Technology or behaviour? Balanced disruption in the race to net zero emissions

Sarah Nelson[a], Julian M. Allwood[a,*]

[a]Department of Engineering, University of Cambridge, Trumpington St, Cambridge CB2 1PZ, United Kingdom

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ABSTRACT

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 study quantifies the disruption to technological markets and individual behaviours embodied in possible decarbonisation pathways for the United Kingdom. We review 12 strategies for decarbonisation proposed by a range of sources, including public and industry bodies, academic organisations and advocacy groups. The broad scope of perspectives yields a large set of possible mitigation options. A novel metric captures the embedded disruption across dual axes of technological and behavioural change. We find a distinct bias towards technological disruption through the pursuit of fast deployment and speculative technologies. Behavioural mitigation remains undervalued. The predominance of supply-side decarbonisation in global climate discourse means that a technological bias, illustrated here for the UK, is seen in mitigation strategies across the world. Historical evidence shows that technological diffusion takes decades, especially in energy markets, while behaviour change can be swifter. A technological bias reduces the likelihood of achieving net zero global emissions in time to limit global warming to 2°C. To win the race against climate change, governments should rebalance policy efforts and spending across technological and behavioural options for mitigation.

1. Introduction

Climate change presents a risk to the future of modern society. Governments across the world are meeting this challenge with ambitious targets to eliminate net emissions by mid-century. Mitigation policies currently focus on decarbonising energy, an undeniable priority but one that alone cannot deliver the Paris Agreement's warming target [1]. Limiting warming to 2°C will mean disrupting markets, systems, infrastructure and behaviour. Disruption takes time. The closing window to entrench change means policies that enable near-term mitigation should be prioritised over slow-burn strategies, at least for now. To paraphrase a well-known aphorism, quick mitigation is good mitigation.

We consider the type and scale of disruption in the United Kingdom's net zero transition and what disruption means for the pace of decarbonisation. The achievable timescale of mitigation depends on the nature and ambition of the proposed disruption. High ambition policies—those which target large changes to markets or activities—have the greatest abatement potential. They will also take the longest time, as physical and social infrastructure is developed. Ambitious, disruptive mitigation strategies also tend to face physical barriers [2, 3], social or political pushback [4] and high costs [5].

Specific definitions of disruption vary in the literature [6]. 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 [7, 8]. Energy and climate researchers have broadened this original concept to consider systemic, policy-driven changes [8]. Ketsopoulou et al. [9] 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. Burt [10] defines disruption as throwing into disorder the current state, generating consequences that persist over time. For climate transitions, disruption is characterised by systemic change with socio-technical interactions [11]. Some distinguish disruption from discontinuity by arguing the latter breaks with past experience to herald a new order [10, 12].

In a policy context, 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 [13]. A successful net zero transition is likely to combine innovative policy with coordinated and intentional change, which Ketsopoulou et al. [9] refer to as purposive disruption. However, sudden and unanticipated policy changes could create disorder and increase disruption to undesirable levels [14].

Our study adopts a general definition of disruption as a swift deviation from current trends. We also distinguish 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' [15]. 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 de-

*Corresponding author: jma42@cam.ac.uk, +44 1223 3 38181
ORCID(s):

Table 1
Definitions of key terms used in this 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 level of 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 any given scenario.

cisions, such as the deployment of heatpumps in homes. The specific definitions for technological and behavioural disruption adopted in this study are used to quantitatively assess mitigation options. Table 1 defines technological and behavioural disruption, along with several other terms used throughout this analysis.

Quantifying the role of disruption in decarbonisation is relatively uncommon, given the extent of research effort into low-carbon transitions. Hanna and Gross [12] 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. In the UK, there is a growing interest in understanding the role of policy in energy system disruptions [9]. Johnstone et al. [11] argue that understanding how ownership, actors and regulation affect the rate, direction and acceptance of disruption should be a core research priority for the net zero transition. Wilson [16] 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 [17] 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. However, sector-specific studies of decarbonisation in electricity [18], transport [19], construction [20] and heating [17] highlight the need for deliberately disruptive policies to achieve net zero. In our review of recent disruption literature, we did not uncover any studies that quantify the disruption of climate policy across various sectors.

Mitigation of climate damages is not the only source of policy disruption. Governments' responses to Covid-19 displayed an extraordinary appetite 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.

In this study we ask whether the disruption embodied in mitigation is balanced across technological adoption and behaviour change. We present a new method for quantifying disruption and apply this method to decarbonisation strategies for the UK. This UK-based analysis is internationally applicable due to the similarity of proposed mitigation pathways in other jurisdictions. Our disruption metric is novel and intentionally simple. We evaluate our methodology and assumptions in Section 2.5.

The remainder of this section describes the context of technological and behavioural change in decarbonisation. Section 2 sets out the method used to estimate disruption. We present the results for several proposed pathways to net zero in Section 3. Finally, we discuss the patterns of disruption, risk preferences and the policy implications of our analysis.

