves net zero emissions by 2050.
	Consumer transformation	High consumer engagement and demand-side flexibility, supported by electrified heat and energy efficiency. Achieves net zero emissions by 2050.
	Leading the way	Fastest credible decarbonisation, requires significant lifestyle change and a mix of electrification and hydrogen. Achieves net zero emissions by 2050.

Scenario ambition provides a brief overview of the goals of each scenario, along with the emissions reduction target.

Sampling method

The selection of decarbonisation scenarios had three objectives. First, to obtain a large set of mitigation options. Second, to survey a broad set of different perspectives. Third, to include reports that were both ‘close to’ and ‘far from’ government policymakers. Candidate reports were identified based on an internet search for ‘UK decarbonisation’ (and synonyms). The focus on policy proposals, including grey literature, meant limiting the search to academic databases such as Scopus would have excluded an important set of results. This search yielded a set of candidate reports of varying political relevance. As Braunreiter and Blumer (2018) point out, some reports may have less influence due to researchers’ and policymakers’ perceptions of the quality of the authors’ organisation. Given that this research addresses the policy impacts of potential scenario bias, candidate reports were ranked by estimates of their political influence.

The review of decarbonisation scenarios proceeded by rank and stopped once the mitigation sample was saturated. At this point, new reports contributed marginally different scales of mitigation but offered no new options. While not an exhaustive list of decarbonisation proposals for the UK, the reviewed reports satisfy the three selection criteria and provide a representative view of the optimal pathways to net zero. The twelve scenarios capture a varied set of perspectives on the challenge and, importantly, yield a diverse domain of mitigation options.

Generating the decarbonisation domain

Identifying consistent decarbonisation scenarios involved detailed reviews of proposed mitigation options, including scale and implementation method. Merging the scenarios provided a set of 98 mitigation options constituting the decarbonisation domain. Comparable results were generated by identifying which of the 98 options were proposed in each scenario. The final step was to cross-check the original reports with the decarbonisation domain using a keyword search for each option. The detailed results of this review can be found in the Appendix B.

Some reports mentioned the merits of potential options but did not directly propose them, such as the ‘speculative options’ considered by the Climate Change Committee (Stark and Thompson, 2019). Speculative proposals were not included in the decarbonisation domain. Even for directly proposed options, creating a comparable decarbonisation domain occasionally required merging similar options across different proposals. Options were merged where the implementation or intent of the proposals were the same.

Direct and indirect mitigation options

Decarbonisation options are classified as achieving direct or indirect mitigation. Direct options reduce the energy-intensity of an activity, or cut emissions from energy generation, agriculture, land use or industry. Indirect options enable mitigation through other avenues. For example, producing hydrogen using electrolysis or steam methane reforming does not reduce emissions (indeed, it will increase emissions unless the electricity is carbon-free or the steam methane reforming is paired with carbon capture and storage). However, replacing fossil fuels with hydrogen in transport, heating and energy generation supports mitigation in these sectors. Indirect options cannot be linked to emissions reductions so are treated separately in the analysis.

5.1.2 Disruption metric

This study quantifies the disruption of mitigation options based on the proposed change in the associated market or activity. Following the definitions given in Table 5.1, technological disruption describes changes in the market share of a technology; behavioural disruption is changes in the behaviour share of an activity.

The disruption metric is based on the percentage change in the market or activity between 2020 and 2050. It takes the absolute value since change is disruptive regardless of direction, and uses the natural logarithm to temper large differences across options. Letting i be the option, p the proposed scenario and d the type of disruption (technological or behavioural), then disruption is given by:

$$\text{Disruption}_{i,p,d} = \ln\left|100 \times \frac{\text{Target share}_{i,p,d} - \text{Baseline share in } 2020_{i,d}}{\text{Baseline share in } 2020_{i,d}}\right|$$

The baseline is calculated using contemporary statistics for the technology or behaviour share in 2020, except in two cases. If an option relates to efficiency, the baseline is indexed to 2020 and disruption measures relative improvements. Similarly, when the relevant baseline is the size of the market rather than a market share, such as for reducing ceramics consumption or total distance travelled, it is again indexed to 2020.

For each option, the target scale was identified in the detailed review of policy scenarios. The scale was usually described quantitatively ('an 80% reduction in sales of emitting vehicles') but was occasionally more vague ('a significant shift towards electric vehicles'). In the latter case this method allocates a quantitative value proportional to the implied ambition. When the target did not match the identified market or activity in the baseline, it assumes a proportional shift consistent with the proposal's description.

Using percentage rather than absolute change gives an indication of the ease of transition by capturing the size of the existing market. For example, going from 50% to 60% market or behaviour share is less disruptive than going from 0.1% to 10.1% because the established option has existing physical or social infrastructure to swiftly facilitate growth. Some proposed options do not currently exist at market scale, such as hydrogen, CCS or demand-side response technologies (Chase et al., 2017; McLaren, 2012; Staffell et al., 2019). In such cases, a 0% baseline share is replaced by 0.0001% to enable calculation while still capturing the barriers to implementation.

Identifying the relevant market and activity

Quantifying disruption required first identifying the relevant market or activity for each proposed option. This was straightforward for most options: reducing meat consumption is related to eating; increasing offshore wind affects the electricity market. However, in some cases—particularly cases where an option affected both markets and behaviour—it was less obvious. Table 5.3 provides examples from different sectors to illustrate how relevant markets and activities are identified. The examples describe the most disruptive options in each sector. Where relevant Table 5.3 includes an example with both technological and behavioural disruption. Additional notes and the classifications for all 98 mitigation options are provided in Appendix B.

Table 5.3 Classifying the market and activity of mitigation options in different sectors of the economy.

Sector	Mitigation option	Technological market or behavioural activity (relevant share)
Agriculture	Hydrogen in farm vehicles and machinery	*Market*: Farm vehicles and machinery (share using hydrogen)
	Reduce meat consumption	*Activity:* Eating (red meat share of adult energy intake)
Buildings	Hydrogen in new homes (1)	*Market:* New build homes (share with hydrogen heat)
	Reduce home temperatures	*Activity:* Home heating (share of time spent in heated home) (2)
	Hydrogen heat in existing homes (3)	*Market:* Existing homes (share with hydrogen heat) *Activity:* Retrofit decisions (share of existing homes with low carbon heat) (4)
Carbon removal	Direct air CCS	*Market*: Negative emissions (share of emissions captured, benchmarked to 2020) (5)
	Use wood in construction	*Market*: New build homes (share with timber frames)
Energy supply	CCS with fossil fuels	*Market*: Electricity generation (share of electricity from fossil fuels with CCS)
	Shiftable energy demand	*Activity:* Energy use (share of homes with shiftable demand)

Table 5.3 continued from previous page

Industry	Hydrogen industrial heat	*Market*: Industrial heat (share from hydrogen)
	Use products for longer	*Activity:* Product purchase and use (share of consumers considering environment in purchase and use decisions) (6)
	Limit steel production and recycle steel	*Market*: Steel production (share produced using scrap) *Activity:* Steel use (consumption, benchmarked to 2020) (7)
Land use	Develop biomass crops	*Market*: Arable land use (share used for biomass)
	Restore peatland	*Market*: Peatland restoration (share in restored state) *Activity:* Land availability (restored peatland as share of total land) (8)
	Increase forested area	*Market*: Afforestation (forests as share of total land) *Activity:* Land availability (forests as share of total land)
Transport	Ammonia for shipping	*Market*: Shipping fuel (share using ammonia)
	Reduce total travel	*Activity:* Travel (overall distance, benchmarked to 2020)
	Electrify cars	*Market*: Passenger cars (electric share of car stock) *Activity:* Car purchase decisions (electric share of car sales)
Waste	Reduce emissions from water management	*Market*: Water management (emissions from waste water management, as share of 2020 emissions)
	Reduce all waste streams	*Market*: Commercial and industrial waste (share of total, benchmarked to 2020) *Activity:* Residential waste (share of total, benchmarked to 2020)

Notes: (1) Where changes are made to new homes, the responsibility for meeting building standards falls on the construction industry and individual decisions (house purchasing) are not affected. (2) This is estimated based on home occupancy factors and an estimation of the heating season (BRE and Department of Energy and Climate Change, 2013; Public Health England, 2018). (3) Retrofits require both technological deployment in the construction market, and behaviour change by homeowners. (4) It is assumed that the behavioural decision to install low carbon heating is the same across modes (electric and hydrogen). (5) The method benchmarks to 2020 emissions for CCS because estimating as a share of projected emissions inflates disruption as total emissions falls. (6) This is exceptionally difficult to judge. This study assumes that consumers who take environmental considerations into account is approximately equivalent to the share for whom durability is important. Using survey results introduces questions of stated preferences versus revealed actions, but the review did not uncover any useful statistics indicating revealed actions for use-life of consumer goods. (7) Where the option requires an absolute reduction in a technology or behaviour, the share is benchmarked to 2020. (8) Restoring peatland and afforestation affects individuals by reducing space for building, while potentially creating more recreational space.

Assessing the disruption metric

The chosen metric is based on simple measures: the proposed change in market or activity share of a technology or behaviour. Several alternatives were considered, including the readiness level of the technology, market concentration, and the social acceptability of the behaviour.

These factors are important in disruption. However, the chosen metric is the most transparent method to quantify disruption. Possible extensions to the metric are discussed in Section 5.3.3.

Assessing whether the results of this analysis can, as hoped, be interpreted as disruption is difficult because no other studies perform similar analysis. However, the report produced by the Climate Change Committee (CCC) provides some guidance. It estimates that 9% of emissions reductions in its scenario arise from changes in societal or consumer behaviours, 38% from deployment of low carbon technologies, and 53% from a combination of technology and behaviour change (Stark and Thompson, 2019, p. 155). Using this study's classification, 9% of the CCC's mitigation options involve only behavioural disruption and 73% involve only technological disruption. The remaining 17% require a combination.

The classification of behavioural mitigation options shows close agreement to the CCC's own estimates. However, the CCC allocates far more mitigation to options which combine technological and behaviour changes than under this study's definitions. Although it does not explain the categorisation, the discrepancy likely occurs because the CCC defines societal and behavioural changes more broadly than in this study. Specifically, the CCC may classify changes in supply-side practices as societal changes, and so identify more options as combining societal and technological change. For example, changing building codes would require construction workers to adjust their behaviour and possibly retrain. This may constitute societal change to the CCC, combined with technological change in low carbon building materials. In contrast, this thesis would classify it as a solely technological disruption because it is a supply-side adjustment. The behavioural classification method used here is a transparent and widely applicable way to capture the demand-side disruption of mitigation options. However, adding a category of market disruption is a potential area for future research.

5.1.3 Estimating mitigation for decarbonisation options

Disruption can be thought of as the risk embodied in a decarbonisation scenario; mitigation is the return. This section describes the process of estimating mitigation for the 98 proposed options. It distinguishes mitigation *potential* and *ambition*. Mitigation potential describes the maximum possible emissions reduction for any option in the decarbonisation domain. Mitigation ambition considers the emissions reduction from a proposed scale of technology or behaviour share, and applies to specific decarbonisation scenarios.

Global emissions shares

The first step to calculate mitigation potential of decarbonisation options is to identify the share of total emissions produced by each relevant market or activity. Calculating these emissions shares is based on the global emissions Sankey diagram in Bajželj et al. (2013). Their study traces emissions from final services, such as personal travel, thermal comfort, construction of buildings and so on, through sector, equipment, device, final energy, fuel and emissions. The Bajželj et al. (2013) framework offers an internally consistent method to estimate mitigation for options acting at different points of the supply chain and across different markets. Differences between the UK and global economies means this study over- or under-estimates true mitigation for some options. However, no such analysis exists for the UK. BEIS (2020a) provides emissions data for some categories but not for final uses, and attributing emissions to final uses is extremely challenging.

The mitigation potential for each option depends on the existing emissions intensity of the market or activity. To estimate this, the option is located within a relevant *class* in the emissions Sankey diagram (Bajželj et al., 2013) by determining where along the supply chain the option acts, from end-user service to energy use. Within that class, the option is allocated a *category* that yields an estimate of the global emissions arising from that activity or market. The category's share of global emissions is then multiplied by the UK's influenceable emissions.

The UK's influenceable emissions

The emissions influenced by UK policy are those generated in UK production, embodied in imports and arising from international aviation and shipping. Production emissions are provided by BEIS (2020a). Imported emissions are based on Davis et al.'s (2011) analysis of the carbon-intensity of trade, which finds that imports equate to 55% of production emissions in the UK. Aviation and shipping emissions are estimated by adjusting reported figures BEIS (2020a) to include the effect of radiative forcing that increases the global warming potential of air travel (Williams and Noland, 2006), based on conversion factors provided for organisational greenhouse gas reporting (BEIS, 2018). These three emissions sources give an estimate of 780MtCO_2.

Two alternative methods for calculating the UK's influencable emissions were considered. The first calculates imported emissions using the share of emissions embedded in trade from Our World in Data (2020), which is based on analysis of trade by Peters et al. (2011) and emissions data from Global Carbon Project (2019). This method yields an estimate of 710MtCO_2, 9% less than the central estimate. The second combines consumption-based emissions (Defra, 2020) with estimates of land-use emissions (BEIS, 2020a) and export emissions (Davis et al., 2011). This gives emissions of 830MtCO_2, 6.1% higher than the central estimate. From these two alternatives, the higher discrepancy of 9% is accepted as the uncertainty in mitigation potential.

Maximum potential mitigation

Mitigation options may not affect all emissions arising from a market or activity. Scaling factors for each option are based on the share of category emissions that an option can abate. Technology scaling factors reflect the maximum practicable deployment. For behavioural options, maximum mitigation relates to what Dietz et al. (2009) call 'plasticity'—the maximum potential adoption of effective instruments. Scaling factors therefore ensure realism in mitigation calculations.

Multiplying UK category emissions by the scaling factor yields maximum potential mitigation. The scaling assumptions over the electricity and hydrogen supply are particularly important. Mitigation from electrification depends on the availability of non-emitting electricity. This study assumes an unlimited supply of renewable generation. Similarly, it assumes that the production of hydrogen is non-emitting. Any option based on the use of hydrogen therefore implies a parallel increase in either steam methane reforming with CCS or renewable-powered electrolysis. Both processes face high barriers to scale that could constrain hydrogen production. The assumptions over electricity and hydrogen are somewhat heroic. The availability of non-emitting electricity and, particularly, the nature and scale of future hydrogen production are two of the most challenging issues in achieving decarbonisation. Calculations under these assumptions are therefore intended as technical maxima.

Estimating mitigation ambition

Mitigation ambition relates the mitigation potential to the target scale in a given scenario. To calculate ambition, a maximum possible share is defined for each option within the context of the identified market or behaviour change. For example, for an option applied to new homes, the maximum share is 100%, meaning that all new builds adopt the change. The ambition ratio is then calculated given the proposed ambition of intervention in each scenario. Again letting i be the option, p be the proposed scenario and d be the type of disruption, then:

$$\text{Ambition}_{i,p,d} = \frac{\text{Target share}_{i,p,d} - \text{Baseline share in 2020}_{i,d}}{\text{Maximum share}_{i,d} - \text{Baseline share in 2020}_{i,d}}$$

Where an option implies both technological (t) and behavioural (b) disruption, this study takes the higher ambition across the two disruption types to capture the dominant effect. Mitigation ambition is given by:

$$\text{Mitigation ambition}_{i,p} = \text{Maximum potential mitigation}_{i} \times max\big(\text{Ambition}_{i,p,t}, \text{Ambition}_{i,p,b}\big)$$

Mitigation ambition provides a signal for each proposed option's environmental return, rather than an exhaustive calculation of the embodied mitigation. Calculations are therefore subject to the double counting caveat. Proposed options are interdependent, meaning mitigation is contingent on the order in which they are applied. For example, reducing electricity demand cuts emissions only if electricity is generated using fossil fuels. If electricity is non-emitting and abundant, these measures do not reduce emissions. This interdependence means the mitigation potential across all options will sum to more than current UK emissions. Mitigation estimates should not be treated as integrated projections of scenario emissions. Instead, they can be used to compare mitigation options.

5.1.4 Illustrating the method with examples

This section clarifies the method further with example calculations of disruption and mitigation for three options proposed by the Centre for Alternative Technology (Centre for Alternative Technology, 2019). The first option is reducing beef and lamb consumption, which requires no technological adoption but significant behaviour change. Second, installing energy and thermal efficiency measures in new homes will require suppliers—builders, architects and developers—to change practices and technology. No behaviour change is necessary from home buyers. The third option is electrifying road passenger transport. This blended option generates technological and behavioural disruption: it requires both the technological diffusion of electric vehicles and individual behaviour changes by car buyers.

Table 5.4 provides the information necessary to calculate technological and behavioural disruption, using the method described in Section 5.1.2. Table 5.5 illustrates the calculations described in Section 5.1.3 to calculate the mitigation ambition for each option. These tables are drawn from Appendix B, which provides these data and assumptions for all proposed mitigation options.

Table 5.4 Example disruption calculations for options proposed by the Centre for Alternative Technology (2019).

Technological factors		**Behavioural factors**		**Centre for Alternative Technology**			
Market	2020 baseline	**Activity**	2020 baseline	Market share	Technological disruption	Activity share	Behavioural disruption
Reduce beef and lamb consumption							
		Eating (red meat share of adult diet by energy intake) (Public Health England, 2018)	6%	N/A	0	0.48% (1)	4.5
Install energy and thermal efficiency measures in new residential builds							
Construction (share of new homes at EPC level C or above) (Ministry of Housing Communities and Local Government, 2019a) (2)	94%			100%	1.8	N/A	0
Electrify road passenger transport							
Passenger vehicles (share of car stock that is electric or hybrid) (Department for Transport, 2020d)	2.3%	Car purchasing (share of car sales that are electric or hybrid) (Department for Transport, 2020e)	8.1%	90%	8.3	100%	7.0

(1) CAT targeted a 92% reduction in beef and lamb consumption. (2) Energy Performance Certificates (EPCs) measure efficiency of buildings.

Table 5.5 Example mitigation calculations.

Global emissions share			**UK maximum mitigation**			**Centre for Alternative Technology**	
Class	Category	Activity/market share	Category emissions	Scaling factor	Mitigation potential	Ambition factor	Mitigation ambition
Reduce beef and lamb consumption							
Land use	Livestock; pasture (1)	58%; 36%	$34MtCO_{2e}$	1	$34MtCO_{2e}$	0.92	$31MtCO_{2e}$
Installing energy and thermal efficiency measures in new homes							
Final service	Residential thermal comfort	5.5%	$43MtCO_{2e}$	0.05 (2)	$2.2MtCO_{2e}$	1	$2.2MtCO_{2e}$
Electrify road passenger transport							
Equipment	Car	6.9%	$54MtCO_{2e}$	1 (3)	$54MtCO_{2e}$	1	$54MtCO_{2e}$

(1) Several assumptions are required to allocate enteric fermentation and land use emissions to cattle and sheep stock: see Appendix B.3. (2) An energy efficient home produces 24% less emissions than the average home (Climate Change Committee, 2019). In 2050, 21.5% of housing stock in 2050 will be new (Allwood et al., 2019; Eames et al., 2013; Jones et al., 2013; Killip, 2008) (3) This study calculates technical maxima so assumes non-emitting electricity.

5.2 Results

This survey yields a set of 98 mitigation options and 538 proposed policies across the twelve decarbonisation scenarios. Here the disruption and mitigation results are presented. The analysis depends on the classification of options and the disruption metric itself. Further detail on each individual option is given in Appendix B.

Table 5.6 provides summary statistics across eight sectors of the economy. The most technologically-disruptive sectors are industry and carbon removal, driven by the adoption of CCS and hydrogen or electricity for industrial processes. High technological disruption in energy supply also arises from CCS and hydrogen, as well as the development of energy storage. Installing heat pumps and developing hydrogen for heating and cooking creates technological disruption in the building sector.

Table 5.6 Summary statistics for the 538 proposed decarbonisation options by sector.

Sector	**Number of options**	**Number of proposals**	**Average mitigation ($MtCO_{2e}$)**	**Average technological disruption**	**Average behavioural disruption**
Agriculture	9	27	11	4.6	2.1
Buildings	15	108	11	6.2	2.3
Carbon removal	3	7	25	7.7	0
Energy supply	18	143	56	6.4	0.83
Industry	18	91	32	7.7	1.2
Land use	5	14	10	4.6	2.2
Transport	23	130	18	8.1	1.9
Waste	8	19	3	3.2	1.8

Mitigation in buildings is the most behaviourally disruptive sector. Demand-side interventions such as retrofitting houses require both technological and behavioural disruption. Homeowners must decide whether to retrofit and which technologies to install. Behavioural end-use changes, such as home heating practices, can be highly disruptive but were only proposed in half of the surveyed reports. Land use changes including restoring peatland and expanding forests cause behavioural disruption by limiting the availability of land for building development. Disruption in agriculture and transport is created by demand-side interventions including changing diets, purchasing electric vehicles and using more public transport.

5.2.1 Disruption under maximum ambition

Each mitigation option has a maximum possible ambition. This maximum scenario does not necessarily reflect the surveyed proposals, but rather takes their suggestions to the logical extremes. Maximum ambition may be 100% adoption of a new technology or behaviour, or complete elimination of an emitting practice. The disruption and mitigation associated with the maximum ambition scenario are presented in Figure 5.2. Bubble size indicates how each option compares in environmental efficacy. For clarity, only some of the mitigation options are labelled.

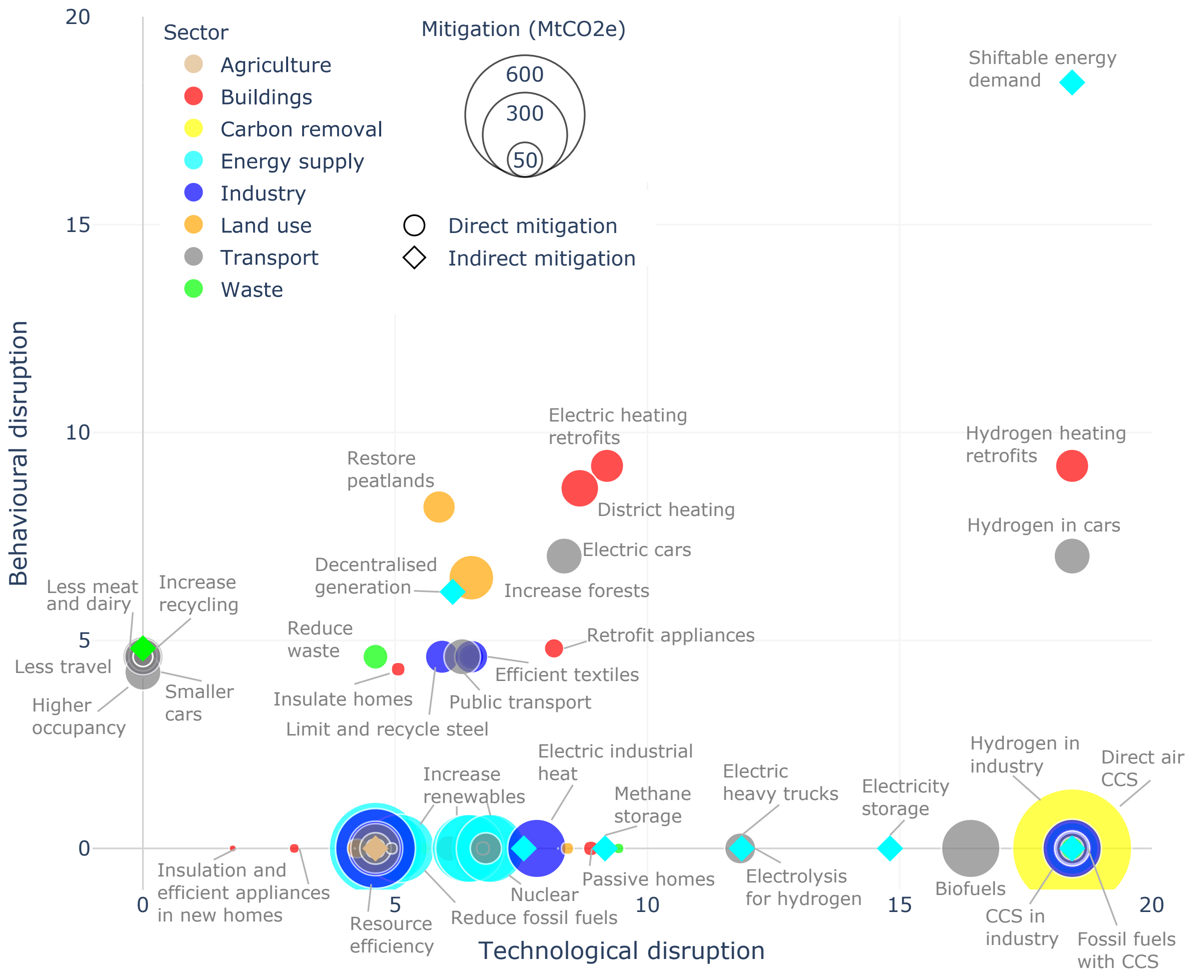

Fig. 5.2 The maximum disruption and abatement for all mitigation options. The size of the bubble gives the relative mitigation potential.