1.1. Reducing emissions with technologies

Technological mitigation is achieved using new methods, systems or devices, usually aiming to reduce the emissions intensity of energy use. Reaching net zero by 2050 means deploying new technologies as quickly as possible. Researchers have turned to past examples of large-scale energy technology adoption to evaluate plausible future deployment rates of renewable generation and carbon capture. Smil [21] estimates that coal, oil and natural gas each took 50 to 60 years to go from 5% to 50% market share. For transitions occurring since 1900, namely nuclear, gas, wind and solar, Gross et al. [22] show the period from invention to 20% of maximum market share tends to be slightly shorter, with a median duration of 43 years. Lovins et al. [23] argue that wind and solar can beat large scale technologies like nuclear on construction speed, addition rate and required project lead time. However, Nelson and Allwood [3] show that the innovation delay between initial conception and commercialisation was around two decades longer for wind and solar than nuclear and gas. For all four technologies, they find an average time to commercialisation of 76 years.

Different types of technologies have vastly different diffusion rates. End-use devices, which are smaller and have a larger potential market, can take less than a decade to penetrate a market [24]. However, decarbonisation requires an overhaul of energy generation. The studies reviewed above assess large-scale energy technologies, for which complex construction and infrastructure impede diffusion [2, 3]. Wilson et al. [25] 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 [26]. Lovins et al. [27] show that less infrastructure means distributed resources can reduce system planning, construction and the operational burden of utilities. However, replacing 'lumpy' technologies with granular ones could reduce coordination and security and increase transaction costs, pollution and material waste.

The duration of diffusion depends on the political and economic context. Countries that roll out technology after it is established elsewhere can be significantly quicker than first movers [24]. This means that technological transitions can accelerate over time as they spread to different countries and markets. Reductions in price further accelerate diffusion. Fouquet [28] evaluates 14 energy transitions to show how high prices can reduce the impetus to switch and lengthen the duration of change. Insufficient government support can also dampen price incentives for private companies to develop and deploy technologies [29]. Capitalising on lower costs as well as smaller size, Lovins et al. [27] argue that distributed energy technologies can reduce financial risks with shorter lead times, portability and lower fuel price volatility.

Accelerating technological diffusion is a key priority of climate policy. Kern and Rogge [30] argue that net zero targets will herald unprecedented rates of technology change. However, historical evidence indicates that large-scale energy transitions can take several decades. Small scale generation technologies have the potential to increase diffusion rates and accelerate decarbonisation, as do effective end-use technologies. But the required scale and pace of decarbonisation demands a more varied toolkit.

1.2. The role of behaviour in mitigation

Demand-side emissions arise through energy use, consumption and travel. Behavioural disruption considers how individual adjustments in these three categories can affect emissions at a global scale. Changing behaviour is complex. Here we review the evidence that behavioural disruption could meaningfully reduce emissions. We conclude this section by summarising what this means for the study of disruption.

The potential for mitigation through behaviour change is significant; the residential and transport sectors each contribute 20% of UK emissions [31]. Behaviour change can also reduce the mitigation burden on other sectors of the economy: Roberts et al. [32] show that it can reduce the cost of rapid decarbonisation by 10-20%. Despite this promise, the role of behaviours in proposed decarbonisation pathways is generally low, which Capstick et al. [33] attribute to a persistent focus on direct but small-scale interventions.

Achieving broader behavioural disruption 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 [34]. Financial incentives can change behaviour [35]. However, cultural values and economic development also play a large role in determining how individuals relate to the climate challenge. Jakučionytė-Skodienė and Liobikienė [36] 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 [36].

Policies to disrupt behaviour must be multifaceted [37] and address the many interconnected ways in which the public engage with energy systems [38]. In particular, communication and the framing of climate change can have a major impact on behaviour. Homar and Kne [39] show that emphasising potential losses due to climate damage can induce behavioural intention by capitalising on the cognitive bias of loss aversion. Other work has found that highlighting society-wide cobenefits, such as improvements in public health or job creation, can increase engagement [40]. Loss aversion also means that contextualising climate change in relation to 'big risks' such as atmospheric tipping points can increase public concern [41]. However, doubt that individuals can achieve meaningful change can reduce the impetus to change behaviour [42].

Technology and behaviours are interconnected. Dietz et al. [35] estimated that households could reduce emissions by around 20% with little or no reduction in wellbeing, largely through the adoption of new technologies or changes in how they use existing ones. However, the success of an intervention can depend on its complexity: technologies that require constant interaction can have limited, or even negative impacts [43]. Education about technology use may be able to improve outcomes for complex interventions. van den Broek [44] suggests addressing energy literacy gaps by explaining how behaviours and financial co-benefits can reduce energy demand. Nonetheless, Adua [43] shows that interventions that require a one-off decision or action should be prioritised over equivalent interactive ones.

Behavioural disruption has the potential to accelerate mitigation, despite the complexities of changing public beliefs and norms. Nelson and Allwood [3] compare the duration of historical energy and social transitions. Changes driven by social concern—over, for example, ozone depletion or the health risks of asbestos—take decades less than the roll out of large energy technologies. Characteristic of many historical shifts, notably the ban of ozone depleting substances, are 'social tipping interventions' [45]. These policies capitalise on rising social concern to activate exponential transfers of behaviours, norms, technological adoption and structural reorganisation. Initiating these dynamics could create a multi-level shift in lifestyles to decarbonise society relatively swiftly [46].