Most options in the maximum scenario are more technologically than behaviourally disruptive. Many rely entirely on technological disruption; the decarbonisation of electricity generation and industry require little behaviour change. In aggregate, hydrogen and CCS are the most disruptive technologies, driving change in buildings, transport, industry, energy and carbon removal.

While overall behavioural change is low in the energy sector, shiftable energy demand is the most disruptive option for both technological and behavioural change. Shiftable energy demand, sometimes called demand-side response, increases the flexibility of the electricity grid by automatically reducing demand in periods of high system stress. Such flexibility is critical in an electricity sector with a high share of intermittent renewable generation (National Grid ESO, 2020). Shiftable demand needs new technologies to adjust energy use, such as smart appliances and vehicle charging, and requires individuals to change energy use behaviours. The high disruption of this option reflects both its important role in decarbonisation and its low 2020 market and activity shares.

Purely behavioural options tend to be significantly less disruptive than technological alternatives. Interesting results are seen in the building sector. Insulation is less disruptive than electrifying heat, but is associated with less mitigation. This is partly a result of this study's methodology. For the maximum ambition scenario it is assumed that the electricity grid is decarbonised, so electrifying heat eliminates all residential heat emissions. In contrast, insulation can reduce residential emissions by up to 24% (Climate Change Committee, 2020a), all else being equal. Of course, this understates the importance of insulation. During the transition to net zero, insulating homes will reduce electricity demand and limit emissions from the not-yet-decarbonised grid. In a 2050 snapshot, however, electrification eliminates more emissions. Returning to disruption, Figure 5.2 shows that insulating new homes requires no behavioural disruption but generates less mitigation than retrofits. New buildings are the responsibility of supply-side parties whose decisions aren't captured in the behavioural classifications. Changing new build practices might be easier than retrofitting but provides less mitigation because the vast majority of homes in the 2050 housing stock have already been built.

Behavioural options may generate spillover technological disruption. For example, lab grown meat is a technologically-disruptive substitute to beef and lamb. Similarly, communication and virtual reality technologies may grow if international travel declines. However, this analysis focuses on the mitigation option itself, and is confined to what is suggested in the surveyed reports. Deeper inspection of individual options is a fruitful area for future research.

5.2.2 Disruption in the proposed decarbonisation scenarios

The proposed decarbonisation scenarios convey a heavy reliance on technological disruption, albeit a more muted one than under maximum ambition. Cluster analysis on the 538 proposed mitigation options identifies groups with similar characteristics. This method uses k-means clustering and determines clusters using the elbow method, which finds the number of clusters that most reasonably balances reductions in the sum of the squared errors against the total number of clusters. Two similar low technological disruption clusters are grouped for brevity and an outlier is omitted. Clustering allows a more general assessment of the decarbonisation scenarios. Figure 5.3 shows the results. Each cluster is labelled with a summary of the grouped options.

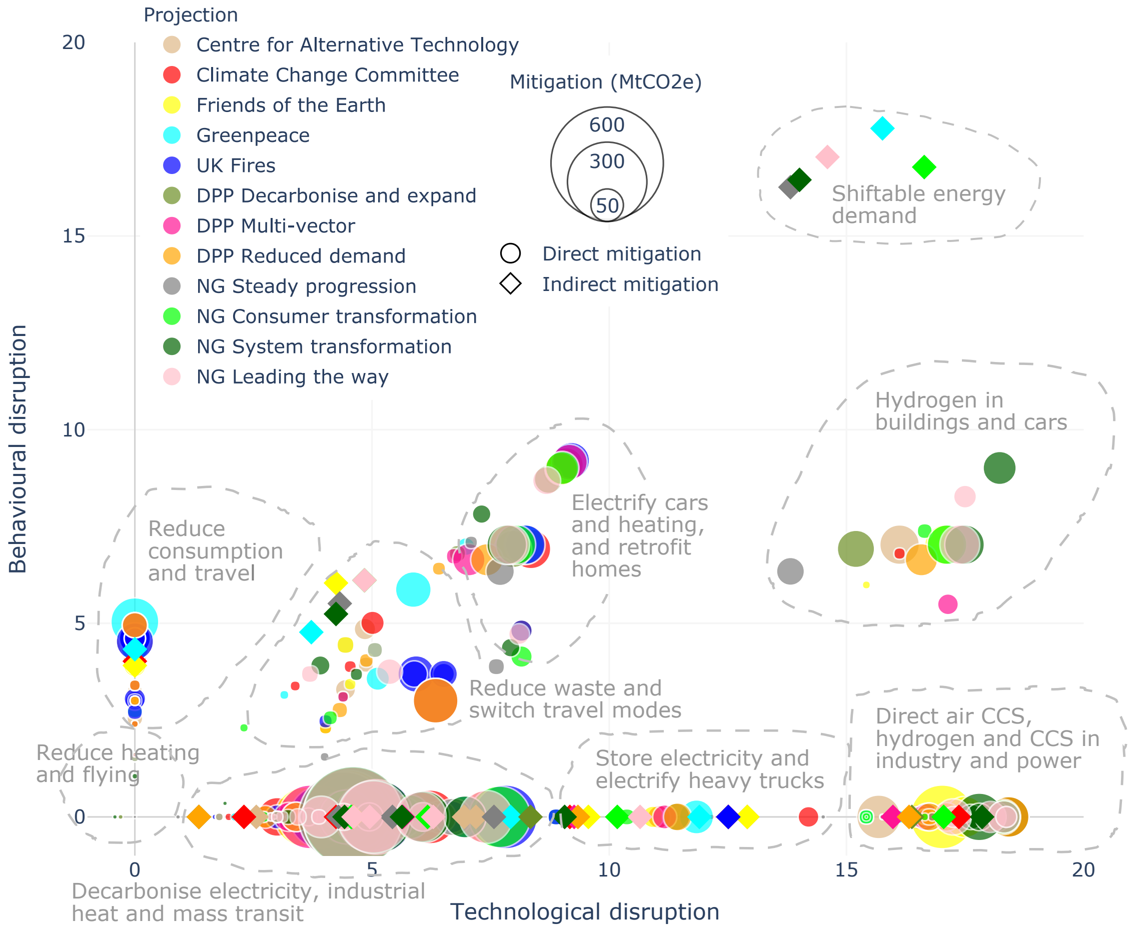

Fig. 5.3 The technological and behavioural disruption for all mitigation options proposed in the scenarios. The size of the bubble gives the relative mitigation potential. Cluster analysis identifies different segments of decarbonisation strategies.

The most technologically disruptive cluster relies on unproven technologies. Proposed mitigation options in this cluster include direct air CCS and hydrogen. Both options could provide significant emissions savings, but are highly speculative and require investment and time to become viable. The most commercially viable iterations of direct air CCS have not progressed far beyond proof-of-concept (McLaren, 2012) and their development faces prohibitive financial constraints. Hydrogen can be effective in transport and energy, but faces high barriers to scale due to large carbon-free energy requirements (Staffell et al., 2019). Despite the drawbacks, these speculative options are considered important in most decarbonisation proposals.

There are no highly disruptive purely behavioural options. In part, this is because most decarbonisation behaviours already exist to some extent. Unlike some technologies, behavioural options do not usually start from a 0% baseline, meaning their disruption is lower. For example, the behavioural option which provides the most mitigation is an increase in the lifetime of consumer goods, proposed by Greenpeace and others. This option reduces emissions by cutting material use. Such a broad recommendation is hard to measure; this study uses consumers' beliefs over the importance of longevity in purchase decisions to proxy behaviours to increase goods' lifetimes. Although this is a difficult transition, people already acknowledge its importance, reflected in the non-zero 2020 baseline. Similarly, improvements to domestic waste management build on existing behaviours. Options affecting diets—reductions in meat and dairy consumption—confer relatively little behavioural disruption because these products constitute a small share of the average diet.

Along with lower disruption, interventions which depend on behavioural change generally have a lower scope for mitigation than their technological counterparts. There are notable exceptions. The results suggest limiting material demand could eliminate a similar amount of emissions as electrifying the car fleet. Halving meat consumption would provide about the same mitigation as retrofitting appliances in all homes. Despite these potentially appealing comparisons, Figure 5.3 highlights the relative dearth of behavioural options. This reflects both the challenges of behaviour change and the under-exploration of large scale demand-side mitigation.

Four clusters create both technological and behavioural disruption by requiring consumer uptake of new technologies and systems. The two least disruptive of these are reducing waste and switching travel modes, and electrifying and retrofitting homes. These are common demand-side strategies that appear in all twelve proposals. The cluster of options utilising hydrogen in buildings and cars is a translation along the technological axis of electrifying and retrofitting homes. The choice between electricity or hydrogen power does not materially affect the decision over whether to buy a low carbon car or retrofit heating. However, carbon-free hydrogen is far more technologically disruptive. The final cluster of supply- and demand-side disruption is the roll out of shiftable energy demand. This option requires technological and behavioural change and has low current adoption.

5.2.3 Comparing decarbonisation scenarios

The proposed mitigation options in all scenarios are skewed towards technological disruption. However, some scenarios rely on technology more than others. Figure 5.4 shows disruption in the twelve proposed scenarios. Mitigation estimates consider the options in isolation so cannot be used to describe the whole mitigation scenario as a sum of parts. Mitigation is therefore omitted from this figure

Fig. 5.4 The technological and behavioural disruption of the mitigation options, for each of the twelve decarbonisation scenarios reviewed.

In the proposals from the Climate Change Committee and National Grid (NG), at least 84% of options have higher technological than behavioural disruption. The least disruptive scenario was proposed by UK Fires, in which 66% of options were more technologically than behaviourally disruptive. This proposal aimed to "respond to climate change using today's technologies with incremental change" (Allwood et al., 2019, p. 1). The outcome is a decarbonisation scenario that implies relatively little overall disruption to markets and lives.

Yet even the most technologically conservative report surveyed provided less than half of mitigation through behaviour change. Figure 5.5 aggregates the results of Figure 5.4 to show the average disruption across all options in each scenario. Every proposal lies below the diagonal, indicating a greater reliance on technological than behavioural disruption.

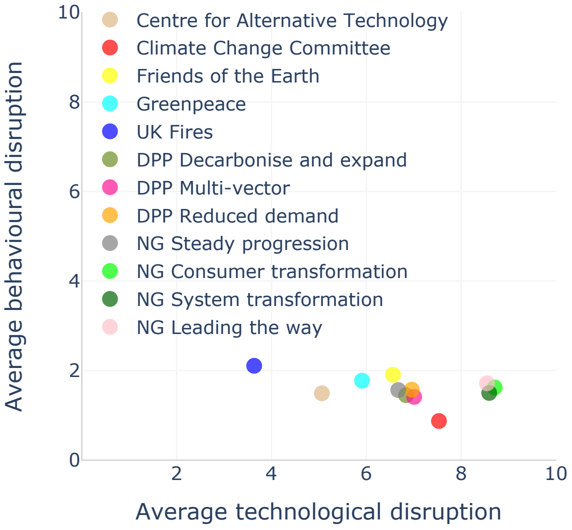

Fig. 5.5 The embodied technological and behavioural disruption of decarbonisation proposals, averaged across all mitigation options.

5.3 Discussion

The results above illustrate an imbalance between technological and behavioural disruption in the net zero pathway. Section 5.3.1 discusses whether this constitutes a bias in climate policy, and why such a bias might arise. Section 5.3.2 then considers what the results mean for wider observations about disruption preferences, particularly in light of the Covid-19 pandemic. Limitations of this study are discussed in Section 5.3.3.

5.3.1 Evidence for a technological disruption bias

There is a distinct preference for technological disruption across the decarbonisation reports. 64% of proposed mitigation options rely exclusively on technological change. These supply-side policies are ‘invisible’ to private individuals—they do not require any consumer buy-in. Purely behavioural mitigation options are less common, making up 20% of proposed options. The remaining 16% of options require both technological adoption and behaviour change.

Technological mitigation options also tend to be more ambitious. The average technological disruption for options requiring some level of technological change was 8.0; the average behavioural disruption for those with behavioural change was 4.9. For purely behavioural options, which require no new technology, the average disruption was 3.5. Some of this difference arises because purely behavioural options are often adjustments of existing behaviour—eating less meat or turning down the thermostat—so are less disruptive than behaviours associated with new demand-side technologies. However, there appears to be a bias against ambitious behaviour change. The maximum portfolio takes the proposed options to their most ambitious scale ignoring all political, social or technical complexities. For this portfolio, options with *only* behavioural change were 19% less disruptive than the set of all behavioural options. For the twelve proposed scenarios, this difference was 28%. This means that purely behavioural options were relatively less ambitious than blended options, which require both technological and behavioural change, in the proposed decarbonisation scenarios. In contrast, purely technological mitigation was equally as disruptive as blended technological options across both the maximum and proposed scenarios.

The results therefore illustrate a bias towards technological disruption. Technological options are more common and more ambitious than their behavioural counterparts. Faith in the development of unproven innovations underlines the technological bias and demonstrates why it is concerning.

Purely technological mitigation is concentrated in the energy and industrial sectors. Some technology transitions are well underway, such as the decarbonisation of the electricity grid and industrial energy efficiency measures. These options face challenges to scale including high construction requirements (Beake and Cole, 2020) and skills shortages (UK Energy Research Centre, 2020) but use technologies which have been deployed at scale for decades. They therefore require relatively little technological disruption. However, a significant portion of mitigation arises from highly disruptive technological options. These technologies are unproven, meaning they have not yet been implemented at scale, without incident, for a protracted period of time (Straub, 2015). It is certainly important that these technologies are investigated and developed where possible. However, relying on their development may reduce the impetus to pursue alternative strategies because the emissions are already ‘accounted for' in carbon forecasts. Markusson et al. (2018) argue that this mitigation deterrence effect, particularly pervasive for negative emissions technologies, undermines climate policy at the highest levels—including in the IPCC's guidance for international climate negotiations.

Prudent future planning means treating speculative options with caution (Brown et al., 2018b). Policymakers should not assume that new technologies will become technically and commercially feasible in time for the net zero transition. Such prudence was largely absent from the surveyed decarbonisation scenarios.

Technological biases across different reports

All decarbonisation scenarios display some level of technological bias. However, some are far more technologically disruptive than others. The CCC and National Grid presented the most technologically disruptive proposals. They are also 'closest' to government; the CCC is a statutory body and National Grid operates the UK's electricity system. Their proposals are probably more influenced by the undeniable political challenges of behavioural interventions. This creates an echo chamber of technological bias. Of course, the other implication of their closeness is that these proposals have significant influence over UK climate and energy policy. Acknowledging the impact of political bias should be a priority for the organisations that must balance decarbonisation and politics.

This balancing act may get easier as the urgency of climate action becomes more widely recognised. Even the most technologically disruptive scenarios are trending towards behavioural change. While politics may influence the recommendations of the CCC and National Grid, behavioural change has had a growing role in their climate proposals in recent years. The CCC's updated 2020 policy proposal includes a *Balanced Net Zero* pathway in which 16% of emissions reductions are attributable to social or behavioural changes (Climate Change Committee, 2020b), up from 9% in 2019 (Stark and Thompson, 2019). Between 2019 and 2020, National Grid replaced decentralisation with societal change as a metric for estimating the speed of decarbonisation (National Grid ESO, 2020). These organisations are moving towards more balanced scenarios, perhaps reflecting the slow but sure shift in public opinion—and therefore politics—towards more interventionist climate policy.

5.3.2 Climate strategies and disruption preferences

People have preferences over disruption. Conceptually, disruption is necessary to reduce emissions but undesirable insofar as it makes mitigation harder and more risky. In a typical optimisation problem with two equally disliked characteristics, one might conclude that the government would select the set of mitigation options which minimises disruption across both technology and behaviour. In Figure 5.5 this would be a scenario near to the origin and along the diagonal. However, this conclusion assumes that people—and the politicians who represent them—dislike technological and behavioural disruption equally. In reality, politicians may be unwilling to pursue behavioural changes due to perceived or real public opposition. They would follow a strategy which is more technologically risky and less behaviourally disruptive.

Figure 5.5 supports the idea of a preference for technological disruption amongst climate decision makers. This preference would intensify the echo chamber of technological bias. Researchers might preemptively skew their proposal towards technological options to improve its reception with politicians (Braunreiter and Blumer, 2018). As discussed above, this is particularly pertinent for organisations closest to government.

A preference for technological disruption means policymakers might overlook potential behavioural mitigation opportunities. This chapter's results suggest that behaviour changes, while more limited than technological options, could provide relatively low-disruption mitigation. Given historical delays in energy technology diffusion, the need for swift decarbonisation means balanced disruption preferences could yield a better, quicker pathway to net zero.

Covid-19 caused sweeping technological and behavioural disruption. Policy responses to the pandemic reveal relatively balanced disruption preferences that illustrate a fundamental difference in the perception of health and climate crises. The pandemic presents an immediate and, importantly, transient threat. In contrast, climate damages could be immense but will likely not be felt in the UK for decades (Hoegh-Guldberg et al., 2018). The British government responded to Covid-19 with virtually unfettered public spending and tight lockdowns. On climate, governments are reluctant to take disruptive action. Climate policy is tailored to minimise cost and inconvenience. The tangible risks of a viral pandemic seem to have shifted disruption preferences to a more even balance between new technologies and behaviour change.

5.3.3 Limitations

This study provides a novel, transparent and easily-evaluated measure of disruption. It is a first pass at quantifying technological and behavioural change across a broad swathe of mitigation options. As such, the methodology has a number of assumptions and possible limitations.

The disruption metric implicitly captures the difficulty of scaling technological and behavioural adoption by comparing a proposal to today's baseline. However, it does not explicitly consider the barriers themselves, including cost. A more comprehensive study of the complexity and potential non-linearity of mitigation options would improve the metric but requires extremely detailed analysis for every mitigation option. Adding a component to capture the readiness level of a technology or the penetration of social norms would inflate the disruption of options which are more technologically or socially abstract. Incorporating cost would increase the disruption of demand-side policies which rely on individual investment. This could help identify options where government subsidies would have the largest effect.

Disruption depends on time: the same change over a shorter period of time will be more disruptive to markets and behaviours. This study does not take into account the effect of different proposed timescales across scenarios. This means that its calculations underestimate the disruption embodied in the scenarios from Centre for Alternative Technology (2019) and Friends of the Earth (2018), which aim to achieve net zero before 2050. However, net zero has been legislated for 2050 in the UK. This analysis focuses on the different combination of mitigation options to achieve this target, rather than variations on the target itself. Incorporating the time horizon of mitigation options is an important area for future research in quantifying decarbonisation disruption.

The disruption metric is applied to a descriptive analysis of decarbonisation reports. The dearth of quantitative reports on behavioural mitigation options therefore limits this analysis. Studies on the potential for socially-driven decarbonisation (e.g., Carmichael, 2019) would yield a more behaviourally disruptive scenario, but have yet to provide a quantitative pathway to net zero. They were therefore not included in the review. Moreover, it may have overlooked a set of particularly disruptive interventions, such as geoengineering, by focusing on relatively mainstream sources. While this analysis considers policies that are perhaps most politically realistic, a wider review may provide a more complete picture.

5.4 Summary of findings

The research in this chapter quantified the disruption to technological markets and individual behaviours embodied in possible decarbonisation pathways for the United Kingdom. A review of twelve strategies for decarbonisation proposed by a range of sources, including public and industry bodies, academic organisations and advocacy groups, yielded a large set of possible mitigation options. A novel metric captured the embedded disruption across dual axes of technological and behavioural change.

The results illustrate a distinct bias towards technological disruption through the pursuit of fast deployment and speculative technologies. Almost two thirds of mitigation options utilised only technological disruption. Behavioural mitigation remains undervalued: disruptions to behaviour are both less common and less ambitious than their technological counterparts. Purely behavioural options contributed only a fifth of proposed decarbonisation strategies.

The technological bias is most clearly evidenced by the pursuit of speculative technologies. Technology doubtless has an important role in decarbonisation; the scale-up of renewable energy and electrification of heating and transport are crucial. These transitions are achievable, if challenging, because they utilise proven technology. Yet renewable energy and electrification are not sufficient to reach net zero. Proposed decarbonisation strategies tend to rely heavily on unproven technologies to meet the mitigation gap, such as CCS and hydrogen power. However, Chapter 4 illustrated that these technologies will likely face significant and time-consuming barriers to scale. Behavioural changes can reduce this mitigation gap. The reviewed scenarios, and indeed UK policy, all include demand-side alternatives such as retrofitting homes and encouraging electric vehicle uptake. But disruptive behavioural interventions, such as regulating meat consumption, are largely off the table.

The stakes of the climate challenge demand a careful balance between 'safe' mitigation and high risk, high reward strategies. The research in this chapter demonstrates that UK climate strategies are currently tipped too far towards disruptive technologies. Achieving net zero with the least possible disruption requires rebalancing decarbonisation to diversify risk.

Chapter 6

Discussion and conclusions

Climate action in the UK and internationally is currently insufficient to meet the Paris Agreement's target of limiting warming to well below 2°C (UNEP, 2020). This thesis addresses the opportunities to accelerate the delivery of domestic targets and support international climate goals. This chapter considers the progress towards answering the overarching research question: *how can policy accelerate the delivery of climate mitigation?* Section 6.1 discusses the three major contributions of this thesis, followed by a review of the implications of these findings for policy and the wider climate debate in Section 6.2. Section 6.3 discusses several promising areas for future study.

6.1 Research contributions

The overarching research question was tackled in three parts. The first research section, presented in Chapter 3, melds political and economic theory with an illustrative economic model to consider the value of carbon stock budgets for overcoming barriers to urgent climate action. This analysis highlighted a prevalent example of policy myopia in current climate discourse: the ubiquitous reliance on unproven technologies for achieving emissions targets. This observation led to research in Chapter 4, which analysed past trends to draw out lessons about the duration and dynamics of technological and social transitions. These lessons then inspired a third research section, which used quantitative analysis to measure the relative reliance on disruption of technological markets and individual behaviours embodied in UK climate strategies. This research is presented in Chapter 5. Together, the final two research questions apply the lessons and logic of past transitions to the likely outcomes of current climate trajectories. This thesis makes three main research contributions.

RQ1: How do political institutions and public beliefs affect the urgency of climate policy?

Short-term incentives mean that politicians do not always act in the long-term interests of their country. This climate policy myopia is evidenced by a high long- to short-term mitigation ratio and exacerbated by biased beliefs amongst voters about climate policy. Surveys in the UK and abroad show that voters underestimate the urgency of climate action when making judgements about its issue salience. Citizens with biased beliefs will not vote to support urgent, farsighted climate policymaking. However, these barriers could be addressed using a global carbon stock budget. A simple economic model shows that a carbon stock budget improves nominal welfare in 2100 fivefold, and increases nominal output by 40%. It is most effective if implemented immediately, and is robust to misestimation regarding the level of the budget. The model bolsters the political argument for a carbon stock budget by demonstrating its economic optimality in the face of deep threshold damages.

RQ2: What can history tell us about the speed of technological and social transitions?

Historical transitions yield lessons for the dynamics and duration of future changes. Two classes of transition will be particularly important for achieving net zero: large-scale technological transitions in the energy sector and social transitions driven by societal concern and behaviour change. This thesis assessed five large-scale energy transitions, including nuclear and solar power, and seven social transitions, including the decline of smoking and asbestos. Detailed chronologies were coupled with quantitative metrics of diffusion to produce transition frameworks that map common policy, technical and social developments to transition growth. Duration estimates show the delay between discovery and rapid uptake is shorter for social transitions, taking on average 38 years compared to 76 years for technological transitions. Technological transitions also achieved a slower rate of growth once diffusion begins. Overall, social transitions tend to be swifter than large-scale technological transitions.

RQ3: What do current climate strategies imply for the UK's timeline to net zero by 2050?

This thesis developed a metric to capture technological and social disruption of decarbonisation strategies by estimating the scale of market or activity change embodied in each mitigation option. Results for twelve UK proposals reveal a *technological bias*: they implicitly depend on extreme technological disruption to achieve net zero by 2050. Two thirds of the 538 proposed mitigation options rely solely on the deployment of new technologies, including highly speculative innovations such as CCS. Only one fifth of options rely on behavioural change to achieve mitigation. Behavioural disruption is currently under-utilised. Disruption takes time. Chapter 4 demonstrated that social change can be swifter than technological diffusion. The observed technological bias therefore means that slow diffusion of new and existing technologies could undermine efforts to reach net zero emissions by 2050.

6.2 Policy implications

The overarching research question of this thesis asks how policy can accelerate mitigation. Its findings therefore yield several broad policy implications: the promise of a carbon stock budget, the potential for swift change through social transition, and the imprudence of relying on speculative technologies. This section discusses each implication and makes several practicable policy recommendations.

A carbon stock budget could reduce climate policy myopia and biased public beliefs

Meaningful climate policy reduces the long-term impacts of climate change. This requires expensive and lengthy overhauls of physical infrastructure, commercial markets and social norms. Politicians have signalled their climate ambitions in these areas with future targets for mitigation, investment and efficiency. However, political institutions do not provide incentives for politicians to support their ambitious climate rhetoric with meaningful action. Voters do not hold them to account for their shortsightedness. Accordingly, current mitigation puts the planet on a path to miss the Paris warming target by a wide margin.

Global climate ambitions could be achieved using a carbon stock budget. Unlike the ‘carbon budgets’ legislated in the UK (Climate Change Committee, 2020b), which set five-yearly emissions targets, a carbon stock budget would *permanently* constrain cumulative *global* emissions. Implementing and enforcing such a target will be challenging. But a self-enforcing incentive system—what Nordhaus (2015) refers to as a ‘climate club’—could be designed to to encourage participation amongst both developed and developing nations.

Suppose that climate scientists, economists and activists collectively advocate for a carbon stock budget, much like emissions targets dominate discussions today. For the public, the concept of a budget is accessible and easily communicated. For governments, it sets an enforceable target that is more effective than net zero at limiting climate damages. A carbon stock budget would act as a long-term commitment mechanism to incentivise farsighted policymaking. Both biased beliefs and myopic policymaking would be reduced.

The argument for carbon stock budgets has been discussed extensively by scientists (e.g., Allen et al., 2009; Millar et al., 2017) and endorsed by economists (van der Ploeg, 2018). There has been some discussion of its value as a political commitment mechanism to combat uncertainty and obfuscation in climate policymaking (Geden, 2018). This thesis contributes to the literature by drawing together theories of policy myopia and rational irrationality amongst voters. It provides an additional political argument for implementing a global carbon stock budget, supported by a quantitative illustration of its economic value. Chapter 3 yields four specific policy recommendations.

Policy recommendations

1. Global climate targets should be redefined in terms of the remaining long-term carbon stock budget. The global budget should be allocated to countries based on past emissions and their ability to abate.
2. Negotiations for a global carbon stock budget should begin immediately, facilitated by consistent, coherent recommendations about the appropriate size of the budget from climate experts.
3. Climate communication should describe emissions as drawing down on a finite carbon stock, and mitigation—or inaction—in terms of the time remaining until the budget is exhausted.
4. Policymakers should respond to increased public support for climate action, inspired by the emphasis on finite carbon stocks, with more urgent mitigation.

Social transitions tend to be be quicker than technological transitions

The net zero transition will be unprecedented in scope and speed; no past evolution has required the same level of change, across as many sectors. Nonetheless, historical transitions can provide guidance for the road to net zero. Chapter 4 yields two major policy implications. First, social transition can be swifter than technological transition, suggesting this is a promising area for future policy. Technological transitions are constrained by physical, social and political barriers that slow deployment. The 'S-curve' diffusion narrative has proliferated the idea that technological transitions can be exponential. This thesis contradicts that orthodoxy. Section 4.3.2 shows that growth rates of social and technological transitions tend to settle to a linear rate—a 'Z-curve'—typically within two decades. After that point, technological deployment is constrained by the realities of engineering and construction, including the political and regulatory procedures required for large-scale infrastructure projects. Similarly, the rate of growth of social transitions, though typically swifter than technological ones, is constrained by behavioural factors such as habituation.

Second, the transition frameworks produced from the detailed timelines offer insights into opportunities and risks during the various stages of social and technological transition. While the variety in diffusion metrics presents challenges for comparability, particularly for social change, these frameworks facilitated comparisons of the time taken for each past example to progress through the various transition stages. The early stages of social transitions can be accelerated by creating a popular movement, encouraged by social leaders or advocacy groups. Social movements are, however, susceptible to changes in the wider economy that redirect funding and attention away from the cause. For technologies, the pre-commercialisation period can be accelerated if there is cross-development with a related technology, but this period is particularly vulnerable to innovation traps and economic downturns. Identifying these opportunities and risks is useful for policymaking. Governments can accelerate transitions by facilitating knowledge flows between industries, maintaining oversight of deployment and ring fencing funding for low carbon technological development.

The research in Chapter 4 contributes to the literature on low carbon transitions. Past examples have long been used to estimate the duration of technological transitions, from the transcendence of cars over horses (Grubler et al., 1999) to the roll out of solar and wind generation (Gross et al., 2018). No studies have yet broadened their scope to include transitions motivated by social concern and defined by behaviour change. Chapter 4 meets this gap by applying methods developed in the technological transition literature to historical social changes. Specific policy recommendations from the second research theme are provided below.

Policy recommendations

1. Climate policy should support social transformation as a promising avenue for swift emissions reduction.
2. Policymakers should utilise the points along transition pathways that provide opportunities to accelerate change, while being wary of where transitions are particularly vulnerable to external factors.
3. Climate forecasts should include the insight that deployment of new energy technologies tends to reach a maximum achievable rate relatively quickly. Thereafter, deployment is linear, constrained by construction requirements and other factors.

Technologies dominate proposed decarbonisation strategies

Technological overhaul will play an important role in net zero. Scaling up renewable generation capacity and electrifying heat, transport and some industrial processes are important mechanisms for domestic and global mitigation (Bouckaert et al., 2021; Stark and Thompson, 2019). However, transition plans also include technologies which have not progressed past laboratory demonstration and are unproven at scale. The extent of that reliance was quantified for the first time in Chapter 5.

Policy proposals are far more likely to disrupt technology markets than individuals' lives. This bias is likely based on the political preconception that technological change is 'easier' than behaviour change, evidenced by the finding that proposals developed closer to government—in government agencies or committees—displayed a particularly strong technological bias. Given the extensive literature on the potential for deep social changes to support decarbonisation (see Section 2.2.3), however, this systemic tendency is unwarranted. Supporting behaviour change could reduce the technological mitigation burden, curtail overall disruption and accelerate decarbonisation.

A growing field of research uses disruption analysis to capture the myriad changes embodied in the net zero transition. The field remains somewhat amorphous, but efforts to formalise it include a framework for comparing transitions along dual axes of *disruptive—continuous* and *emergent—purposive* (Ketsopoulou et al., 2021). This framework provides a useful qualitative and illustrative tool (see Figure 2.10), but is not supported by a formal quantitative method. The research in Chapter 5 provides such a tool. Its results contribute to the ongoing debate about the role of technology and behaviour in decarbonisation, and bolster calls for a bigger role for social change in the net zero transition. Drawing together the research in Chapters 4 and 5 provides several specific policy recommendations.

Policy recommendations

1. To increase the likelihood of swift and successful mitigation, governments should aim to balance disruption across technology deployment and behaviour change.
2. Accelerating decarbonisation will mean allocating more funding to interventions proven to reduce energy demand.
3. Governments should undertake a meaningful exploration of the role of policy in achieving social tipping points for more climate-friendly consumption patterns.

6.2.1 Wider applications

This section discusses the wider implications of this research, which are relevant for stakeholders including policymakers, businesses and individuals.

Climate policy should shift focus from pursing marginal adjustments to systemic change

The majority of climate policies enacted to date have been market-based programmes to adjust incentives for decision-makers. Examples include environmental taxes on energy companies, subsidies for heat pumps in homes and emissions trading schemes. All are grounded in the economic theory which pursues marginal adjustments—changing decisions 'in the margin' by affecting incentives on the last unit consumed or purchased. Though theoretical—most policymakers will not think in terms of marginal analysis—this tendency feeds into the narrative of a gradual, supply-side, incentive-based approach to climate action. So far, this approach has, perhaps unsurprisingly, yielded only marginal changes. It will not be sufficient to meet global climate targets.

Chapter 3 provides an economic and political argument for a non-marginal approach to climate action. In particular, it proposed shifting the focus from annual emissions targets to long-term carbon stock targets, which constrain cumulative emissions. Emissions targets embody the marginal thinking of current climate policy by focusing on an annualised approach which (1) has a weaker link to climate outcomes and (2) provides few restrictions on near-term emissions, thus failing to constrain cumulative stocks. While goal-setting can be good (when supported by sufficient policy implementation), picking the wrong metrics can obfuscate outcomes and misdirect efforts.

One of the clear policy recommendations of Chapter 3 is that targets should be redefined in terms of the remaining long-term carbon stock budget, and that global climate discourse should reflect that shift. This is but one example of the wider implication of this research: that domestic policy, target-setting, international agendas and climate communication should shift focus from marginal adjustments to deep, systemic changes. This may mean relating climate action to threshold risks, which has been shown in social experiments to increase cooperation in achieving targets (Barrett and Dannenberg, 2014). It may also mean moving from price incentives to bans and regulations, for which there appears to be a growing appetite (Bouckaert et al., 2021). Shifting climate discourse would not only support deep policy changes but could also initiate or accelerate individual actions to support decarbonisation. It should be a priority for climate policymakers and researchers alike.

Speculative technologies delay mitigation and increase potential disruption

This thesis showed that UK decarbonisation strategies derive most of their emissions savings from supply-side solutions, often in the form of highly speculative new technologies. It also demonstrated that technological innovation is generally slow, and usually slower than social transitions. These findings suggest that the observed technological bias is slowing decarbonisation. It is necessary, however, to distinguish *existing* and *risky* technologies. Achieving net zero in three decades means utilising all the tools at our disposal—and many of them are technological. However, limiting the risk of overshooting net zero means approaching long-promised 'silver bullet' technologies such as direct air CCS with a healthy dose of scepticism. Given the significant damages associated with 2°C warming or more, gambling on future innovations is reckless.

Policies that enable near-term mitigation should be prioritised over slow-burn strategies, at least for now. For policymakers, this research supports the argument that options that are proven, relying on existing technology, infrastructure and accepted behaviours, should be pursued at pace. Many such options exist, and a large majority of them combine the diffusion of common, small-scale technologies with the adoption of new behaviours. Examples include rolling out heatpumps in homes or reducing the weight of passenger vehicles. This is one of the central conclusions of this thesis, and is discussed above. However, it has several wider implications.

The fact that technology cannot provide a 'silver bullet' quickly enough to achieve net zero by 2050 has two major implications for individuals. First, we will inevitably see changes to behaviours, routines, purchases and activities over the next three decades as low carbon lifestyles become the norm. At present, this is seen largely as a sacrifice that will reduce quality of life. However, many of the changes have significant cobenefits for health, wellbeing, living costs. There is growing support for climate action (European Commission, 2019)—even if it has yet to translate into climate voting (as discussed in Chapter 3). A transition of climate beliefs, supported by the shift in focus from marginal to systemic change and further emphasis on cobenefits, would facilitate the behaviour changes necessary to meet the technological emissions gap.

The second implication for individuals is that the longer this bias towards speculative technologies persists, the deeper and more disruptive the eventual behaviour changes will have to be. Every year spent waiting for low carbon innovations reduces the remaining stock of cumulative emissions available before temperature overshoot becomes inevitable. In effect, every year of inaction means more mitigation is necessary in the decade before 2050. At that point, waiting will no longer be possible: mitigation will have to be achieved with only existing technologies and behaviour change. Given its short time frame, such a transition has the potential to be highly disruptive. This creates an additional incentive for both policymakers and individuals to support mitigation options that can be initiated in the near-term.

The technological bias is a global phenomenon. Chapter 5 analysed decarbonisation strategies for the UK. However, the implications of the results are internationally applicable. In particular, the overt reliance on CCS is globally ubiquitous. This was best evidenced by the International Energy Agency's recent report, *Net Zero by 2050*, which presented a roadmap for decarbonising the energy sector. Almost half of the report's proposed emissions savings were derived from technologies which are currently under development, including electrification, hydrogen, bioenergy and fossil fuel CCS (Bouckaert et al., 2021, p. 16). Their conservative

CCS scenario limits fossil fuel CCS capture to 150MtCO_2, but requires 16% more renewable electricity and 60% more hydrogen. Clearly, technological bias is not just a UK tendency. One might argue that a global bias at least means more effort is going towards achieving innovation and diffusion. However, the same could be said of transitions relying on existing technologies and behaviours. Network effects mean global dynamics could in fact be more profitable for accelerating behaviour changes than technological innovation. A global acceptance that meaningful climate action must happen immediately, and utilise existing mitigation levers rather than waiting for speculative innovations, will increase the chances of limiting warming to 2°C.

The 'lowest-hanging fruit' for decarbonisation involve behaviour change

Behaviour changes are often seen as a last resort of decarbonisation: amongst policymakers there is a preference for supply-side adjustments that are 'invisible' to end users. However, this analysis shows that the scale of technological revolution required for supply-side decarbonisation means that many demand-side changes are, in fact, less disruptive. Contrary to the conventional wisdom that most low-hanging fruit are purely technological (and have already been plucked (International Energy Agency, 2017)), some of the most promising avenues to near-term decarbonisation combine new behaviours with existing technologies to support a transition to a net zero society.

While technological options tend to provide more aggregate mitigation, they can also be highly disruptive—by requiring exceptionally fast development or massive scale. On the other hand, options involving social adoption already have the groundwork laid, with concern over climate change high and some shifts underway. The results of Chapter 4 show that policies can accelerate behavioural change further. Historical transitions, including seatbelt uptake and the elimination of ozone depleting substances and leaded petrol, demonstrate how aggressive policies coupled with a willingness to change behaviour and adoption of mature technologies can lead to swift and successful transitions.

Achieving behaviour change is challenging. It can be hampered by habituation, complexity of new behaviours, climate scepticism, poor communication and financial barriers (see Section 2.2.3). But technological innovation, and even the scale-up of existing technologies such as nuclear power, are challenging too. The barriers they face—construction, safety, regulation—also tend to be more immutable than social roadblocks. As a result, Chapter 4 shows behaviours can propagate more quickly, a vital observation as the clock ticks down to 2050.

Behavioural transitions are in some ways less risky than their technological counterparts—we know it is possible, albeit difficult, to achieve them. Perhaps behaviour changes can best be viewed as an insurance policy against technological failure. If the promised low carbon innovations are unsuccessful, or cannot be deployed in time, then behaviour change can provide a buffer period during which technical development can continue. This insurance value—along with the fact that they can achieve mitigation with relatively little disruption—means that behaviour changes offer some of the swiftest and safest opportunities to accelerate net zero. Decarbonisation strategies should reflect that.

6.3 Areas for future research

This thesis pursues a broad research question, and employs interdisciplinary methods to contribute to literature across a number of fields. It yields several avenues for future research.

Measure overshoot risk and myopic mitigation deterrence

The research in this thesis identified several barriers to urgency climate policy: political myopia; ambiguous emissions targets; slow technological transitions; a bias towards innovation; reluctance to pursue behaviour change. This work's central novelty is combining these risks into a single discussion with the goal of accelerating climate action. The first major avenue for further research is to continue developing metrics to highlight the risk and myopia of current mitigation strategies. This thesis takes the first step, by presenting a metric of disruption. Two further metrics would bolster the economic, engineering, political and social arguments for urgent decarbonisation based on existing technologies and behaviour. The first would capture the *overshoot risk* for climate targets embodied in different decarbonisation strategies. The second would measure the *mitigation deterrence* of climate strategies by relating climate myopia to emissions pathways and climate outcomes.

Overshoot risk refers to the likelihood that a particular set of mitigation options leads to a jurisdiction missing its climate target—be that a domestic net zero commitment or the global 2°C target. Measuring overshoot risk would combine concepts of disruption with the results from Chapter 4's transition analysis that identifies the delays and barriers of technological and social change. Translating disruption and delays into overshoot risk underlines the climate policy tradeoffs which are currently being largely ignored in policy narrative: that delaying mitigation and forgoing opportunities for near-term abatement increases the risk of future overshoot—and future damages.

The overshoot risk metric could build on the disruption analysis presented in this thesis, which included an implicit consideration of risk. The disruption metric focused exclusively on scale. Future research to quantify overshoot risk should include the impact of deployment speed and complexity of a technology or behaviour. If it were related to warming targets, the overshoot risk metric would also need to consider the complex scientific relationships between emissions pathways, carbon stocks and surface temperatures.

A mitigation deterrence metric would progress the body of research combating climate policy myopia. This thesis defined climate policy myopia as a high long- to short-term mitigation ratio. Future research could quantify this imbalance by measuring the reliance on late-stage mitigation. Such a metric would be related to the overshoot risk metric discussed above. However, it would focus exclusively on emissions forecasts and be utilised in political debates to highlight the recklessness of relying on future ‘silver bullet’ innovations.

A metric to explicitly measure the myopia embodied in climate policy proposals would offer a political tool to accelerate decarbonisation. By highlighting climate myopia, such a metric would allow researchers, activists and farsighted politicians or policymakers to confront those who curry favour with lobbies or voters by putting the burden of mitigation on future generations. It could be used to hold politicians to account over their climate carelessness.

Mitigation deterrence is a concept developed by Markusson et al. (2018) to describe the reduction or delay of mitigation resulting from consideration of alternative options. It is closely related to climate policy myopia, although mitigation deterrence emphasises the role of alternatives rather than general political barriers. As the authors note, mitigation deterrence is not innately problematic. But, since temperatures are related to carbon stocks rather than annual emissions, delaying emissions reduction does tend to increase climate risks and reduce cobenefits.

Measuring overshoot risk and myopic mitigation deterrence would emphasise where political (mis)incentives are increasing climate exposure and impeding policy progress. It would support the compelling argument for immediate action based on currently available mitigation options.

Identify specific opportunities and constraints in accelerating the net zero transition

This thesis illustrates that historical transitions faced common opportunities and vulnerabilities. Future research should leverage this insight to develop ambitious, cross-sector proposals to accelerate the delivery of climate targets. Identifying opportunities and protecting against vulnerabilities will require two different approaches.

The first research agenda should be a broad, interdisciplinary programme to identify levers to accelerate transitions. Researchers could assess how growing social pressure can instigate meaningful climate policies. Social movements can be accelerated by campaigns or leaders who ‘capture the public imagination’. Future research should investigate how best to communicate climate risks to capture imaginations, cement climate risks in people’s lived experiences and accelerate individual change. Previous research on the impact of climate communication is mixed, but has largely focused on a relatively narrow set of frames: climate damages; cobenefits; social norms (Homar and Kne, 2021). Including a broader set of options, including carbon stock budgeting, social collapse, and the role of climate leaders, could yield valuable insights.

Future research should also aim to identify, propose and develop the novel policies, markets and products that will accelerate the pathway to net zero. Two particular areas could create significant change. The first addresses the current under-exploration of meaningful policies to incentivise behaviours and norm change. This research could be modelled on—or undertaken alongside—the UK government's Behavioural Insights Team (formerly the Nudge Unit), which uses behavioural science and economics to improve policy. It could build on research on the role of policy in social change (Young and Middlemiss, 2012), the potential for social tipping point interventions (Otto et al., 2020), and the value of different public and private entities in engaging individuals in low carbon transitions (Chilvers et al., 2021). The second area is developing proposals for 'greening the financial system'. Achieving net zero, be it through technological or social means, will require huge investments over the coming decades (Climate Change Committee, 2020b). There is growing appetite amongst institutional investors to ameliorate climate-related financial risks by decarbonising portfolios, but this has yet to translate into widespread carbon divestment (GFANZ, 2021). Future research should consider how to capitalise on this movement to channel investment into the sectors which have the greatest potential for near-term change.

The second goal to ameliorate vulnerabilities and constraints will require detailed analysis of transitions' dynamics. Past technological and social transitions have been constrained by a variety of factors, including construction in energy transitions and political license in social transitions. Determining the exact nature of these constraints would be a valuable field of research. Take construction: detailed analysis of the process, duration and roadblocks of construction of energy transitions would be necessary to provide additional guidance on the likely scale up of wind and solar, and the eventual deployment of CCS. Existing studies that consider a single transition in detail have largely focused on the innovation and diffusion process (Kern, 2012) or time and cost barriers (Sovacool, 2016), rather than physical constraints of construction (though of course these are related). Similarly, social transitions exhibited periods when a 'loss of momentum' put the transition in jeopardy, and also times when public figures, interventions and communication could be particularly effective. Understanding potential restrictions on the low carbon transition will be critical to overcoming them.

Formalise disruption studies for low carbon transitions

Applying concepts of disruption to low carbon transitions is a relatively recent development. The field is currently nebulous, with many definitions of transition and a number of proposed frameworks for qualitative analysis (Wilson and Tyfield, 2018). Drawing together the growing research interest to formalise disruption studies would be beneficial.

Recent work by the UK Energy Research Council has made the first steps in this direction by defining disruption in contrast to continuity (Ketsopoulou et al., 2021). Their definition has a quantitative element, based on trends in the diffusion of a disruption. Incorporating measurable benchmarks into a widely-accepted definition is a promising avenue to formalise disruption studies. It would also offer an opportunity to link the nascent disruption literature to the established field of transitions, particularly technological and energy transitions.

Quantifying the definition points to the second step in formalising disruption studies—creating a universal metric of disruption. This thesis has presented a metric which separates disruption into the constituent parts of technological and behavioural change for the specific purpose of decomposing low carbon change. The core intent of this research was to evaluate decarbonisation strategies and spark debate on the role of behaviour and technology, rather than to develop a metric. However, it can provide a springboard for other researchers to progress the field. Future work to quantify aggregate disruption could take guidance from the literature which parameterises the S-curve of innovation and includes a measure of the 'half-life' of diffusion (e.g., Bento et al., 2018; Lund, 2006).

A corollary of formalising disruption studies is developing a method to capture uncertainty in quantitative analysis of disruptions and transitions. This thesis presented two novel methodologies that combine qualitative analysis with metrics. Progressing these methodologies to capture the uncertainty inherent in low carbon disruption analysis is a profitable area of future research. Many parallels exist between the methods employed in transition and disruption analysis—both combine qualitative and quantitative observations with a novel quantification method. Transition analysis is well established, particularly for historical energy transitions. However, past work on energy technologies has largely failed to estimate uncertainty in the quantification of transition duration. A metric that was able to capture both technological and social uncertainty would support comparisons between transitions and highlight where additional analysis could reduce ambiguity. An uncertainty tool developed for transitions could also be applied to disruption analysis. This would help to highlight which proposed mitigation options are most risky, both in the level of disruption and uncertainty.

Compare international patterns of technological and behavioural disruption

Chapter 5 assessed the balance of technological and behavioural disruption in decarbonisation strategies for the UK. Its conclusions are internationally applicable due to the uniformity of domestic and international mitigation plans. Nonetheless, the fact that some countries have had more success in decarbonising than others suggests there is value in comparing international case studies. Coupling a formalised metric of disruption with international comparisons could yield insights in two important areas.

First, international case studies would highlight how the particular context of a transition affects its disruptiveness. For example, increasing the share of nuclear in the UK is not particularly disruptive—while it requires huge efforts of engineering, construction and regulatory oversight, the technology is mature. Moreover, public opposition to nuclear power in the UK is mild. In contrast, increasing nuclear generation in Japan would be hugely disruptive, due to the ongoing effects of the Fukushima incident (Hayashi and Hughes, 2013). New nuclear plants would require extensive regulatory oversight and possibly the development of new earthquake and tsunami safety measures. It would also face considerable public opposition. This example shows how international comparisons could support evaluation of the complexity of a technology or behaviour and its influence on a transition's duration and disruption.

Second, further comparisons may highlight jurisdictions where a different approach has produced mitigation with relatively little disruption. This may not be possible at a national level, given the uniformity of national decarbonisation strategies. However, at a subnational level, there may be cities and communities with particularly ambitious schemes that could provide guidance about how policy can support low carbon disruption. Large technological transitions generally require government funding, so subnational policies are likely to focus on interventions with a behavioural component, such as transport policy or housing retrofits. Given this thesis' conclusion that these policies offer opportunities to accelerate mitigation, highlighting success stories in these areas would provide valuable guidance for the net zero transition.

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Appendix A

Timelines of historical transitions

This appendix provides detailed timelines of the technological and social transitions analysed in Chapter 4. These historical timelines and the quantitative analysis of growth rates (see Figures 4.9 and 4.10) were used to identify transition stages and develop the frameworks in Figures 4.3 and 4.7,

Tables A.1 to A.5 give the timelines for technological transitions: nuclear power, solar power, wind power, combined-cycle gas turbines and carbon capture and storage. Tables A.6 to A.12 give the social and hybrid transition timelines: asbestos, leaded petrol, ozone depleting substances, seatbelts, congestion charging, smoking and electric vehicles. The initial stages of transition, which are evidenced by historical events, are noted in each timeline.

Table A.1 History of nuclear power

1919	**No supply (World):** Rutherford shows that nuclear rearrangement occurs when alpha particles are fired into nitrogen (World Nuclear Association, 2020a).
1939	Otto Hahn and Fritz Strassmann show that the nuclear reaction can release atoms to generate a self-perpetuating chain reaction. World War II breaks out in Europe, and nuclear programmes around the world refocus on the military applications of nuclear power (World Nuclear Association, 2020a).
1941	MAUD Committee in the UK publishes reports on *Use of Uranium for a Bomb* and *Use of Uranium as a Source of Power*. The reports concluded that it was not worth pursuing the latter during wartime (World Nuclear Association, 2020a).
1945	In France, the Atomic Energy Commission (Commissariat á l'énergie atomique – CEA) is established. The CEA is responsible for nuclear policy and R&D (World Nuclear Association, 2020b).
1945	The USA drops atomic bombs on Hiroshima and Nagasaki in Japan, in the first week of August. This is less than a month after the first successful test in New Mexico. Japan surrenders and World War II ends. Attention then returns to nuclear as a source of power (World Nuclear Association, 2020a).
1951	**Limited non-market supply (World):** First nuclear reactor, Experimental Breeder in Idaho, produces trivial amount of energy (World Nuclear Association, 2020a).
1953	In the US, President Eisenhower launches the Atoms for Peace programme to reorient research effort into nuclear power (World Nuclear Association, 2020a).

1954	The USSR develops the first nuclear energy generator used for heat and electricity, at The Institute of Physics and Power Engineering in Obninsk.The reactor, named AM-1 (Atom Mirny, or peaceful atom) had a design capacity of 5 megawatts electric (MWe). The same year, the USA launches the first nuclear-powered submarine, the *USS Nautilus*. Submarines use pressurised water reactor (PWR) technology (World Nuclear Association, 2020a).
1955	The world's first fast neutron reactor, BR-1, begins operating in Obninsk, USSR. The BR-1 produces no power, but is precursor to BR-5, which is used for research necessary to design sodium based fast breeder reactors (World Nuclear Association, 2020a).
1957	The Idaho demonstration project enables the USA nuclear programme to develop the Shippingport demonstration PWR reactor in Pennsylvania. The 60MWe reactor operates until 1982 (World Nuclear Association, 2020a).
1959	**Rapid growth (France):** CEA and state-owned Electricité de France develop the first commercial nuclear reactor, Marcoule G2, based on natural uranium gas-graphite technology (World Nuclear Association, 2020b).
1960	First commercial PWR reactor goes live in the USA, designed by Westinghouse. Also in 1960, GE start the first commercial boiling water reactor (BWR) (Dresden-1). Both have capacity of 250MWe (World Nuclear Association, 2020a).
1969	There is a safety incident at the St Laurent A gas-cooled graphite reactors in France (about 50 kg of fuel melted in unit 1), constituting a International Nuclear and Radiological Event Scale Level 4 of 7 (World Nuclear Association, 2020b).
1973	The first large high-powered reactor begins operating near Leningrad, USSR (World Nuclear Association, 2020a).
1974	After the first oil price shock, the French government votes to pivot energy efforts into nuclear power. Despite having significant engineering expertise, France does not have a wealth of natural energy resources, so nuclear is a logical focus for energy security (World Nuclear Association, 2020b).
1979	There is a partial meltdown at the Three Mile Island nuclear power plant in USA. Part of the core of one of the reactors melts when a cooling malfunction occurs, destroying the reactor. No one is injured or killed (World Nuclear Association, 2020d).
1980	A second INES Level 4 incident at St Laurant A in France. Annealing occurred in the graphite of unit 2, causing a brief heat excursion (World Nuclear Association, 2020b).
1986	The Chernobyl nuclear accident kills two plant workers due to the explosion, and 28 people soon after due to acute radiation syndrome (World Nuclear Association, 2020e).
1999	A parliamentary debate reaffirms France's three goals of energy policy: energy security, minimising emissions and controlling nuclear risk. It is accepted that renewable options are not a feasible possibility to replace nuclear in the near future (World Nuclear Association, 2020b).
2005	The French government lays out a detailed plan to develop European Pressurised Water Reactor (Flamanville 3) as a test case for 40 more to be built from 2021. The same year, the government establishes legislation for energy policy and security—nuclear power central to this (World Nuclear Association, 2020b).
2006	The CEA receives a EUR3.8 billion R&D contract from the government to develop two types of fast breeder reactors. The plans for Flamanville are confirmed after a public debate (World Nuclear Association, 2020b).
2007	Construction begins at Flamanville 3 (World Nuclear Association, 2020b).

2008	The Nuclear Policy Council (CPN) is established by presidential decree. The CPN includes the president, cabinet secretaries, the head of the CEA and military chiefs. The establishment of the Council emphasises the importance of nuclear power in France (World Nuclear Association, 2020b).
2010	Électricité de France announces that it will not be proceeding with a planned nuclear power plant at Penly. The previous year, the French president announced the project, but in 2010 the safety regulator rejects EdF's proposal for the project. EdF halts the project, and states that it had no plans to build new capacity in France to be open before 2025 (World Nuclear Association, 2020b).
2011	A large earthquake in Japan results in a nuclear meltdown at the Fukushima power plant. The disaster lead to a trend away from nuclear power, in Japan and across the world (Hayashi and Hughes, 2013).
2011	After a six-month review prompted by the Fukushima disaster, the French safety regulator proposes new 'hard core' safety mechanisms to ensure reactors are secure against natural disasters (World Nuclear Association, 2020b).
2013	The French government runs a national debate on nuclear policy after President Holland is elected, gathering more than 170,000 responses. The report concludes that ramping down nuclear will risk a power price shock as no sufficient alternative exists (World Nuclear Association, 2020b).
2015	The *Energy Transition for Green Growth Bill* is proposed in 2014 in the French National Assembly, which limits nuclear generating capacity to current (2014) levels, and aims to reduce nuclear's contribution to energy supply to 50% by 2025. The bill is passed to the Senate who, in 2015, amend it to remove the cap, although the 50% target remains (World Nuclear Association, 2020b).
2017	The French president reiterates the importance of nuclear power for clean energy, saying nuclear is 'the most carbon-free way to produce electricity with renewable' (World Nuclear Association, 2020b).
2018	The tradeoff between renewable and nuclear targets is reaffirmed in the energy plan, and the year for 50% nuclear energy is reset at 2035 (World Nuclear Association, 2020b).

Table A.2 History of solar power

1905	**No supply (World):** Albert Einstein publishes paper on the photoelectric effect, which explains how light can generate energy (Sabas, 2016).
1954	**Limited non-market supply (World):** Daryl Chapin, Calvin Fuller, and Gerald Pearson at Bell Laboratories develop the first modern solar cell, a silicon photovoltaic (PV). This first model is not designed for outdoor use (Green, 2005).
1955	The first PV cell designed for outdoor use is made by Bell Labs. The module consists of 48 10cm sub-modules assembled inside and aluminium case. Each sub-module contains 9 smaller cells set in silicon oil in a plastic case. The module is tested in Georgia, USA, and has a efficiency of around 2%. The same year, National Fabricated Products licences Bell Labs' technology and create first commercial solar cell. It is unsuccessful (Green, 2005).
1956	National Fabricated Products is sold to Hoffman Electronics, which pivots development into space applications for solar power—powering satellites in space using PV cells (Green, 2005).
1964	Progress on terrestrial applications of solar cell is maintained by Sharp in Japan. Sharp establishes limited production of cells in their Nara manufacturing plant (Green, 2005).
1966	Sharp's cells from Nara are used to power a 225W lighthouse in Ogami Island. This is the most powerful solar lighthouse at the time, and a strong demonstration of PV technology. Between 1961 and 1972, Sharp convert 256 lighthouses along the Japanese coastline to solar power (Green, 2005).

1973	The oil crisis stimulates low-cost solar technology. In the USA, the Solar Power Corporation is established, developing a small module with 5-6% efficiency rating. Their commercial module has five cells mounted in a glass-fibre-reinforced printed circuit board and covered by silicone rubber. These modules are priced at US$20/W per 1000 units (Green, 2005).
1975	The USA government establishes procurement programmes to stimulate PV research. In 1975-76, it purchases 54kW worth of solar modules from US-based manufacturers. Efficiency is between 4.8% and 6.5% and the cost between US$20/W and US$39/W (in 1980 dollars) (Green, 2005).
1976	Testing in Australia shows PV cells perform poorly in harsh conditions (parrots eating silicone, dust blowing, hail). Based on these tests, future cells are to be made with a glass covering, rather than silicone/rubber (Green, 2005).
1977	Spectrolab in the USA develop method for laminating cells to glass cover sheet, a precursor to modern designs. They also develop screenprinting for cell fabrication, which becomes widely used. Testing concludes that Spectrolab's modules are most hardy in harsh and variable outdoor conditions (Green, 2005).
1977	German government funding for research, development and demonstration increases significantly, with funding allocated to 71 universities, firms and research institutes over a 12-year period (Jacobsson et al., 2004).
1982	In the mid-1970s startup established by former Spectrolab employees was purchased by ARCO, a large oil company. By 1982, ARCO is offering a 5-year warranty on their solar cells (Green, 2005).
1983	The first German demonstration project is commissioned, financed by the Federal government, using cells from German manufacturer AEG. The project is the largest in Europe at the time, with 300kW capacity (Jacobsson et al., 2004).
1986	The Förderveirein Solarenergie organisation is established, consisting of scientists, industry representative and members of the public. The organisation soon develops with the concept of 'cost covering payments', and advocates for their use in solar energy in Germany. This prompts the development of feed-in tariffs (FiTs) (Jacobsson et al., 2004).
1988	German parliamentary resolution calls for more research into renewable energy following the 1986 Chernobyl disaster (Jacobsson et al., 2004).
1989	**Rapid growth (Germany):** 1000 Roofs Solar Power Programme begins, to install solar cells in homes across Germany. The programme aims to develop installation know-how (Brown and Hendry, 2009).
1991	Germany's Electricity Feed-in Law comes into force. Utilities are required to accept feed-in of green electricity, and pay generators 90% of energy retail price for the generation. This is considerably higher than the cost of conventional energy generation (Frondel et al., 2010).
1992	BP Solar offers a module with an efficiency of 14.3%. This efficiency is far higher than competitors, enabled by a manufacturing approach based on plating contacts (Green, 2005).
1997	Sanyo in Japan begins production of cells with 15.2% efficiency, and announces that they will produce 16.1% efficiency cells by 2004 (Green, 2005).
1998	The European Union electricity market is liberalised, resulting in falling energy prices—and falling feed-in tariffs (Frondel et al., 2010).
1999	The 100,000 Roofs Solar Power Programme is approved, aiming to expand the progress of the 1000 Roofs Programme. The programme achieves 66,000 installations, around 350,000kW, between 2000 and 2005 (Brown and Hendry, 2009).

2000	The Renewable Energy Sources (EEG) Law is passed, legislating the priority of renewable energy sources in electricity generation. The law obliges utilities to purchase green generation and aims to achieve environmental targets. The EEG guarantees stable feed-in tariffs for up to 20 years, providing favourable conditions for long-term solar investment (Frondel et al., 2010; Pfeiffer, 2010).
2003	Following an initiative by the German Ministry of Economics, the EEG is amended so that energy-intensive industries will exempt from energy surcharge, under the Special Equalisation Scheme Act, aiming to make sure German industries stay competitive offshore. The Act is important to maintain consensus on the EEG (Leiren and Reimer, 2018).
2005	The European Emissions Trading Scheme (ETS) is established, imposing a cost on emissions that made renewables relatively cheaper (though still far from absolutely cheaper) (Frondel et al., 2010).
2009	A revision to the EEG aims to achieve renewable generation for 30% of German electricity supply by 2020. To this end, FiT systems are adjusted and secured (Pfeiffer, 2010).
2011	After the Fukushima disaster in March, a temporary shut down was imposed on the existing nuclear expansion; in July, the Parliament voted to shut down eight nuclear plants and phase out the remaining nine by 2022 (Leiren and Reimer, 2018).
2015	After an EEG amendment proposes a transition from FiTs to an auctioning system for renewable generators, to a mixed reception, and the first renewable energy auctions are held in 2015 (Leiren and Reimer, 2018).

Table A.3 History of wind power

1887	**No supply (World):** Professor James Blyth in Anderson's College, Glasgow builds the first windmills for electricity production. Blyth builds three models, one of which powers his home for 25 years (Jones and Bouamane, 2011).
1888	American inventor Charles F. Brush builds a wind turbine in his backyard. The turbine has 17-meter rotor blades and generates 12kW of electricity. Brush stores power in batteries (Jones and Bouamane, 2011).
1891	Paul la Cour, a Danish high school teacher, becomes the first person to conduct systematic tests of wind turbines. He invents a turbine which powers his school and the local area, and sparks the development of wind power in Denmark (Jones and Bouamane, 2011).
1894	British engineer R. A. Fessenden builds an experimental turbine in London. He launches Rollason Wind Motor Company to build turbines for the countryside (Jones and Bouamane, 2011).
1920	The focus on developing coal-burning power stations during the interwar years leads to a downturn in wind turbine development. The number of turbines in Denmark falls by a third between 1920 and 1940 (Jones and Bouamane, 2011).
1925	During the 1920s, significant theoretical contributions are made. Professor Albert Betz of the German aerodynamics research center performs theoretical studies on wind turbines, and Hermann Glauert of the British Royal Aircraft Establishment develops an aerodynamic theory for wind turbines (Jones and Bouamane, 2011).
1927	Mercellus Jones of the USA invents the first three-bladed wind turbine (Jones and Bouamane, 2011).
1931	French engineer George Darrieus invents the first vertical axis wind turbine, patenting it in the USA. The vertical axis allows the turbine to generate power from wind blowing in any direction, rather than having to be manually reoriented (Jones and Bouamane, 2011).

1942 **Limited non-market supply (World):** F.L.Smidth & Co develop modern three-bladed turbine with aerodynamic winds and concrete tower with output of 40-70kW. The turbine in Bogo, Denmark was part of a wind energy system that ran the supply for the island (Jones and Bouamane, 2011).

1951 An engineer with the Federal Power Commission applies to the USA Congress for $2 million funding to develop a large wind power plant. His design is for turbines with a capacity of around 7000kW, and his proposal includes integration into the federal power system. Congress rejects the proposal (Jones and Bouamane, 2011).

1959 Johannes Juul, a Danish engineer, invents a turbine which is the precursor to modern turbines. His ‘Gedster’ turbine produced 400,000 kW a year. Juul’s invention of emergency aerodynamic tip breaks is still used in turbines today (Jones and Bouamane, 2011).

1973 The first oil crisis drives up oil prices across the world. Denmark relies on imported oil for 90% of its energy supply, and this crisis has a significant economic effect. It stimulates a shift away from oil energy, and electricity companies announce their intention to invest in nuclear (IRENA and GWEC, 2013).

1976 The Danish government publishes the First Energy Plan, focused on energy savings and the intention to shift to nuclear power. The Plan imposes energy taxes in order to raise funds for R&D (IRENA and GWEC, 2013).

1979 A second oil crisis occurs, again sparking economic difficulties. Denmark establishes a Ministry for Energy (IRENA and GWEC, 2013).

1981 The Second Energy Plan is published in Denmark. It establishes strong incentives for domestic energy production, including subsidies for wind turbines. (IRENA and GWEC, 2013).

1982 **Rapid growth (Denmark):** The idea of wind energy cooperatives establishes a market for commercial windmills in communities (IRENA and GWEC, 2013).

1985 The Danish government votes to exclude nuclear power from energy planning. Instead, the Ministry of Energy and utility companies reach the ‘100MW Agreement’ to develop 100MW of wind power before 1990, with a 30% grant for capital costs (IRENA and GWEC, 2013).

1988 As the reliability and cost-effectiveness of turbines develop, the government reduces capital subsidies. In 1988, parliament votes to repeal the subsidy altogether (IRENA and GWEC, 2013).

1990 The Third Energy Plan sets goal to provide 10% of electricity from wind by 2020. The Danish Energy Agency develops Danish Wind Turbine Certification Scheme, which requires onshore and offshore turbines to meet certain safety and performance standards (IRENA and GWEC, 2013; UN ESCAP, 2012).

1992 Denmark introduces a carbon tax. The FiT is initially set at 85% of retail energy prices (IRENA and GWEC, 2013; UN ESCAP, 2012).

1993 The FiT is fixed (decoupled from energy prices) at 85% of utilities production and distribution costs. In addition, wind turbines are granted a refund of the carbon tax and a partial refund of the energy tax, which increases revenues in the first years of operation (IRENA and GWEC, 2013).

1999 The Danish government votes to liberalise the energy market by 2002. The reform sets a target for 20% energy supply from renewables by 2003, largely from wind and biomass. It also repeals its FiT, and plans to support wind energy through renewable portfolio standards with tradeable green certificates. However, the legislation for the green certificates does not pass through parliament (IRENA and GWEC, 2013).

2002 The government aims to increase the competitiveness of its renewable energy sector. As part of this strategy, two of five planned offshore wind projects are abandoned (IRENA and GWEC, 2013).

2004	There is a considerable restructuring of the Danish energy market. Power companies are privatised; distribution, transmission and distribution are separated (IRENA and GWEC, 2013).
2009	The European Renewable Energy Directive creates target to reach 30% renewables by 2020 (IRENA and GWEC, 2013).
2012	A new energy agreement is made to cover 50% of electricity demand with wind power by 2020, and build 3300MW new wind capacity (IRENA and GWEC, 2013).

Table A.4 History of closed-cycle gas turbines

1905	**No supply (World):** French engineers Armengaud and Lemale build the first gas turbine capable of producing power (Watson, 1997).
1930s	Intensive public funding for aircraft jet engines in Germany and the UK yields technological spillovers for CCGT (Watson, 1997).
1936	The first industrial gas turbine is developed by Brown Boveri in Switzerland. It generates 1MW of energy (Kern, 2012).
1939	The first industrial turbine in commercial service is installed, again by Brown Boveri in Switzerland (Watson, 1997).
1948	General Electric in the USA reuse waste heat from their first gas turbine elsewhere in the facility where it is installed. This is a precursor to combined cycle turbine (Watson, 1997).
1949	**Limited non-market supply (World):** The first fully-fired combined cycle turbine is installed in conjunction with a steam plant, by General Electric in the USA. Meanwhile, Brown Boveri in Switzerland investigate the potential to use waste heat, and install the first CCGT in Switzerland in 1956 (Watson, 1997).
1960s	Electricity blackouts in the USA and UK stimulate demand for CCGT, which have very fast start-up times. Sales following the blackouts enable manufacturers to reinvest revenues to advance CCGT technology (Watson, 2004).
1970s	New CCGT begin to reach 100MW capacity, with efficiencies of around 40%. The exhaust heat of new turbines is sufficiently hot that it raises enough heat to drive a steam turbine without additional firing, enabling the high efficiencies (Watson, 1997).
1973	OPEC's decision to restrict the flow of oil and gas drives up the price, resulting in the first oil crisis. Natural gas became an expensive energy alternative, and demand for CCGT falls (Watson, 2004).
1975	The European Union implements Directive 75/404/EEC on maintenance of minimum stocks of oil, and restricting the use of natural gas in power stations. This directive aims to reduce the risk of interruptions to the power supply. In effect, this means that CCGT cannot be used in Europe (including the UK) (of Lords, 2018).
1977	The USA government provides R&D funding for CCGT through the High Temperature Turbine Technology programme (Watson, 1997).
1978	The Japanese Moonlight programme begins, allocating public funding to CCGT development. At the same time, the Public Utility Regulatory Policy Act in the USA is passed, encouraging the use of alternative fuels, including gas turbines in combined cycle systems (Eckhardt, 2013; Watson, 1997).
1980s	The surge in demand leads to fierce competition and extremely swift development of new turbines. This creates some reliability issues and associated delays (Watson, 1997).

1982	For the next decade, capital costs for installing CCGT increase. This bucks the trend of previous decades, and is thought to be due to increased complexity and fewer installations (Colpier and Cornland, 2002).
1983	The UK Energy Act is passed, allowing independent power producers into the market—who generally favour CCGT power plants. However, because of the EU restrictions, this had little immediate impact (Kern, 2012).
1989	**Rapid growth (UK):** The UK Electricity Act results in significant privatisation and liberalisation of the electricity market. Simultaneously the government strengthens environmental regulation on coal and other energy generators, making CCGT relatively cheap. The first UK CCGT order is placed—Roosecote (224Mw) by Lakeland Power Ltd (Kern, 2012).
1990	Under the new liberalised energy market, the Central Electricity Generating Board (CEGB), the monopoly generation and transmission company, is privatised into National Power and PowerGen. Where CEGB had previously preferred coal plants, the new companies abandon these plans and focus on natural gas (Kern, 2012).
1990s	Banks' short loan periods make CCGT more appealing, because their shorter construction periods allow for swifter revenue generation and debt repayments (Kern, 2012; Watson, 2004).
1991	The first CCGT plants come online in the UK, having been ordered in 1989 after electricity market liberalisation (Kern, 2012).
1997	The UK's Labour government places a moratorium on new orders of CCGT in an attempt to protect the failing coal industry (Winskel, 2002).
2000	During the late 1990s and early 2000s, a boom of orders from the USA leads to a bottleneck and increase in price for CCGT (Kern, 2012).
2001	The EC Large Combustion Plants Directive leads the UK to tighten environmental regulation of power plants, to reduce sulphur dioxide emissions. It becomes cheaper to build new CCGT plants than to retrofit coal plants to meet the new standards (Kern, 2012).
2008	The Global Financial Crisis occurs, and UK energy demand falls (BEIS, 2019a).
2009	The late 2000s see the price of CCGT rise due to increases in the price of raw materials (Kern, 2012).
2010	Six workers are killed in a natural gas explosion at a CCGT plant in Connecticut, USA. The incident investigation found similarities to other explosions in CCGT plants in the USA (U.S. Chemical Safety and Hzard Investigations Board, 2010).

Table A.5 History of carbon capture and storage

1936	**No supply (World):** Two British plants install limestone slurry scrubbing for flue gas desulpherisation. This is the first example of postcombustion capture of pollutants (Rochelle, 2009).
1972	Val Verde oil field becomes the first example of large-scale use of waste CO_2 from natural gas streams. A group of oil companies initiates the Val Verde project to demonstrate the use of CO_2 to increase yield from oil fields. This becomes known as enhanced oil recovery (EOR) (IEA, 2016).
1982	The Enid Fertiliser plant in Oklahoma, USA, start sending their waste CO_2 to a nearby oil field for EOR. Between 1982 and 2016 it compresses and transports around 680,000tCO_2 a year (IEA, 2016).
1986	Shute Creek facility in Wyoming, USA, which processes natural gas from a nearby gas field, begins processing waste CO_2 for EOR. Shute Creek sells around 4-5MtCO_2 per year (IEA, 2016).

1989	The Carbon Capture and Sequestration Technologies Program at MIT opens. This programme conducts research into CCS and utilisation of CO_2, from technological, economic and political lenses (MIT, 2016).
1996	**Limited non-market supply (World):** Statoil's Sleipner West gas field in Norway begins operations as the first dedicated CO_2 capture and storage facility. Sleipner was in the planning phase when the offshore carbon tax was imposed; Statoil changed the plans to incorporate CCS. CO_2 is separated offshore and injected into porous sandstone under the ocean and trapped by a 700m thick layer of sealing rock. Between 1996 and 2016, about 1MtCO_2 a year has been stored (IEA, 2016).
1997	A white paper sponsored by the USA Department of Energy is published, entitled *CO_2 capture, reuse, and storage technologies for mitigating global climate change*, authored by researchers from the MIT Carbon Capture and Sequestration Technologies Program (Herzog et al., 1997).
2003	The first ministerial-level meeting of the Carbon Sequestration Leadership Forum, a high-level initiative focused on developing the technological, regulatory and legal basis for CCS (IEA, 2016).
2004	The In Salah CO_2 storage project commences in Algeria. This project operates at a natural gas plant and is designed for dedicated storage and monitoring, with an annual capacity of 1Mt. Operations are suspended in 2011 (IEA, 2016).
2005	IPCC Special Report on Carbon Capture and Storage is published. The report summarised the science, status, costs and climate potential of CCS (IEA, 2016; IPCC, 2005).
2007	UK government launches a £1billion demonstration fund for post-combustion CCS on coal plants. After all other bidders pull out, this fund is awarded to a collaboration between ScottishPower, National Grid and Shell, to develop CCS at the Longannet coal-fired power plant in Scotland (Kern et al., 2016).
2007	The European Commission proposes the world's first example of dedicated CCS legislation, to establish a regulatory framework for CCS, including permitting of exploration and storage. The CCS Directive (Directive 2009/31/EC) is passed in 2009 (Kerr et al., 2009).
2008	The International Energy Agency launches the International CCS Regulators' Network, a forum to discuss the development of CCS regulatory frameworks (Kerr et al., 2009).
2008	Snohvit liquefied natural gas plant in Norway begins production, separating and storing CO_2 from the gas stream in non-petroleum bearing rock formations. This project closely monitors the behaviour of CO_2 stored underground (IEA, 2016).
2008	The Carbon Capture and Storage Early Deployment Bill is introduced to USA Congress, aiming to accelerate the development of CCS. The Bill promotes industry-led deployment, and proposes a coordinated mechanism for funding and research. The Bill fails to pass congress in 2008 and 2009 (Kerr et al., 2009).
2009	The Global Financial Crisis and disappointing progress at the Copenhagen Conference of the Parties (COP15) stalls progress on CCS. Between 2010 and 2016, more than 20 advanced large-scale demonstration projects are cancelled and government funding in Europe, the USA and Australia is withdrawn or scaled back (IEA, 2016).
2009	The Scottish government establish a Regulatory Group to consider the process for regulation and permitting of a CCS project. They publish a CCS Regulatory Test Toolkit (Department of Energy and Climate Change, 2012).
2009	The Climate Change Act is passed in the UK, setting a legally binding target to reduce net emissions by 80% by 2050. CCS is a key part of this strategy (Kern et al., 2016).
2011	The Longannet project is cancelled, due to projected costs exceeding the £1billion available (Kern et al., 2016).

2011	In Salah project in Algeria is halted, although monitoring continues (IEA, 2016).
2012	The Department of Energy and Climate Change publishes the *CCS Roadmap*, which launches a £135million fund for research and development, a UK CCS Research Centre, and the £1 billion CCS Commercialisation Programme. It also sets out the government's proposed Energy Market Reform to develop a market for low carbon energy (Department of Energy and Climate Change, 2012).
2014	Boundary Dam CCS project begins in Saskatchewan, Canada. This project retrofits a coal-fired generation unit with CCS technology and sells CO_2 for EOR. It is the first large-scale project of CO_2 separation that is not inherently necessary for product quality (IEA, 2016).
2014	The UK government announces that White Head and Peterhead CCS demonstration projects will both received funding (Kern et al., 2016).
2014	The European Commissions announces EUR300million funding for the proposed White Rose front-end engineering and design project (Kern et al., 2016).
2015	Quest CCS facility in Canada begins operation. This plan separates and stores carbon from hydrogen production for oil refining, capturing $4MtCO_2$ between 2015 and 2019 (Global CCS Institute, 2019).
2015	The UK government cancels the CCS Commercialisation Programme, and redirects the £1billion fund. The Programme was in the final stages of project selection; cancellation comes days before COP21 in Paris. Two major demonstration projects in the UK—White Rose and Peterhead—are withdrawn (IEA, 2016).
2016	A demonstration project begins in La Porte, Texas, USA for a new method of capturing CO_2 from natural gas combined cycles or coal-based synthesis gas. This method, known as the Allam cycle or supercritical CO_2 cycles, combusts gas at high pressure with high-purity oxygen and recycled CO_2. The hot, high-pressure gas expands in a turbine chamber to generate electricity (Global CCS Institute, 2019; IEA, 2016).
2018	The UK government publishes *The UK carbon capture, usage and storage deployment pathway: an action plan*, setting out the pathway to large-scale CCS deployment by 2030 (BEIS, 2018).
2019	The Climate Change Committee publishes *Net Zero*, which relies heavily on CCS. In response, the Climate Change Act is amended to set a net zero target by 2050 (Stark and Thompson, 2019).
2019	The UK's first demonstration project for bioenergy CCS (BECCS) begins at Drax Power Station in North Yorkshire. The pilot is the first demonstration of CCS from the combustion of 100% biomass foodstock in the world. It aims to capture $1tCO_2$ a day during the pilot (Drax Group, 2019).

Table A.6 History of asbestos

1924	**No change (World):** First medical paper on the health impacts of asbestos by William Cooke is published in the *British Medical Journal*. The paper relates the illness and death from fibrosis of the lungs and tuberculosis of a worker in the Rochedale asbestos factory (Bartrip, 2004).
1930	The Merewether and Price Report is published, commissioned by Britain's factory inspectorate. The large survey concludes that occupational exposure to asbestos causes fibrosis of the lungs, which could lead to death. It defines this disease as pulminary asbestosis (Bartrip, 2004).
1931	**Niche change (World):** Upon recommendation of the Merewether and Price Report, the UK government enacts the Asbestos Industry Regulations, which requires the suppression of dust in asbestos factories (Bartrip, 2004).

1955	Richard Doll establishes a causal association between asbestosis and lung cancer. However, he and other occupational health experts attribute the relative infrequency of asbestosis to dust control in asbestos factories (Bartrip, 2004).
1960s	A third asbestos related disease is discovered, mesothelioma. Moreover, it is found that asbestos diseases are not confined only to asbestos factory workers. Evidence of growing incidences of asbestos-related diseases (Bartrip, 2004).
1961	The Factories Act extends the standards of the Asbestos Industry Regulations to all industries (Oracle Asbestos, 2020).
1964	Media attention grows about the health hazards of asbestos (Bartrip, 2004).
1967	**Tipping point (UK):** A British asbestos factory worker successfully sues their employer for occupational asbestos exposure. This is the first successful personal injury claim for asbestos in the world (Oracle Asbestos, 2020).
1970	The Voluntary Asbestos Import Ban is negotiated between the asbestos industry and government. The ban only applies to blue asbestos (imported from South Africa and Australia), which is uncommon anyway (Oracle Asbestos, 2020).
1972	Denmark imposes the first partial asbestos ban in the world, restricting the use of asbestos for insulation (Allen et al., 2017).
1974	The Health and Safety at Work Act is passed, requiring employers to ensure employees are not exposed to health and safety risks and have information about conditions which may impact their health (Oracle Asbestos, 2020).
1980	A second Voluntary Import Ban is agreed, for brown asbestos, which makes up less than 2% of 1980s world production (Oracle Asbestos, 2020).
1983	The Asbestos Licensing Regulations requires contractors handling asbestos to receive training and licensing with the Health and Safety Executive (Oracle Asbestos, 2020).
1985	The Asbestos Prohibition Regulations bans production and import of blue and brown asbestos products (around 5% of 1980s asbestos use). The same year, the Asbestos Products Safety Regulations ban asbestos spraying (some exceptions) and insulation. Other types of asbestos are still available (Oracle Asbestos, 2020).
1987	The Control of Asbestos at Work Regulations makes employers responsible for the health of employees and visitors who may be exposed to asbestos fibres. The regulations applies to any activities directly handling asbestos (Oracle Asbestos, 2020).
1992	The Asbestos Prohibition Regulations are extended to several other types of asbestos and ban all spraying of asbestos (Oracle Asbestos, 2020).
1999	The UK extends the Asbestos Prohibition Regulations to all types of asbestos. A number of asbestos types have delayed prohibition dates (Oracle Asbestos, 2020).
1999	The European Commission announces an EU ban on remaining asbestos use by 2005 (Bartrip, 2004).
2002	The Control of Asbestos at Work Regulations are amended to require that employers manage asbestos in all non-domestic premises. This hugely increases the coverage of the regulations—employers are required to assess all properties before 2004 (Oracle Asbestos, 2020).

Table A.7 History of leaded petrol

1922	Tetraethyl-lead is added to petrol in order to improve engine performance, and reduce the ‘knock’ problem of early engines, which caused overheating, loss of power, wasted gasoline and engine damage (Landrigan, 2002; Seyferth, 2003).
1923	**No change (World):** The first cases of death and illness due to leaded gas manufacturing emerge from Standard Oil and DuPont plants (Seyferth, 2003).
1925	The new president of Ethyl Gasoline Corporation suspends sale of leaded gasoline until its health impacts can be assessed (Seyferth, 2003).
1925	The USA Surgeon General appoints a committee to investigate the health risks of leaded petrol, comprised of medical and industrial experts. Their report finds no health risk to the public and no grounds to ban the product (Seyferth, 2003).
1926	Ethyl Gasoline Corporation resumes the sale of leaded gasoline (Seyferth, 2003).
1936	At least 90% of gasoline sold in the USA contains lead (Seyferth, 2003).
1963	More than 98% of gasoline sold in the USA contains lead (Seyferth, 2003).
1970	The US Clean Air Act is amended, requiring new cars with catalytic converters to use unleaded fuel and mandating the phase down of leaded gasoline (Newell and Rogers, 2003; OECD and UNEP, 1999).
1970	**Niche change (World):** GM announces that all new cars will have catalytic converters, in accordance with the Clean Air Act amendment. Because leaded petrol damages catalytic converters, this in effect means that all new GM cars must use unleaded gas (Seyferth, 2003).
1971	Germany imposes the first dedicated legislation to limit the amount of lead in petrol. The Gasoline Lead Content Regulation bans the production and import of petrol with lead content greater than 0.4 grams per litre (g/L). The allowable lead content is reduced again in 1976 (Hagner, 1999).
1974	**Tipping point (USA):** The Clean Air Act amendments come into force, requiring cars with catalytic converters to use unleaded fuel and refineries to produce sufficient unleaded gas to meet demand (Newell and Rogers, 2003; OECD and UNEP, 1999).
1982	The permissible level of lead in gasoline sold in the USA falls from 0.52g/L to 0.28g/L. The USA Environmental Protection Agency (EPA) brings in a system of tradeable lead permits to protect small manufacturers (Newell and Rogers, 2003; Seyferth, 2003).
1986	The permissible level of lead is reduced again, to 0.026g/L. All refineries must comply with this standard (Seyferth, 2003).
1993	Austria becomes the first country to entirely ban leaded petrol. Other nations soon follow—Canada (1993); Slovakia (1994); Denmark and Sweden (1995) and others (OECD and UNEP, 1999).
1996	All leaded gasoline is prohibited in the US. By this time, almost no leaded gasoline is being sold (Newell and Rogers, 2003).

Table A.8 History of ozone depleting substances

1970	Studies show that stratospheric ozone molecules (O_3) are destroyed by interactions with nitrogen oxide. In the US, this sparks concern about the stratospheric damage caused by supersonic travel. It is hypothesised that UV-B radiation could cause skin cancer (Morrisette, 1989; Solomon, 1999).

1974	**No change (World):** Study shows that chlorine molecules can result in a catalytic cycle that destroys ozone molecules. Molina & Rowland then publish study showing that man-made chlorofluorocarbons (CFCs) are a significant source of stratospheric chlorine and ozone damage (Molina and Rowland, 1974; Solomon, 1999).
1975	The National Science Foundation and the Council on Environmental Quality establish the Interagency Task Force on Inadvertent Modification of the Stratosphere (IMOS) to develop a response to stratospheric depletion. The IMOS report is released later in 1975 and supports the link between ozone depletion and heightened risk of skin cancer. However, IMOS highlights the difficulty of regulating CFC use—no existing agency have a framework for implementing and enforcing bans. The National Academy of Sciences (NAS) initiate a more detailed study of the CFC problem (Morrisette, 1989).
1976	The NAS report is released, reporting that existing legislation is insufficient to control CFC use and recommending new legislation (Morrisette, 1989).
1976	**Niche change (World):** Aerosol demand falls dramatically as concerns over the stratospheric damage of CFCs heightens (even before a ban is implemented) (Morrisette, 1989).
1976	The Toxic Substance Control Act is passed, giving the EPA regulatory authority over CFCs. The EPA forms a working group which determines a two-phase programme to regulate first non-essential uses then essential uses of CFCs under the Act (Morrisette, 1989).
1977	The UN Environmental Programme (UNEP) adopts the World Plan of Action for the Ozone Layer to coordinate research efforts into the effect of CFCs (Morrisette, 1989).
1978	The USA bans non-essential use of aerosols. Canada and Norway do the same; the European Union rejects a proposed ban (Morrisette, 1989).
1985	Ozone depletion is first measured at the British Antarctic Station at Halley by Farman, Gardiner, and Shanklin. Their results are soon confirmed by measurements from space (Solomon, 1999).
1985	The UNEP develops the Vienna Convention for the Protection of the Ozone Layer, which is adopted by 43 states. The agreement calls for the protection of health and the environment from risks imposed by ozone depletion and calls for international cooperation in research and interventions (Morrisette, 1989).
1986	The chemical industry begins research for substitutes products, the success of which depends on economic and regulatory incentives. In March, major producer DuPont announces that substitutes could be available within five years if market incentives supported R&D but that research into substitutes had halted in the early 1980s. In October, an industry lobby group endorses a reasonable global limit on the growth of CFC production. DuPont, which holds 25% of global market share, calls for a worldwide limit on *total* emissions (rather than growth) (Haas et al., 1993).
1987	The end of a global recession heralds high CFC demand growth. Despite initial falls, demand grew by about 5% since 1983 (Morrisette, 1989).
1987	New leadership at the EPA pursues more ambitious reduction of CFCs production and use, which creates a rift in the USA administration. Concerns over the industrial and economic implications of a CFC ban raise opposition (Morrisette, 1989).
1987	**Tipping point (USA):** Senate passes a resolution supporting a 50% reduction and eventual phase out of CFCs (Morrisette, 1989).
1988	The USA ratifies the Montreal Protocol. The Protocol caps production of CFCs at 1986 levels for developed countries, with a plan to reduce to 50% within 10 years (Morrisette, 1989).
1988	DuPont announces its intention to phase-out the production of CFCs. DuPont had been developing substitutes (Morrisette, 1989).

1990	The London Amendment to the Montreal Protocol requires a complete phase-out of CFC production in developed countries by 2000 and in developing countries by 2010 (Environmental Protection Agency, 2020).
1992	The Copenhagen Amendment to the Montreal Protocol accelerates phase-out, requiring complete phase out in developed countries by 1996. It also adds a phase-out requirement for developed countries of hydrochlorofluorocarbons (one of the major substitutes for CFCs) by 2004 (Environmental Protection Agency, 2020).

Table A.9 History of seatbelts

1922	**No change (World):** Car racing pioneer Barney Oldfield introduces belts into race cars. The belts are modified from those used in aircraft. Other race car drivers soon follow (Ronan, 1979).
1930	**Niche change (World):** Physician C. J. Strickland founds the Automobile Safety League of America. Strickland advocates the safety benefits of seat belts and padded dashboards (Kashyap et al., 2017).
1930s	Doctors, safety engineers and pilots champion belt use (Ronan, 1979).
1954	Sports Car Club of America requires that race drivers wear seat belts (Government Activities and Transportation Subcommittee, 1988).
1955	Dr C. Hunter Sheldon publishes vehement report for seat belts in the the *Journal of American Medical Association* (Eastman, 1981).
1955	The Australian Road Safety Council requests that the Motor Vehicle Standards Committee reports on the possibilities of introducing in-built vehicle safety measures. The Committee recommends that belts are needed immediately (Milne, 1985).
1957	Volvo equips cars for belts (Government Activities and Transportation Subcommittee, 1988).
1959	Volvo engineer Nils Bohlin invents the modern 3-point seat belt. This design is suited to the occupant's body and provides significantly better protection than the 2-point belt. The three-point belt is first introduced in the Volvo Amazon in 1959 (Volvo Car USA, 2009).
1959	Senate of the Commonwealth Parliament establishes a Select Committee to investigate how to establish sound road safety practices in Australia (Milne, 1985).
1960	Australian government runs a publicity campaign to promote the installation and wearing of seat belts that meet Australian standards (Milne, 1985).
1960	The Select Committee recommend that vehicle manufacturers install belts in all vehicles and call for an education campaign to promote seat belt wearing (Milne, 1985).
1962	The first of a series of reports by McCausland & Herbert conclusively demonstrates the value of seat belts under extreme conditions in the Snowy Mountains, New South Wales (Milne, 1985).
1964	**Tipping point (Australia):** South Australia introduces new legislation making it compulsory for all new passenger vehicles to have anchorages for seat belts (Milne, 1985).
1960s	Several large public sector fleets voluntarily fit their vehicles with belts, including the Federal Departments of Civil Aviation, Supply, Interior, Works, the Royal Australian Air Force and many state government departments (Milne, 1985).
1969	The Joint Select Committee on Road Safety recommends that seat belt wearing should become compulsory within 2 years. The report also recommends compulsory fitting of belts in passenger vehicles and an intensive publicity campaign (Milne, 1985).
1970	Victoria introduces compulsory seat belt wearing legislation (Milne, 1985).

1971	New South Wales introduces compulsory seat belt wearing legislation (Milne, 1985).
1972	Encouraged by the increase in wearing rates in Victoria following legislation, the Federal government applies compulsory seat belt legislation across Australia (Milne, 1985).

Table A.10 History of traffic congestion charging

1968	**No change (World):** A.A. Walters publishes *The Economics of Road User Charges* for the OECD, which sets out the theory and practice of congestion charging (Walters, 1968).
1975	Singapore implements congestion charging, the only example before London's congestion charge (Santos et al., 2008).
1994	The Ministry of Transport commissions the *Smeed Report* in response to concerns over central London congestion. The report concludes that direct road user charges would be more effective than existing vehicle taxes (Leape, 2006).
1995	The Department of Transport establishes the London Congestion Charging Research Program. Its report supports congestion charging, and concludes that it would generate net revenues and economic benefits (Leape, 2006).
1997	Drivers in central London spend 50% of trips travelling less than 5 miles per hour. Average traffic speeds had been steadily decreasing since 1977 (Santos et al., 2008).
1999	**Niche change (World):** Surveys find 67% of the general public support congestion charges if net revenues are directed into transport improvements, and 73% support if community are consulted on how to spend revenues (Santos et al., 2008).
1999	The Greater London Authority Act is passed, creating an authority consisting of the mayor of London and the London Assembly. The Act gives the mayor the power to implement road user charges and requires that net revenues are earmarked for transport improvements for at least ten years (Santos et al., 2008).
2000	New mayor is elected in London, Ken Livingstone. Congestion charging is a major part of his campaign (Santos et al., 2008).
2000	Technical studies on the practicalities of congestion charging in London are commissioned by the Government Office for London. A report from the London Congestion Charging (LCC) Research Programme, as well as the *Roach Charging Options for London* are published (Santos et al., 2008).
2001	**Tipping point (London, UK):** The mayor's draft transport strategy is published, including a proposal for LLC. More than 87% of organisations who respond to the draft strategy support LLC. 60% of individual public responses oppose LLC (Santos et al., 2008).
2002	Central London average vehicle speed reaches a low of 9 miles per hour (Santos et al., 2008).
2003	The London Congestion Charge is implemented. Drivers pay £5 for driving or parking in the congestion zone between 7:00am and 6:30pm Monday to Friday. Discounts or exemptions exist for residents, buses, disabled people, emergency vehicles and electric vehicles (Leape, 2006; Santos et al., 2008).
2004	Public consultation begins on the Western Extension to the congestion zone and a proposed price increase. The consultation continues through 2005. 70% of members of the public oppose the zone extension; 76% oppose the charge increase (Santos et al., 2008).
2005	The LCC is increased from £5 to £8 (Santos et al., 2008).
2006	Heavy road works in central London reduces the benefits of the congestion charge, along with reallocation of spare space to other modes of transport (Santos et al., 2008).

2006	Buffer zone residences became eligible for 90% discount after they report being charged for visiting their local amenities (Santos et al., 2008).
2007	The congestion zone is extended to the west, to include Westminster, Kensington and Chelsea. The charging period is shortened—now ending at 6pm (Santos et al., 2008).
2007	Stockholm, Denmark implements congestion charging (Börjesson et al., 2012).
2008	New York City considers but rejects a congestion zone (Schaller, 2010).
2010	The LCC increases from £8 to £10 (Oxera Consulting, 2018).
2011	The Western extension of the congestion zone is removed (Oxera Consulting, 2018).
2014	The LCC increases from £10 to £11.50 (Oxera Consulting, 2018).

Table A.11 History of smoking

1939	**No change (World):** Franz Hermann Müller at Cologne Hospital publishes the first population study on smoking, showing that people with lung cancer are far more likely to have smoked (Proctor, 2012).
1943	Study by Eberhard Schairer and Eric Schöniger at the University of Jena confirms Müller's result (Proctor, 2012).
1943	A 47% increase in cigarette tax raises prices in the UK, resulting in a 14% reduction in male smoking rates (ASH, 2017).
1953	Cigarette manufacturers private acknowledge the risks of smoking, whilst still promoting their benefits. The American Tobacco Company sponsored an animal testing study to determine whether it was tobacco or paper that caused cancer (Proctor, 2012).
1954	The American Cancer Society's National Board of Directors publicly acknowledges that there is an association between smoking and cancer (Proctor, 2012).
1958	**Niche change (World):** The first Health Authority smoking withdrawal clinic is established in Salford, UK (ASH, 2017).
1962	The Royal College of Physicians publish its first report on smoking, *Smoking and Health*, to much publicity. It recommends a number of restrictions, including on the sale of tobacco to children, advertising, smoking in a public space, and higher taxation (ASH, 2017).
1964	Medical Research Council researchers Doll and Hill publish results of a survey about smoking, finding that since 1951 about half of British doctors who smoked had given up, and those that did experienced a lower rate of cancer (Doll and Hill, 1954).
1965	The government bans cigarette advertisements under a new law, the 1964 Television Act (ASH, 2017).
1969	The Health Education Council launches first anti-smoking campaign – 'why learn about lung cancer the hard way?' (ASH, 2017).
1970	WHO publishes *The limitation of smoking*, which calls for bans on cigarette advertisement. WHO bans smoking at meetings (ASH, 2017).
1971	London Transport tightens restrictions on smoking in underground trains; the proportion of non-smoking carriages increases from 50% to 75% (ASH, 2017).
1976	The UK Treasury announces an increase in cigarette tax of 3.5%. Specific and ad valorem tax system is introduced (ASH, 2017).
1978	The Independent Broadcasting Authority of the UK labels cigarettes and tobacco 'unacceptable products' and bans them from commercial radio (ASH, 2017).
1986	The Protection of Children (Tobacco) Act is passed, making it illegal to sell any tobacco product to those under 16 (ASH, 2017).

1989	**Tipping point (UK):** Birmingham City Council proposes tobacco legislation to ban smoking in all indoor public places and transport by 2000 (ASH, 2017).
1991	Cigarette taxes increase by £0.16. The Chancellor cites the health arguments to support the increase (ASH, 2017).
1992	The Secretary of State for Health announces a target to reduce adult smoking prevalence by 40% by 2000 (World Health Organization, 2003).
2004	Ireland becomes the first country to implement a smoking ban in public places and workplaces, despite warnings that it would damage the hospitality industry. (ASH, 2017).
2005	Scotland passes a similar ban on smoking in workplaces and public spaces (ASH, 2017).
2007	Wales and Northern Ireland implement smokefree legislation in April. England follows in July. Compliance is at 97% within two weeks of the English ban (ASH, 2017).

Table A.12 History of electric vehicles

1989	**Niche change (World):** Norwegian music group a-ha and environmental NGO Bellona join forces to promote battery electric vehicles (BEVs) in Norway (Norwegian Electric Vehicle Association, 2020).
1990	Import taxes for BEVs are temporarily abolished to encourage uptake. The abolition is made permanent in 1996 (Norwegian Electric Vehicle Association, 2020).
1994	During the Winter Olympics in Lillehammer, Norwegian EV producer PIVCO (later Think) successfully demonstrates and operates 12 EVs (Norwegian Electric Vehicle Association, 2020).
1995	The Norwegian Electric Vehicle Association is established, aiming to promote interest, uptake and infrastructure for EVs (Norwegian Electric Vehicle Association, 2020).
1996	**Tipping point (Norway):** The annual registration tax is reduced for EVs. The 1991 abolition of import taxes for BEVs is made permanent (Norwegian Electric Vehicle Association, 2020).
1997	Electric vehicles are exempted from road tolls across Norway (Norwegian Electric Vehicle Association, 2020).
1997	The first mass-produced EV is introduced—the Toyota Prius. Its worldwide release in 2000 generates a wider interest and market for EVs (U.S. Department of Energy, 2019).
1999	Special registration plates for EVs are introduced in Norway, identified with the letters EL. EVs are allowed to park for free in public parking areas (Norwegian Electric Vehicle Association, 2020).
2000	Company car tax is reduced for EVs (Norwegian Electric Vehicle Association, 2020).
2001	Value-added tax is eliminated for EV purchases, usually 25% in Norway (Norwegian Electric Vehicle Association, 2020; Zeniewski, 2017).
2003	The Oslo local authority allows EVs to use bus lanes (Norwegian Electric Vehicle Association, 2020).
2005	EV access to bus lanes is made permanent and extended nationwide. This, along with the exemption for VAT, is cited as one of the most effective measures for EV sales in Norway (Norwegian Electric Vehicle Association, 2020; Zeniewski, 2017).
2006	Tesla Motors announces its intention to produce a luxury EV with a range of more than 300km (U.S. Department of Energy, 2019).
2008	The Norwegian government introduces a progressive CO_2 tax component on vehicle purchases, increasing the costs of fossil fuel cars. The government justifies this in two ways: (1) an effort to reduce greenhouse gases; and (2) a trade-off for investing in more EV infrastructure (Zeniewski, 2017).
2008	Oslo local authority launches a programme to develop municipal charging infrastructure (Norwegian Electric Vehicle Association, 2020).

2009	The Norwegian government launches a programme to establish 1900 charging points by 2011. The programme, Transnova, is allocated EUR7 million of funding. EVs are allowed free access to road ferries (Norwegian Electric Vehicle Association, 2020).
2010	Worldwide focus on low carbon transport and advances in battery technology increase commercial interest and supply of EVs. Prices fall. The Chevy Volt is launched, and is the first commercially-available plug-in hybrid EV (PHEV) (Zeniewski, 2017); (U.S. Department of Energy, 2019).
2011	The Mitsubishi i-iEV is launched in Norway, and sells 1150 in the first year. Nissan Leaf is launched in Norway, and goes on to become the country's best selling EV (Norwegian Electric Vehicle Association, 2020; U.S. Department of Energy, 2019).
2012	The Norwegian Climate Policy Settlement sets a net zero emissions target and states that existing incentives for EVs will be upheld until at least 2017, or until 50,000 EVs are registered (Zeniewski, 2017).
2013	The costs of EV batteries fall by up to 50% in four years due to research and investment stimulated by growing worldwide EV demand. The Tesla Model S is launched in Norway and soon becomes extremely popular (Ingram, 2013; U.S. Department of Energy, 2019).
2015	The weight portion of vehicle tax is reduced by 26% for PHEVs. The VAT exemption on EVs is extended to leased vehicles (Steinbacher et al., 2018).
2017	The Chinese EV market sees a 72% increase in EV sales in a single year. Worldwide EV sales exceed one million units for the first time (Hertzke et al., 2018).
2018	The Nissan Leaf is the best-selling vehicle in Norway. This is the first time an EV tops annual car sales in any country (Nissan, 2019).
2018	The National Transport Plan 2018-2029 announces a target for all new passenger cars and light vans sold in 2025 to be zero-emissions vehicles. All new urban buses will be electric or use biogas. Heavy duty vehicles are exempt, but by 2030 75% of new long distances coaches and 50% of new trucks will be zero emissions (Norwegian Ministry of Transport and Communications, 2018).

Appendix B

Disruption domain and scenario analysis

This appendix provides supporting information for the disruption analysis presented in Chapter 5. The tables provide the details drawn from the review of decarbonisation scenarios used to produce Figures 5.3 through 5.5. Section B.1 presents the decarbonisation domain—the 98 mitigation options drawn from all twelve decarbonisation scenarios. Additional details about the technological market and behavioural activity identified for each option are provided. Section B.2 gives an overview and example of the detailed tables for each decarbonisation scenarios (a link to the full tables is provided). The results of the decarbonisation metric calculations are given in Section B.3. Finally, Section B.4 gives the tables for calculating maximum potential mitigation for each option.

B.1 Decarbonisation domain

Table B.1 presents the decarbonisation domain: a summary of all 98 mitigation options proposed across all twelve scenarios. Each option has an alpha-numeric code used in later tables to identify the mitigation options, especially where scenario-specific details are provided. The first two letters of the code refers to the sector in which the mitigation option acts. Namely: AG (agriculture); BU (buildings); CR (carbon removal); ES (energy supply); IN (industry); LU (land use, land use change and forestry), TR (transport), W (waste).

Table B.1 The 98 mitigation options constituting the decarbonisation domain.

Code	Option
AG01	Reduce beef and lamb consumption.
AG02	Reduce pig and poultry consumption.
AG03	Reduce dairy consumption.
AG04	Shift to indoor horticultural production.

Table B.1 continued from previous page

AG05	Adopt low-carbon on-farm practices.
AG06	Electrify on-farm vehicles and machinery.
AG07	Deploy hydrogen in on-farm vehicles and machinery.
AG08	Limit industrial animal feed.
AG09	Limit frozen meals and air-freighted food.
BU01	Reduce average temperatures in homes.
BU02	Install energy and thermal efficiency measures in new residential buildings.
BU03	Install energy and thermal efficiency measures in existing residential buildings.
BU04	Install energy and thermal efficiency measures in new commercial buildings.
BU05	Install energy and thermal efficiency measures in existing commercial buildings.
BU06	Set Passivhaus standards for new residential buildings.
BU07	Install energy efficient appliances in new residential buildings.
BU08	Install energy efficient appliances in existing residential buildings.
BU09	Incrementally improve appliance efficiency.
BU10	Electrify heat in new residential buildings.
BU11	Electrify heat in existing residential buildings.
BU12	Deploy hydrogen heating in new residential buildings.
BU13	Deploy hydrogen heating in existing residential buildings.
BU14	Develop district heating networks for residential heating.
BU15	Deploy low-carbon heat in commercial buildings.
CR01	Deploy direct air CCS (DACCS).
CR02	Use wood in construction.
ES01	Deploy CCS with fossil fuel generation.
ES02	Deploy bioenergy with CCS for power generation (BECCS).
ES03	Reduce unabated fossil fuel use in energy.
ES04	Increase total electricity share of energy supply.
ES05	Increase renewable electricity generation.
ES06	Increase offshore wind generation.
ES07	Increase onshore wind generation.
ES08	Increase solar photovoltaic generation.
ES09	Increase nuclear generation.
ES10	Decentralised renewable generation in homes, commercial buildings, industry and farms.
ES11	Develop short-term electricity storage.
ES12	Develop methane gas storage for back-up electricity generation.
ES13	Develop shiftable energy demand mechanisms.
ES14	Produce hydrogen by steam methane reforming with CCS.
ES15	Produce hydrogen by electrolysis.
ES16	Produce energy from biogas and biofuels.
ES17	Control methane leakage from gas networks.
ES18	Develop interconnection network.
IN01	Deploy CCS for industrial process emissions.
IN02	Improve industrial energy efficiency.

Table B.1 continued from previous page

IN03	Reduce F-gas emissions.
IN04	Electrify heat in industry.
IN05	Deploy hydrogen for heat in industry.
IN06	Improve industrial resource efficiency.
IN07	Increase lifetimes of consumer goods.
IN08	Use materials-saving construction processes.
IN09	Limit coal, iron ore and limestone mining.
IN10	Limit cement production.
IN11	Limit new steel production and shift to recycling scrap steel.
IN12	Limit aluminium production and shift to recycling scrap aluminium.
IN13	Limit paper production.
IN14	Limit ceramics production.
IN15	Limit and electrify glass production.
IN16	Produce more energy-efficient textiles.
IN17	Electrify off-road industrial machinery.
IN18	Deploy hydrogen in industrial machinery.
LU01	Increase forested area.
LU02	Actively manage woodlands.
LU03	Restore peatland
LU04	Limit green field development.
LU05	Develop crops for biomass.
TR01	Reduce overall distance travelled.
TR02	Electrify road passenger transport.
TR03	Deploy hydrogen fuel in road passenger transport.
TR04	Incrementally improve vehicle efficiency.
TR05	Reduce average car size.
TR06	Shift from cars to low-carbon transport modes.
TR07	Increase car occupancy.
TR08	Limit road expansion.
TR09	Electrify HGVs.
TR10	Deploy hydrogen in HGVs.
TR11	Reduce HGV mileage with logistic improvements.
TR12	Transfer freight from road to rail.
TR13	Electrify rail.
TR14	Deploy hydrogen in rail.
TR15	Incrementally improve rail efficiency.
TR16	Reduce international aviation demand.
TR17	Replace domestic aviation with rail.
TR18	Develop hybrid electric aircraft.
TR19	Improve aviation fuel efficiency.
TR20	Deploy biofuels for aviation.
TR21	Deploy ammonia for shipping.

Table B.1 continued from previous page

TR22	Limit shipping.
TR23	Deploy biofuels for transport energy.
W01	Reduce all waste streams.
W02	Increase recycling.
W03	Reduce food and biodegradable waste.
W04	Manage increased wood waste from construction.
W05	Improve landfill management.
W06	Use biodegradable waste for energy production through anaerobic digestion.
W07	Use food waste for pig feed.
W08	Reduce non-CO_2 emissions from waste water management.

Further information on the decarbonisation domain is provided in Tables B.2 and B.3. For each option that includes a technological component, Table B.2 provides the market it affects and the specific share measured. Similarly, for each option with a behavioural component, Table B.3 gives the activity it affects and the specific behavioural share measured. Each table also provides the maximum possible share (Max share (%)) and the market share in 2020 (2020 share (%)). Additional notes and assumptions for each option are provided in the footnotes where relevant. Options are identified by the code defined in Table B.1.

Table B.2 Market details for decarbonisation options with technological change

Code	Market	Max share (%)	2020 share (%)
AG04	Horticulture (proportion of UK utilised agricultural area used for horticulture) (DEFRA, 2017)[1]	0	1.1
AG05	On-farm practices (proportion of UK agricultural emissions arising from on-farm practices, benchmarked to 2020) (National Atmospheric Emissions Inventory and BEIS, 2018)[2]	0	47.8
AG06	On-farm practices (proportion of on-farm vehicles and machinery powered by electricity)[3]	100	0
AG07	On-farm practices (proportion of on-farm vehicles and machinery powered by hydrogen)	100	0
AG08	Cereals market (proportion of UK cereal consumption used for animal feed) (Agriculture and Horticulture Development Board, 2018)	0	52.7

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[1] Reduced if horticultural production moves inside.

[2] Assume that emissions are inversely proportional to deployment of low-carbon practices. Behaviour change (which may be part of the low-carbon practices) is assumed to be in a professional capacity—so not considered.

[3] Assume negligible electrification of on-farm vehicles and machinery in 2020 (no disaggregated information available; agricultural vehicles are merged with other vehicles in Department for Transport data.)

Table B.2 continued from previous page

BU02	New residential construction (proportion of new homes built to EPC level C or above) (Ministry of Housing Communities and Local Government, 2019a)[4]	100	94.4
BU03	Existing residential retrofit (proportion of existing homes at EPC level C or above) (Ministry of Housing Communities and Local Government, 2019a)	100	38.8
BU04	New commercial construction (proportion of new non-domestic buildings at EPC level C or above) (Ministry of Housing Communities and Local Government, 2019a)[5]	100	49.83
BU05	Existing commercial retrofit (proportion of all non-domestic buildings at EPC level C or above) (Ministry of Housing Communities and Local Government, 2019a)[5]	100	38.2
BU06	New residential construction (proportion of new homes built to EPC level A) (Ministry of Housing Communities and Local Government, 2019a)	100	1.37
BU07	New residential construction (proportion of new homes built to EPC level B or above) (Ministry of Housing Communities and Local Government, 2019a)[6]	100	83.2
BU08	Existing residential retrofit (proportion of existing homes at EPC level B or above) (Ministry of Housing Communities and Local Government, 2019a)[6]	100	2.8
BU09	Appliances (benchmarked to 2020)	200	100
BU10	New residential heat mix (heat pumps installed in new buildings, as share of all heat technologies) (Dawson, 2014)[7]	100	51
BU11	Existing residential heat mix (proportion of homes with electric heating) (Ministry of Housing Communities and Local Government, 2019c)	100	1
BU12	New residential heat mix (proportion of new homes with hydrogen heating) (Ministry of Housing Communities and Local Government, 2019c)[7]	100	0
BU13	Existing residential heat mix (proportion of homes with hydrogen heating) (Ministry of Housing Communities and Local Government, 2019c)	100	0
BU14	Existing residential heat mix (proportion of homes with communal heating) (Ministry of Housing Communities and Local Government, 2019c)	100	1.7
BU15	Commercial heat mix (proportion of commercial heating needs met with electricity) (BEIS, 2016)	100	18.8
CR01	Direct carbon removal (capture, benchmarked to share of 2020 emissions) (Climate Change Committee, 2020a)	100	0

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[4] Energy Performance Certificates (EPCs) measure energy and thermal efficiency of UK buildings. Change applied to construction practices; does not require behaviour change from individuals.

[5] Change applied to commercial buildings; does not require behaviour change from individuals.

[6] Assume that efficient appliances are installed in new homes with very high EPCs.

[7] Change applied to construction practices; does not require behaviour change from individuals.

Table B.2 continued from previous page

CR02	New residential construction (proportion of new buildings with timber frames) (The BioComposites Centre, 2019)[7]	100	28
ES01	Carbon capture and storage (CCS with fossil fuel electricity generation, as proportion of total UK electricity generation) (Climate Change Committee, 2020a)	100	0
ES02	Electricity generation (BECCS as proportion of total UK electricity generation) (Climate Change Committee, 2020a)	100	0.00008
ES03	Energy supply (proportion of UK energy supply from coal, petroleum and gas) (BEIS, 2020e)	0	73.8
ES04	Energy supply (proportion of energy from electricity) (BEIS, 2020c,e)	100	40.3
ES05	Electricity generation (proportion of electricity generated by renewable energy) (BEIS, 2020e)	100	37.9
ES06	Electricity generation (offshore wind as proportion of total electricity generation) (BEIS, 2020d,f)	100	9.9
ES07	Electricity generation (onshore wind as proportion of total electricity generation) (BEIS, 2020d,f)	100	14.1
ES08	Electricity generation (solar PV as proportion of total electricity generation) (BEIS, 2020d,f)	100	13.3
ES09	Electricity generation (nuclear as proportion of total electricity generation) (BEIS, 2020d)	100	9.2
ES10	Electricity generation (proportion of electricity generation coming from decentralised generation) (BEIS, 2020d)	100	17.7
ES11	Electricity storage (energy storage as a proportion of electricity supply) (Renewable Energy Association and UK Energy Storage, 2016)	100	0.0037
ES12	Energy storage (methane gas storage as proportion of total energy supply) (BEIS, 2020f,g)	100	1.04
ES13	Energy demand side response (reduction in peak energy demand resulting from DSR) (Chase et al., 2017)	100	0
ES14	Energy supply (hydrogen produced by steam methane reforming with CCS as a proportion of UK energy supply) (BEIS, 2020f; Vivid Economics, 2019)	100	0
ES15	Energy supply (hydrogen produced by electrolysis as a proportion of UK energy supply) (BEIS, 2020f; Vivid Economics, 2019)	100	0.07
ES16	Energy supply (bioenergy and waste generation as a proportion of UK energy supply) (BEIS, 2020f)	100	10.6
ES17	Fugitive emissions (fugitive methane emissions as proportion of 2020 emissions) (National Atmospheric Emissions Inventory and BEIS, 2020)	0	3.33
ES18	Energy interconnection (interconnector capacity as proportion of total energy capacity) (BEIS, 2020d,f)	100	5.02
IN01	Industrial emissions (UK proportion of non-combustion industrial emissions captured by CCS) (Climate Change Committee, 2020a)	100	0
IN02	Existing commercial retrofit (efficiency benchmarked to 2020)	200	100

Table B.2 continued from previous page

IN03	F-gas use (F-gases emissions as a share of 2020 emissions) (BEIS, 2020b)[8]	0	3.1
IN04	Industrial heat (proportion of industrial heat provided by electricity) (BEIS, 2019b)	100	3.9
IN05	Industrial heat (proportion of industrial heat provided by hydrogen) (BEIS, 2019b)	100	0
IN06	Industrial resource use (efficiency, benchmarked to 2020)	200	100
IN08	Construction (proportion of UK waste generated by construction, demolition and excavation) (Defra, 2020)[9]	0	62
IN11	Scrap steel recycling (proportion of steel produced using scrap electric arc furnaces) (WSP et al., 2015)	100	21
IN12	Aluminium recycling (proportion of aluminium consumed from scrap recycling) (European Alumnium, 2020)[10]	100	30
IN15	Glass production (proportion of energy needs in UK glass manufacturing met by electricity) (WSP Parson Brinkerhoff; and DNV GL, 2015)	100	13
IN16	Textiles recycling (proportion of UK textiles which are recycled) (Allwood et al., 2006)	100	13
IN17	Industrial machinery (proportion of off-road machinery powered by electricity) (Lajunen et al., 2016)	100	0
IN18	Industrial machinery (proportion of off-road machinery powered by hydrogen energy) (Lajunen et al., 2016)	100	0
LU01	Afforestation (proportion of total land in UK that is forested) (Forest Research, 2020)[11]	100	13
LU02	Woodland management (proportion of total woodland in UK that is managed) (Forestry Commission, 2019)	100	59
LU03	Peatland restoration (proportion of UK peatland in near natural or rewetted state) (Office for National Statistics, 2019a)[12]	100	22
LU04	Land development (proportion of new homes built on previously undeveloped land) (Ministry of Housing Communities and Local Government, 2019b)[13]	0	46
LU05	Cropland (crops used for bioenergy as proportion of UK arable land) (DEFRA, 2019)	100	2.2
TR02	Car and van stock (proportion of UK passenger car stock which is electric or hybrid) (Department for Transport, 2020d)	100	2.3
TR03	Car and van stock (proportion of UK passenger car stock which is hydrogen-fuelled) (Department for Transport, 2020d)	100	0
TR04	Car and van efficiency (efficiency, benchmarked to 2020)	200	100

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[8] Assume emissions is proportional to technological adoption.

[9] Assume proportion of total waste is inversely proportional to materials-saving construction.

[10] Assume that UK proportion of aluminium consumed from scrap recycling is same as EU share of production.

[11] Requires technical deployment for effective afforestation (eg, picking appropriate species).

[12] Restoring wetlands is technologically challenging.

[13] Change applied to new developments; does not require behaviour change from individuals.

Table B.2 continued from previous page

TR06	Public transport (proportion of land passenger kilometers travelled by bus, rail or cycle in UK) (Department for Transport, 2019c)	100	15.2
TR09	Heavy goods vehicles (proportion of UK HGV stock powered by battery electric) (Department for Transport, 2020c)	100	0.072
TR10	Heavy goods vehicles (proportion of UK HGV stock powered by hydrogen) (Department for Transport, 2020c)	100	0
TR11	Land freight (proportion of freight moved by road) (Department for Transport, 2019a)	0	78.7
TR12	Land freight (proportion of freight moved by rail) (Department for Transport, 2019a)	100	10
TR13	Rail network (proportion of UK rail that is electric) (Institution of Mechanical Engineers, 2018)	100	42
TR14	Rail network (proportion of UK rail that is hydrogen-fuelled) (Institution of Mechanical Engineers, 2018)	100	0
TR15	Rail network (efficiency, benchmarked to 2020)	200	100
TR18	Aviation technology (proportion of plans using hybrid electric) (Read, 2020)	100	0
TR19	Aviation fuel (efficiency, benchmarked to 2020)	200	100
TR20	Aviation fuel (proportion of planes powered by biofuels) (Bosch et al., 2017)	100	0
TR21	Shipping (proportion of shipping using ammonia) (Craglia et al., 2020)	100	0
TR23	Transport fuel mix (proportion of UK vehicle stock powered by biofuels) (Department for Transport, 2020d)[14]	100	0.00075
W01	Commercial waste (proportion of total waste from commercial and industry, benchmarked to 2020) (DEFRA, 2020b)	0	18
W04	Biodegradable waste management (proportion of wood waste recycled) (Community Wood Recycling, 2020)[15]	100	60
W05	Landfill waste management (estimated share of municipal landfill waste which is biodegradable) (DEFRA, 2018)[16]	0	51.2
W06	Biodegradable waste management (energy plant capacity from waste as a proportion of total energy plant capacity) (BEIS, 2020d,f)	100	2.6
W07	Food waste processing (proportion of food waste going to pig feed) (DEFRA, 2018)[17]	100	6.2

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[14] Assume half the cars powered by gas use biogas, representative of the wider vehicle stock.

[15] Assume that other effective management processes will increase alongside recycling.

[16] Assume effective waste management reduces erroneous landfilling of biodegradable waste, or reduces emissions from waste through the use of silos etc.

[17] Using kitchen or catering waste for pig feed is currently illegal under the Transmissible Spongiform Encephalopathies Regulations (EC No 999/2001) (DEFRA, 2020b). However, the commercial sector diverts around 660,000 tonnes of *surplus* food to animal feed, out of a total 10.6 million tonnes (DEFRA, 2018). We assume that domestic food waste is collected as normal to be diverted to pig feed, requiring no behavioural change.

Table B.2 continued from previous page

W08	Waste water management (waste water emissions as share of UK emissions) (Community Wood Recycling, 2020)[18]	100	0.8

Table B.3 Market details for decarbonisation options with behavioural change

Code	Activity	Max share (%)	2020 share (%)
AG01	Consumption (beef and lamb as share of average adult diet by energy intake) (Food Standards Agency and Public Health England, 2018)	0	6
AG02	Consumption (pig and poultry as share of average adult diet by energy intake) (Food Standards Agency and Public Health England, 2018)	0	8.2
AG03	Consumption (dairy as share of average adult diet by energy intake) (Food Standards Agency and Public Health England, 2018)	0	10.8
AG09	Frozen and imported food consumption (proportion of consumer food expenditure on frozen or air freighted food) (British Frozen Food Federation, 2019; DEFRA, 2020a; Poore and Nemecek, 2018; Ritchie, 2020)	0	6.2
BU01	Home heating practices (average proportion of time spent in a heated home) (BRE and Department of Energy and Climate Change, 2013; Public Health England, 2018)	0	27.4
BU03	Home retrofit decisions (average installation rate of energy efficiency measures through retrofit (excl. smart meter)) (Ministry of Housing Communities and Local Government, 2019d)	100	57.3
BU08	Home retrofit decisions (proportion of home energy appliances to rating A or above) (Ministry of Housing Communities and Local Government, 2019a)[19]	100	44.8
BU11	Home retrofit decisions (proportion of homes with low carbon heating) (Ministry of Housing Communities and Local Government, 2019d)	100	1
BU13	Home retrofit decisions (proportion of homes with low carbon heating) (Ministry of Housing Communities and Local Government, 2019d)[20]	100	1
BU14	Home retrofit decisions (proportion of homes with communal heating) (Ministry of Housing Communities and Local Government, 2019d)	100	1.7
ES10	Home retrofit decisions (proportion of total housing stock with renewable generation) (Ofgem, 2019)	100	17.3
ES13	Home energy-use timing decisions (proportion of residential energy demand utilising shiftable demand mechanisms) (Chase et al., 2017)	100	0
IN07	Attitudes to product use-life (proportion of consumers taking environmental factors into account) (Langley et al., 2013)[21]	100	52
IN09	Coal, iron and limestone use (behaviour benchmarked to 2020)	0	100

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[18] Assume emissions is proportional to technology adoption.

[19] Assume that efficient appliances are installed in homes with very high EPCs.

[20] Assume the behavioural change required to install electric heating is the same as that to install hydrogen.

[21] Approximate proportion of individuals for whom durability is a priority.

Table B.3 continued from previous page

IN10	Cement use (behaviour benchmarked to 2020)	0	100
IN11	Steel use (behaviour benchmarked to 2020)	0	100
IN12	Aluminium use (behaviour benchmarked to 2020)	0	100
IN13	Paper use (behaviour benchmarked to 2020)	0	100
IN14	Ceramics use (behaviour benchmarked to 2020)	0	100
IN15	Glass use (behaviour benchmarked to 2020)	0	100
IN16	Textile maintenance (proportion of domestic energy-use in washing and drying) (Dodson and Slater, 2019; Zimmerman et al., 2012)	0	8.3
LU01	Land availability (proportion of total land in UK that is forested) (Forest Research, 2020)[22]	100	13
LU03	Land availability (proportion of total land in UK that is restored peatland) (Office for National Statistics, 2019a)[23]	100	2.6
TR01	Overall travel distance (behaviour benchmarked to 2020)	0	100
TR02	Car purchases (proportion of UK passenger car sales which are low carbon) (Department for Transport, 2020e)[24]	100	8.1
TR03	Car purchases (proportion of UK passenger car sales which are low carbon) (Department for Transport, 2020e)[25]	100	8.1
TR05	Car purchases (share of new registrations which are mini, supermini or lower medium segment) (Society of Motor Manufacturers and Traders, 2020)	100	59
TR06	Car use (proportion of land passenger kilometers travelled by cars, vans, taxis or motorcycles in UK) (Department for Transport, 2019c)	0	84.8
TR07	Car use (proportion of car trips taken alone) (Department for Transport, 2020b)	0	62
TR08	Private vehicle use (proportion of trips travelled by car, van, motorcycle or other private transport) (Department for Transport, 2019b)[26]	0	63.0
TR16	Air travel (proportion of UK residents' international trips taken by air) (Office for National Statistics, 2020)	0	85.4
TR17	Air travel (proportion of travellers taking domestic flights once or more a year) (Department for Transport, 2020f)	0	6
TR22	Availability of shipped goods (proportion of imported goods arriving by ship, by value) (HM Revenue and Customs, 2020)	0	58.0
W01	Domestic waste (proportion of total waste from households, benchmarked to 2020) (DEFRA, 2018)	0	12
W02	Recycling decisions (domestic recycling rate as proportion of possible recycling arisings) (DEFRA, 2018)	100	45

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[22] Affects individuals by reducing space for urbanisation or agriculture (more recreational space).

[23] Restoring wetlands affects individuals due to land availability.

[24] Assume behaviour change is the same for electric and hydrogen vehicles.

[25] Assume behaviour change is the same for electric and hydrogen vehicles.

[26] Assume the size of the road network affects the number of car trips (behavioural factor).

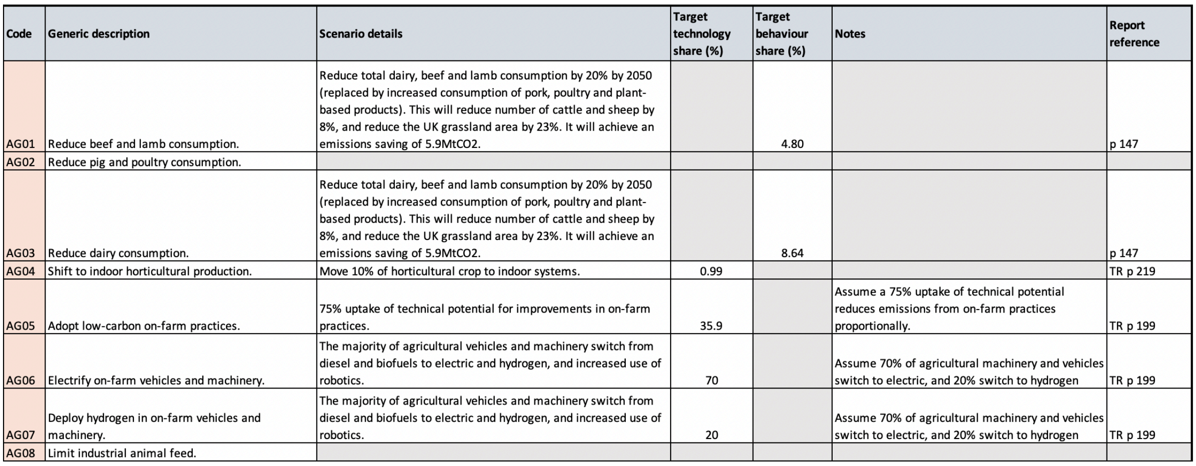
Table B.3 continued from previous page

W03	Domestic waste (proportion of municipal waste that is biodegradable) (DEFRA, 2018)	0	49.2

B.2 Decarbonisation scenarios

The specific decarbonisation scenarios are captured in detailed tables, with information about each report's proposed suggestions and any necessary assumptions. The tables are extensive; for brevity, this appendix includes only a single example table in Section B.2. Tables for the remaining eleven scenarios can be found in the supplementary information of the publication associated with this research (Nelson and Allwood, 2021).

Figure B.1 provides a screenshot of one of the tables in the supplementary information. Each table provides detailed information about the scenario's proposed options (where relevant), linked to the domain by the options' alpha-numeric codes. The detail drawn from the report is then translated into a target technology or market share (or both). Notes are provided about assumptions and any additional information, along with the relevant page reference for each proposed option.



Code	Generic description	Scenario details	Target technology share (%)	Target behaviour share (%)	Notes	Report reference
AG01	Reduce beef and lamb consumption.	Reduce total dairy, beef and lamb consumption by 20% by 2050 (replaced by increased consumption of pork, poultry and plant-based products). This will reduce number of cattle and sheep by 8%, and reduce the UK grassland area by 23%. It will achieve an emissions saving of 5.9MtCO2.		4.80		p 147
AG02	Reduce pig and poultry consumption.					
AG03	Reduce dairy consumption.	Reduce total dairy, beef and lamb consumption by 20% by 2050 (replaced by increased consumption of pork, poultry and plant-based products). This will reduce number of cattle and sheep by 8%, and reduce the UK grassland area by 23%. It will achieve an emissions saving of 5.9MtCO2.		8.64		p 147
AG04	Shift to indoor horticultural production.	Move 10% of horticultural crop to indoor systems.	0.99			TR p 219
AG05	Adopt low-carbon on-farm practices.	75% uptake of technical potential for improvements in on-farm practices.	35.9		Assume a 75% uptake of technical potential reduces emissions from on-farm practices proportionally.	TR p 199
AG06	Electrify on-farm vehicles and machinery.	The majority of agricultural vehicles and machinery switch from diesel and biofuels to electric and hydrogen, and increased use of robotics.	70		Assume 70% of agricultural machinery and vehicles switch to electric, and 20% switch to hydrogen	TR p 199
AG07	Deploy hydrogen in on-farm vehicles and machinery.	The majority of agricultural vehicles and machinery switch from diesel and biofuels to electric and hydrogen, and increased use of robotics.	20		Assume 70% of agricultural machinery and vehicles switch to electric, and 20% switch to hydrogen	TR p 199
AG08	Limit industrial animal feed.					

Fig. B.1 Example of the data tables used in disruption analysis.

Example scenario table

The decarbonisation scenario for Centre for Alternative Technology (2019) is provided in Tables B.4 and B.5. Unlike in the supplementary material of Nelson and Allwood (2021), this section separates the report's proposed mitigation options by technological and behavioural disruption. Table B.4 provides details about options which incorporate technological change, and Table B.5 gives options which incorporate behavioural change. Specifically, each table provides:

- Code: The code for each option, mapping this proposal to the overall decarbonisation domain.
- Scenario details: Specific details from the report, which may provide scale and/or implementation mechanisms for each proposed option.
- Share (%): The target technology/behavioural scale as a share of the technological market or behavioural activity identified in Table B.1.
- Page: The specific page reference for each option.

Additional notes and assumptions are provided in the footnotes.

Table B.4 Technological decarbonisation options from the Centre for Alternative Technology (2019)

Code	Scenario details	Share (%)	Page
AG08	Reduce cropland for industrial feed by half. Only 25% of cropland is used for animal feed.[27]	26	p 82, 92
BU02	All new buildings built to high standards. Reduce energy demand for heating and cooling from 13TWh to 5TWh.	100	p 46
BU03	All existing homes retrofitted.	100	p 46
BU04	All new buildings built to high standards. Reduce energy demand for heating and cooling from 13TWh to 5TWh.	100	p 40
BU05	All commercial buildings retrofitted.	100	p 46
BU06	All new houses built to Passivhaus standard or similar.	100	p 46
BU07	100% installation of energy efficient cooking, lighting and electrical appliances. Reduces cooking, lighting and appliance energy demand by 40% to 112TWh.	100	p 43
BU08	100% installation of energy efficient cooking, lighting and electrical appliances. Reduces cooking, lighting and appliance energy demand by 40% to 112TWh.	100	p43
BU09	Efficiency improvements reduce energy demand for cooking, lighting and electrical appliances by 40%.	140	p47
BU10	Heat pumps meet 76.5% of heating and hot water energy demand.	76.5	p46
BU11	Heat pumps meet 76.5% of heating and hot water energy demand.	76.5	p 46
BU15	Heat pumps meet 76.5% of heating and hot water energy demand.	76.5	p 46
CR02	The amount of ‘woody’ construction increases due to using more plant-based materials in buildings.[28]	56	p 80
ES03	Renewable energy meets all energy needs.	0	p 32
ES04	66% of energy needs are met by electricity.	66	p 55

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[27] Assume cropland share is proportional to the production share.

[28] Assume that the number of homes with timber frames doubles.

Table B.4 continued from previous page

ES05	Renewable energy meets all energy needs.	100	p 32
ES06	Wind provides around 50% of electricity, with offshore providing 44% of total.	44	p61
ES07	Wind provides around 50% of electricity, with onshore providing 6% of total.	6	p61
ES08	Solar PV provides 9.5% of total renewable electricity.	9.5	p 61
ES09	No nuclear energy.	0	p 32
ES10	Solar PV and solar thermal generation covers around 20% of UK roof area, and contribute 14.5% of total energy.	20	p 61
ES11	Short-term energy storage mechanisms meet demand 15% of the time.	15	p 69
ES12	80TWh of methane gas storage is maintained to meet shortfalls during cold and calm periods.	11.8	p 70
ES15	Biogas and carbon neutral synthetic fuels (hydrogen and CO_2 from biomass) meet demand 11% of the time (around 2% of total demand). Electrolysis uses half of surplus electricity (125TWh) to make hydrogen. 20TWh of biogas or carbon neutral synthetic fuel burned to make 10TWh.[29]	1	p 69
ES16	Biogas and carbon neutral synthetic fuels (hydrogen and CO_2 from biomass) meet demand 11% of the time (around 2% of total demand).[30]	1	p 69
ES17	Leakage rate of methane from gas networks remains the same. Gas use falls so total leakage falls.[31]	1.25	p 76
IN02	Efficiency gains reduce industrial energy intensity by 25%. Industrial energy use stays constant as population and industry grow.	125	p 47
IN03	77% reduction in F-gas emissions.	0.71	p 75
IN04	68% of industrial energy demand is met with electricity.	68	p 47
IN11	Emissions from steel remain constant.[32]	21	p 75
IN12	Emissions from aluminium, lime, soda ash, fletton brick and other chemicals fall by 49%.[33]	30	p 75
IN17	68% of industrial energy demand is met with electricity.	68	p 47
LU01	Additional 3.1Mha forest area is planted. Forest is doubled to 24% of UK land area. 1.7Mha used for enjoyment/biodiversity, the remainder harvested.	24	p 106
LU02	Manage existing forests sustainably—replanting trees, looking after ancient woodlands.	100	p 106
LU03	Restore 50% of UK peatland. Results in capture of 1.9MtCO_2 per year.	50	p 106
LU04	Existing buildings and under-occupied areas are developed instead of new buildings/land.	0	p 76

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[29] Assume 1% of total demand is met by hydrogen, and 1% by biogas.

[30] Assume 1% of total demand is met by hydrogen, and 1% by biogas.

[31] Assume that reduction in gas use reduces leakage emissions by 89% —difference between current use of gas as a proportion of energy supply (31.4%) and methane gas storage (11.8%).

[32] Report suggests electrolysis/recycling as a method to make steel, but does not include in scenario.

[33] Assume that emissions are proportional to production. No details given about aluminium recycling.

Table B.4 continued from previous page

LU05	4.2Mha of land converted to growing various grasses for biomass. 230TWh biomass energy produced.[34]	19.2	p 93
TR02	90% of road passenger transport is electric.	90	p 52
TR03	Carbon neutral synthetic fuel and hydrogen power the remaining road passenger vehicles.	10	p 52
TR04	Higher vehicle efficiency (across all modes) means total energy demand is decreased from 380TWh to 154TWh per year in 2050.	160	p 52
TR06	Increase buses, coaches and rail mileage by 100%, doubling share to meet 28% of domestic transport needs. Reduce car mileage by 23.5%, from 81% to 62% of domestic transport needs.	28	p 51
TR09	90% of HGV and other heavy commercial vehicles switch to carbon zero fuel. 50% electric, 30% carbon neutral synthetic fuel, 10% hydrogen.	50	p 53
TR10	90% of HGV and other heavy commercial vehicles switch to carbon zero fuel. 50% electric 30% carbon neutral synthetic fuel, 10% hydrogen.[35]	40	p 53
TR12	30% of road freight switches to rail; rail freight doubles.	20.04	p3
TR13	95% of rail is electric.	95	p 52
TR19	Aviation fuel use per passenger could improve by 1% per year in the next few decades.	135	p 52
TR20	Carbon neutral synthetic fuels are used to fuel planes. Mix of CO_2 emitted from burning biomass and hydrogen.	100	p 52
TR23	Energy demand of synthetic liquid fuels—biofuels and carbon neutral synthetic fuels—is 48% of total in 2030.	48.1	p 53
W04	Of additional wood waste from construction, 1/3 goes to biochar, and 2/3 go into silo waste storage. 1.6MtCO_2 captured in biochar, 4.3MtCO_2 in silos.[36]	100	p 80
W05	Landfills are stored in silos, so negligible methane escapes. Existing methane capture is improved. Landfill emissions fall 75%.[37]	12.8	p 80
W06	All biodegradable waste produces energy through anaerobic digestion of biomass.[38]	5.2	p 79
W07	Remaining food waste feeds pigs or is composted.[39]	100	p 79

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[34] Total land area of the UK is 24.2Mha (The Commonwealth, 2020)

[35] Assuming similar technological requirements to carbon neutral synthetic fuels and hydrogen.

[36] Assume all wood waste is managed.

[37] Assume emissions reduction is proportional to market change—a 75% reduction in the share of landfill waste that is biodegradable.

[38] Assume diverting all waste to AD doubles the amount of waste available for energy supply.

[39] Assume that while the total is halved, all the remaining food waste is used as pig feed.

Table B.5 Behavioural decarbonisation options from the Centre for Alternative Technology (2019)

Code	Scenario details	Share (%)	Page
AG01	Beef and lamb consumption reduced by 92%. Grassland needs for meat production reduced by 82%.	0.5	p 92
AG02	Pig and chicken consumption reduced by 58%. Grassland needs for meat production reduced by 82%.	3.4	p 92
AG03	Dairy consumption reduced by 59%. Grassland needs for dairy reduced by 65%.	4.4	p 92
AG09	Reduce food imports from 42% to 17% of food consumed. Moving freight by air is eliminated for all but essential items.	2.5	p83, p51
BU01	Reduce average home temperature from 17.5°C to 16.7°C.[40]	26.1	p 46
BU03	All existing homes are retrofitted.	100	p 46
BU08	100% installation of energy efficient cooking, lighting and electrical appliances. Reduces cooking, lighting and appliance energy demand by 40% to 112TWh.	100	p43
BU11	Heat pumps meet 76.5% of heating and hot water energy demand.	76.5	p 46
IN07	Place greater emphasis on the longevity and reparability of products.[41]	100	p 47
IN10	Emissions from cement production fall by 75%.	75	p 75
IN11	Emissions from steel remain constant.	100	p 75
IN12	Emissions from aluminium, lime, soda ash, fletton brick and other chemicals fall by 49%.[42]	49	p 75
IN14	Emissions from aluminium, lime, soda ash, fletton brick and other chemicals fall by 49%.	49	p 75
LU01	Additional 3.1Mha forest area is planted. Forest is doubled to 24% of UK land area. 1.7Mha used for enjoyment/biodiversity.	24	p 106
LU03	Restore 50% of UK peatland. Results in capture of 1.9MtCO_2 per year.	6	p 106
TR01	Total domestic distance travelled reduces 13%.	87	p 51
TR02	90% of road passenger transport is electric.	100	p 52
TR03	Carbon neutral synthetic fuel and hydrogen power the remaining road passenger vehicles.	100	p 52
TR06	Increase buses, coaches and rail mileage by 100%, doubling share to meet 28% of domestic transport needs. Reduce car mileage by 23.5%, from 81% to 62% of domestic transport needs.	62	p 51
TR07	Average car occupancy increases from 1.6 to 2 people.[43]	46.5	p 52
TR16	International aviation falls by 2/3. Combined with energy efficiency improvements, reduces aviation emissions by 75%	28.2	p 52
TR17	All non-emergency domestic aviation is replaced by rail.	0	p 52
W03	Food waste is halved.	24.6	p 79

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[40] Estimated as a proportional drop in the share of time spent in a heated home.

[41] Assume everyone adopts these beliefs.

[42] Assume that emissions are proportional to production. No details given about aluminium recycling.

[43] Assume the car occupancy increase results from a proportional reduction in the number of trips taken alone.

B.3 Disruption results

Disruption is measured using the decarbonisation scenarios gathered from each report. The disruption metric is described in detail in Section 5.1.2. Letting i be the option, p the proposed scenario and d the type of disruption (technological or behavioural), then disruption is given by:

$$\text{Disruption}_{i,p,d} = \ln \left| 100 \times \frac{\text{Target share}_{i,p,d} - \text{Baseline share in } 2020_{i,d}}{\text{Baseline share in } 2020_{i,d}} \right|$$

The target share is drawn from the the tables described in Section B.2. The baseline share is drawn from the decarbonisation domain. In Tables B.2 and B.3, this is '2020 share (%)'.

The results of disruption calculations are given below. Table B.6 provides the technological disruption results, and Table B.7 gives the behavioural disruption results. Where a cell is empty, this means that the decarbonisation scenario did not include a proposed target for this particular mitigation option. The first column (Code) in Tables B.6 and B.7 identify mitigation options in the decarbonisation domain. The remaining columns refer to the disruption scenario:

- CAT: Centre for Alternative Technology (2019)
- CCC: Climate Change Committee (Stark and Thompson, 2019)
- FE: Friends of the Earth (2018)
- GP: Greenpeace (2019)
- NGCT: National Grid ESO (2020), Consumer Transformation
- NGLW: National Grid ESO (2020), Lead the Way
- NGSP: National Grid ESO (2020), Steady Progression
- NGST: National Grid ESO (2020), System Transformation
- DPPD: Deep Decarbonisation Pathways Project (Pye et al., 2015), Decarbonise and Expand
- DPPM: Deep Decarbonisation Pathways Project (Pye et al., 2015), Multi-vector Transition
- DPPR: Deep Decarbonisation Pathways Project (Pye et al., 2015), Reduce demand
- UKF: UK Fires (Allwood et al., 2019)
- Max: The maximum ambition scenario, which takes 'Max share' from Tables B.2 and B.3 as the target share.

Table B.6 Technological disruption results

Code	CAT	CCC	FE	GP	NGCT	NGLW	NGSP	NGST	DPPD	DPPM	DPPR	UKF	Max
AG04		2.3											4.6
AG05		3.2	3.9	3.7								-0.4	4.6
AG06		18.1			17.2	17.2	17.2	17.2					18.4
AG07		16.8											18.4
AG08	3.9			4.6									4.6
BU02	1.8			1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8		1.8
BU03	5.1	4.5	4.5	5.1	5.1	5.1	4	4.7	4.4	4.4	4.9	5.1	5.1
BU04	4.6	4.6	4.6	4.6					4.6	4.6	4.6		4.6
BU05	5.1	5.1							4.4	4.4	4.9		5.1
BU06	8.9		8.9	8.9								8.9	8.9
BU07	3	3	3	3	3		3	3				3	3
BU08	8.2	8.2	8.2		8.2	8.1	7.6	7.9				8.2	8.2
BU09	3.7	4.1										3.7	4.6
BU10	3.9	4.6		4.6	4.1	2.9	2.9	4.2	4.6	4.6	4.6	4.6	4.6
BU11	8.9	9.1	9.0		9.0	8.7	7.1	7.3	8.7	9.2	9.0	9.2	9.2
BU12			17.0	16.1	16.7	17.5	16.8	18.2					18.4
BU13		16.1	15.4		16.7	17.5		18.2					18.4
BU14				7.0					6.8	6.7	6.4		8.7
BU15	5.7	6.1		6.1		6.1		6.1	5.8	6.1	5.8	6.1	6.1
CR01		12.2	17.0										18.4
CR02	4.6	3.8		4.4								4.4	5.6
ES01		17.0							16.5	16.6	17.1		18.4
ES02		15.8			15.9	16.2		16.1					18.6
ES03	4.6	4.6	3.6	4.6	4.6	4.6	4.4	4.6	4.6	3.7	4.5	4.6	4.6
ES04	4.2				4.5	3.9	4.4	-0.4	-0.3	3.2	2.8	5	5
ES05	5.1	4.0	5.1	4.7	4.9	5.0	4.7	5.1				5.1	5.1
ES06	5.8	6.2	5.4	4.9	5.8	6.0	5.6	6.1	4.0	5.4	5.2	5.8	6.8
ES07	4.0	3.2	2.4	2.1	4.3	4.4	0.9	3.2	4.0	1.3	2.6	3.9	6.4
ES08	3.3	2.0	2.4	3.6	2.7	3.4	3.8	3.7				3.6	6.5
ES09	4.6	4.0			4.7	3.1	3.6	4.9	5.2	5.3	6.1		6.9
ES10	2.6	4.2	4.2	3.7	4.8	4.8	4.3	4.2					6.1
ES11	12.9	12.5	12.9	11.9								12.5	14.8
ES12	6.9				6.2	6.3	5.4	5.6	1.4	5.7	1.4		9.2
ES13				15.8	16.6	14.6	13.8	14.0					18.4
ES14		17.4	4.6		17.1	4.6		17.9	16.4	16.0	16.3		18.4
ES15	7.2	9.2	9.6	7.9	10.2	10.7	7.6	9.1	8.3	9.3	9.3		11.9
ES16	4.5	4.4			5.5	5.7	3.2	4.8	4.4	2.4	4.2		6.7
ES17	4.1	1.5		3.4									4.6
ES18		4.6		4.6	4.6	4.9	4.3	4.4					7.6
IN01		18.4	17.7	16.1					18.4	18.1	18.4		18.4

Table B.6 continued from previous page

IN02	3.2	3			4.4	3	2.7	3	3	3	3	1.7	4.6
IN03	4.3	4.5		4.6								4.4	4.6
IN04	7.4	7.4	6.8	6.9	7.7	7.4	6.7	7.0	6.4	6.2	6.1	7.8	7.8
IN05		16.5	17.5	15.4	15.4	17.3		17.8	16.7	16.7	16.75		18.4
IN06		3		4.6								3.9	4.6
IN08												3.9	4.6
IN11	0								6.3	6.3	6.3	5.9	5.9
IN12	4.9											6.5	6.5
IN15			5.7									6.5	6.5
IN16												5.9	6.5
IN17	18.0	17.6		17.5	18.3	18.0	17.4	17.6					18.4
IN18		17.6			15.4	17.3		17.8	16.7	16.7	16.8		18.4
LU01	4.4	3.4	4.4	3.2									6.5
LU02	4.2	3.6											4.2
LU03	4.9	5.0		5.9									5.9
LU04	4.6			4.2									4.6
LU05	6.7	4.4		4.6									8.4
TR02	8.3	8.4	7.9	8.2	8.0	7.9	7.7	7.8	8.0	7.0	7.4	8.2	8.4
TR03	16.1	10.0	17.1		17.1	17.4	13.8	17.5	15.2	17.1	16.6		18.4
TR04	4.1	4.2							3.4	3.4	3.4	3	4.6
TR06	4.4	4.0	4.0	5.1	4.1	5.4		1.9			4.3	4.0	6.3
TR09	11.2	11.1	10.9	11.8	10.4	9.5	7.9	9.5	11.4	11.17	11.4		11.8
TR10	17.5	17.6	17.7		18.2	18.3	14.5	18.3	16.6	17.7	17.1		18.4
TR11		2.3		2.5								3.6	4.6
TR12	4.6											6.7	6.8
TR13	4.8	3.4		4.9	4.9	4.9	3.0	3.0				4.9	4.9
TR14		17.0						15.4					18.4
TR15												4.4	4.6
TR18		15.8		18.4	15.8	15.8		15.8					18.4
TR19	3.6	3.9			3.9	3.9		3.9					4.6
TR20	18.4	16.1			16.1	16.1		16.1					18.4
TR21		18.4		18.4	18.4	18.4		18.4	18.4	18.4	18.4		18.4
TR23	15.7	14.2											16.4
W01			3.9		2.3	3.7		3.9					4.6
W04	4.2	3.5											4.2
W05	4.3												4.6
W06	4.6		4.6	4.6									8.2
W07	7.3		7.3	7.3									7.3
W08		3											9.4

Table B.7 Behavioural disruption results

Code	CAT	CCC	FE	GP	NGCT	NGLW	NGSP	NGST	UKF	DPPD	DPPM	DPPR	Max
AG01	4.5	3.0	3.9	4.4					4.6				4.6
AG02	4.1		3.9	4.4									4.6
AG03	4.1	3.0	3.9	3.9									4.6
AG09	4.1								4.6				4.6
BU01	1.5				1.5	1.5	0.0	1.1	1.5				4.6
BU03	4.3	3.9	3.4	4.3	4.3	4.3	1.6	3.7	4.3	3.1	3.1	4.0	4.3
BU08	4.8	4.8	4.8		4.1	4.7	3.9	4.4	4.8				4.8
BU11	8.9	9.1	9.0		9.0	8.7	7.1	7.8	9.2	8.7	9.2	9.0	9.2
BU13		6.8	6.0		7.4	8.3		9.0					9.2
BU14				7.0						6.8	6.7	6.4	8.7
ES10		0.0	6.0	4.8	6.1	6.1	5.5	5.2					6.2
ES13				17.8	16.8	17.0	16.3	16.5					18.4
IN07	4.5			5.0					4.5				4.5
IN09				4.6					4.6	3.0	3.0	3.0	4.6
IN10	3.2								4.6	2.4	2.4	2.4	4.6
IN11	0.0								3.7	3.0	3.0	3.0	4.6
IN12	3.9								3.7	3.0	3.0	3.0	4.6
IN13									4.4	3.4	3.4	3.4	4.6
IN14	3.9								4.1				4.6
IN15			0.0						3.7				4.6
IN16									3.7				4.6
LU01	4.4	3.4	4.4	3.2									6.5
LU03	4.9	5.0		5.9									8.2
TR01	2.6								3.0				4.6
TR02	7.0	6.9	7.0	7.0	7.0	7.0	6.3	7.0	7.0	6.9	6.6	6.6	7.0
TR03	7.0	0.0	7.0		7.0	7.0	6.3	7.0		6.9	5.5	6.6	7.0
TR05									3.1				4.2
TR06	3.3	2.3	2.3	3.6	2.6	3.8		0.4	2.5			2.8	4.6
TR07	3.2								3.0				4.6
TR08			2.8	2.8					2.7				4.6
TR16	4.2	0.0	0.0	3.0	0.0	0.0		0.0	4.6	0.0	0.0	3.0	4.6
TR17	4.6	1.6	0.0	4.6	1.6	1.6		1.6	4.6				4.6
TR22									4.6	5.0	5.0	5.0	4.6
W01			3.9		2.3	3.7		3.9					4.6
W02		4.0	3.9	4.3									4.8
W03	3.9	3.0	3.9										4.6

B.4 Mitigation

The calculations to estimate mitigation are detailed in Section 5.1.3. The process draws heavily on the global emissions Sankey diagram presented in Bajželj et al. (2013). Each mitigation is allocated a *class* and *category* in the Sankey, which determines the share of global emissions allocated to that category. This is then scaled to the UK using the total UK influenceable emissions as calculated in Section 5.1.3. A scaling factor is then identified, which takes into account any limitations on the mitigation potential—a decarbonisation option may be able to eliminate only a portion of its sector's emissions. For example, measures to new homes can affect only around 20% of 2050 housing emissions, because 80% of the 2050 housing stock has already been built. The results of the mitigation calculations for each option in the decarbonisation domain are given in Table B.8.

Table B.8 The maximum potential mitigation for each decarbonisation option.

Code	Class	Category	UK emissions ($MtCO_2$)	Scale factor	Max mitigation ($MtCO_2$)
AG01	Land-use	Livestock, pasture	33.8[44]	1.0	34
AG02	Land-use	Livestock, pasture	9.8[44]	1.0	10
AG03	Land-use	Livestock, pasture	22.2[44]	1.0	22
AG04	Land-use	Food crops	67.0	1.0[45]	67
AG05	Land management	Fertiliser use, erosion and tilling	19.6	1.0	20
AG06	Equipment	Tractor	6.3	1.0	6
AG07	Equipment	Tractor	6.3	1.0[46]	6
AG08	Land-use	Feedlots	14.3	1.0	14
AG09	Final service	Food to residential/commercial	32.6	1.0[47]	33
BU01	Final service	Thermal comfort to residential	42.8	1.0	43
BU02	Final service	Thermal comfort to residential	42.8	0.1[48]	2
BU03	Final service	Thermal comfort to residential	42.8	0.2[49]	8

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[44] Assume proportion of emissions to different types of livestock is the same as each animal's share of UK enteric fermentation emissions, provided by BEIS (2020b). Assume pasture emissions are proportional to the share of grazing home fed production (DEFRA, 2017). Assume that the size of the herd (dairy/beef) is proportional to share of enteric fermentation for cattle.

[45] Reduction in land use will increase electricity use.

[46] Assume hydrogen is carbon free.

[47] Eliminate this branch of emissions (18% of emissions from each residential and commercial, from Bajželj et al. (2013)). Assume it arises from frozen or air-freighted food.

[48] Assume that an energy efficient home produces 24% less emissions when used in the same way as current housing stock (Holmes et al., 2019). Assume that by 2050, 21.5% of housing stock is new (average of Allwood et al. (2019); Eames et al. (2013); Jones et al. (2013); Killip (2008)).

[49] 78.5% of existing stock still in use in 2050. Assume potential emissions savings same as for new buildings.

Table B.8 continued from previous page

BU04	Final service	Thermal comfort to commercial and public	27.5	0.1[50]	1
BU05	Final service	Thermal comfort to commercial and public	27.5	0.2[52]	5
BU06	Final service	Thermal comfort to residential	42.8	0.2[51]	9
BU07	Equipment	Residential to Appliances	38.3	0.1[52]	4
BU08	Equipment	Residential to Appliances	38.3	0.4[52]	16
BU09	Equipment	Appliances	62.7	1.0	63
BU10	Equipment	Residential to heated space and hot water system	58.5	0.2[53]	13
BU11	Equipment	Residential to heated space and hot water system	58.5	0.8[53]	46
BU12	Equipment	Residential to heated space and hot water system	58.5	0.2[53]	13
BU13	Equipment	Residential to heated space and hot water system	58.5	0.8[53]	46
BU14	Equipment	Residential to heated space and hot water system	58.5	1.0	59
BU15	Equipment	Commercial and public to heated space and hot water system	27.5	1.0[53][54]	28
CR01	Emissions	CO_2	578.7	1.0	579
CR02	Final service	Construction of buildings and infrastructure	117.9	0.1[55]	8
ES01	Final energy	Direct gas use, direct coal use	105.6	1.0	106
ES02	Final energy	Biomass burner	4.5	1.0	4
ES03	Fuel	Natural gas, Coal, share of Oil going to electricity[56]	346.0	1.0	346

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[50] Assume same rates of emissions savings and new buildings for commercial and residential housing.

[51] 21.5% of residential homes new. Assume Passivhaus homes have no heating emissions.

[52] 34% of emissions from houses arising from appliances. Assume energy efficient appliances reduce energy needs (and emissions) by 51.75% (average reduction reported in Department of Energy & Climate Change (2014)).

[53] Assume that, with a carbon zero grid, electric and hydrogen homes save 100% of their thermal emissions (21% of residential emissions to hot water system, 31% to heated space, from Bajželj et al. (2013)).

[54] Assume this means 100% of commercial building on electric or hydrogen.

[55] Assume 21.5% of homes and commercial buildings are new in 2050. Substituting timber in masonry saves approx. 20% of embodied emissions, and substituting in cross laminated timber (CLT) or concrete structures are approximately 60% (Spear et al., 2019). The share of commercial/public dwellings is 8% (Piddington et al., 2020). Assume that all commercial/public buildings are CLT or concrete, and dwellings classified as 'flats' (20.9% (Piddington et al., 2020)) are CLT or concrete, the rest are masonry.

[56] 7% of electricity emissions are allocated to oil (Bajželj et al., 2013). Rest of oil is in transport.

Table B.8 continued from previous page

ES04	Final energy	Non-transport Direct Oil use, direct gas use, direct coal use, refineries, extraction[57]	170.8	1.0	171
ES05	Final energy	Electricity and public heat	189.4	1.0	189
ES06	Final energy	Electricity and public heat	189.4	1.0	189
ES07	Final energy	Electricity and public heat	189.4	1.0	189
ES08	Final energy	Electricity and public heat	189.4	1.0	189
ES09	Final energy	Electricity and public heat	189.4	1.0	189
ES10	Final energy	Electricity and public heat	189.4	1.0	189
ES11	Final energy	Electricity and public heat	189.4	1.0	189
ES12	Final energy	Electricity and public heat	189.4	1.0	189
ES13	Final energy	Electricity and public heat	189.4	1.0	189
ES14	Final energy	Direct gas use	46.2	0.0[58]	0
ES15	Final energy	Electricity and public heat	189.4	0.0[58]	0
ES16	Final energy	Biofuels and dry biomass	6.4	1.0[59]	6
ES17	Final energy	Fugitive emissions to natural gas[60]	8.8	1.0	9
ES18	Final energy	Electricity and public heat	189.4	0.0[58]	0
IN01	Device	Non-energy use, chemical use and cement kiln	57.2	1.0	57
IN02	Final service	Industrial equipment	22.6	1.0	23
IN03	Emissions	F-gas	14.5	1.0	14
IN04	Equipment	Fired system, steam system, industrial facilities to heated space and hot water systems[61]	143.7	1.0	144
IN05	Equipment	Fired system, steam system, industrial facilities to heated space and hot water systems[61]	143.7	1.0	144
IN06	Sector	All industrial sectors	262.3	1.0	262
IN07	Final service	Communication and textiles	47.6	1.0	48
IN08	Final service	Construction of buildings and infrastructure	117.9	1.0	118
IN09	Fuel	Coal[62]	3.5	1.0	4
IN10	Sector	Cement[63][64]	15.2	1.0	15

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[57] 1% of lighting, 77% of oil burners and 45% of non-energy use emissions allocated to oil (Bajželj et al., 2013). Rest of oil is in transport.

[58] Supporting activity.

[59] CCC estimates maximum net carbon gains from biomass and solid fuel recovery as 6.4MtCO_2 (Brown et al., 2018a). Assume that 100% of the 3.72% can be abated or offset with bioenergy.

[60] 18% of fugitive emissions arise from natural gas (Bajželj et al., 2013).

[61] 20% of industry facilities to hot water system, 45% to heating (Bajželj et al., 2013).

[62] Emissions share from Bajželj et al. (2013) SI Table S1 - Mining and Quarrying industry.

[63] Assume that 35% of 'cement' category in Bajželj et al. (2013) is from cement (they include glass and ceramics in cement category).

[64] Shares are calculated based on proportional emissions from EU-Merci.

Table B.8 continued from previous page

IN11	Sector	Steel	45.9	1.0	46
IN12	Sector	Non-ferrous	15.9	1.0	16
IN13	Sector	Paper	13.8	1.0	14
IN14	Sector	Other[65][64]	1.7	1.0	2
IN15	Sector	Other[64][66][64]	26.0	1.0	26
IN16	Final service	Washing to residential and commercial and public[67]	45.3	1.0	45
IN17	Equipment	Driven system	48.6	1.0	49
IN18	Equipment	Driven system	48.6	1.0	49
LU01	Process	Land use change	94.0	0.9[68]	83
LU02	Land-use	Forestry	14.4	1.0[69]	14
LU03	Process	Land use change	94.0	0.4[70]	44
LU04	Land management	Clearing for settlements	10.3	1.0	10
LU05	Land management	Clearing for biomass	6.3	1.0[71]	6
TR01	Final service	Personal travel	66.9	1.0	67
TR02	Equipment	Car	53.6	1.0	54
TR03	Equipment	Car	53.6	1.0	54
TR04	Equipment	Car, bus truck.	101.3	1.0	101
TR05	Equipment	Car	53.6	1.0	54
TR06	Equipment	Car	53.6	1.0	54
TR07	Equipment	Car	53.6	0.6[72]	33
TR08	Equipment	Car	53.6	1.0[73]	54
TR09	Equipment	Truck	39.6	1.0	40
TR10	Equipment	Truck	39.6	1.0	40
TR11	Equipment	Truck	39.6	1.0	40
TR12	Equipment	Truck	39.6	1.0	40
TR13	Equipment	Rail	4.8	1.0	5
TR14	Equipment	Rail	4.8	1.0	5
TR15	Equipment	Rail	4.8	1.0	5
TR16	Equipment	Plane	14.6	1.0	15

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[65] Assume that 4% of ‘cement’ category in Bajželj et al. (2013) is from ceramics.

[66] Assume that 61% of ‘cement’ category in Bajželj et al. (2013) is from glass.

[67] Assuming that the energy savings from different usage outweighs the energy savings from different production processes. (28% of residential and 20% of commercial emissions arise from washing in Bajželj et al. (2013)).

[68] Assume forestry is a carbon sink. Assume that mitigation potential is proportional to the unforested land.

[69] Assume active management increases the carbon sink proportionally. Read et al. (2009) shows the potential for mitigation from forest management is limited in 2050, but significant in the interim. Assume the active management of woodlands would be applied to all new forests, so abatement would continue.

[70] Maximum realisable mitigation from peatland restoration, estimated in Brown et al. (2018a).

[71] CCC estimates maximum net carbon gains from SRF as 6.4MtCO_2 (Brown et al., 2018a). Assume that 100% of the 3.72% can be abated or offset with bioenergy.

[72] Eliminate emissions attributable to driving alone (62% of car trips are taken alone (Department for Transport, 2020b)).

[73] Eliminate emissions proportionally based on assumption that limiting road expansion reduces driving.

Table B.8 continued from previous page

TR17	Equipment	Plane	14.6	1.0	15
TR18	Device	Aircraft engine	14.5	1.0	14
TR19	Device	Aircraft engine	14.5	1.0	14
TR20	Device	Aircraft engine	14.5	1.0	14
TR21	Equipment	Ship	15.6	1.0	16
TR22	Equipment	Ship	15.6	1.0	16
TR23	Sector	Passenger transport, Freight	137.0	1.0	137
W01	Final service	Waste	25.8	1.0	26
W02	Sector	Waste	20.6	0.0[74]	0
W03	Sector	Waste	0.0	1.0	0
W04	Land management	Waste	0.0	1.0	0
W05	Land management	Waste	20.6	1.0	21
W06	Land management	Waste	0.0	1.0	0
W07	Land management	Waste, feedlots	0.0	1.0	0
W08	Land management	Waste	4.9	1.0	5

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[74] Supporting activity—reduces the energy and resources to make new products.