The extensive research on low-carbon behaviours illus-

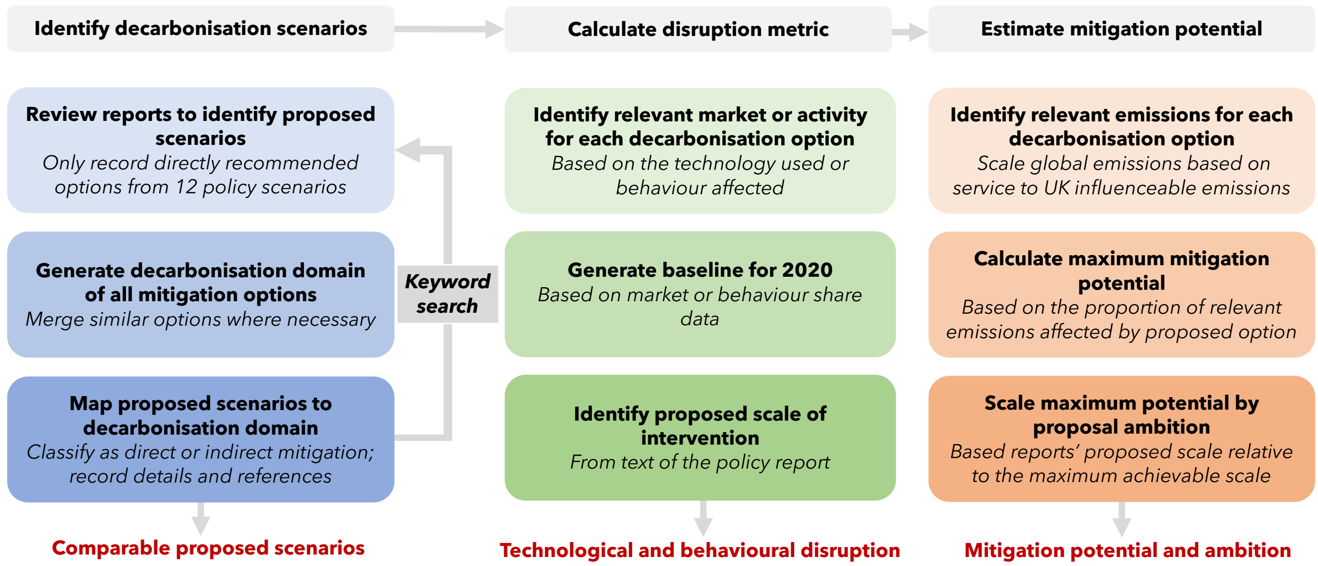

Figure 1: The method used to evaluate the behavioural and technological disruption embodied in decarbonisation proposals.

trates both the opportunity and complexity of achieving behavioural disruption. Our study's method is intentionally simple and we omit some of these complexities. However, by disseminating disruption into its behavioural and technological components, we can measure the role of behaviour in decarbonisation. Our methodology, detailed below, advances efforts to quantify the diffusion of low-carbon behaviours.

2. Materials and methods

We evaluate the balance of disruption in mitigation proposals in three stages. First, we review several reports that each propose a set of options to reduce emissions (Section 2.1). Our method determines comparable lists of policy options from the decarbonisation proposals. Second, we develop a metric to capture the technological and behavioural disruption embodied in the proposals (Section 2.2). Finally, we estimate the mitigation potential of each decarbonisation option (Section 2.3). We provide example calculations in Section 2.4 and discussion the limitations of our method in Section 2.5. Our method is summarised in Figure 1. Details about mitigation options and scenarios are available in the supplementary material.

2.1. Identifying decarbonisation scenarios

Table 2 summarises the 12 scenarios assessed in this study, drawn from seven decarbonisation reports that cover a broad range of sectors including industry and advocacy groups and a government advisory committee.

2.1.1. Sampling method

In selecting decarbonisation scenarios, we 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). Our focus on policy proposals, including grey literature, meant we chose not to limit our search to academic databases such as Scopus. Given that we are interested in the policy impacts of potential scenario bias, we ranked candidate reports by our estimates of their political influence.[1].

We then collected mitigation options from each report, proceeding by rank and stopping once our 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 our three selection criteria and provide a representative view of the optimal pathways to net zero. The 12 scenarios capture a varied set of perspectives on the challenge and, importantly, yield a diverse domain of mitigation options.

2.1.2. Classifying mitigation options

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. We then identified which of the 98 options were proposed in each scenario to generate comparable results. The final step was to cross-check the original reports with the decarbonisation domain using a keyword search for each option. The detailed mitigation options, along with each report's specific proposal, can be found in the supplementary material.

[1] As Braunreiter and Blumer [54] point out, some reports may have less influence due to researchers' and policymakers' perception of the quality of the author organisation.

Table 2
List of decarbonisation scenarios. Scenario ambition provides a brief overview of the goals of each scenario, along with the emissions reduction target.

Source	Scenario	Scenario ambition
Government reports		
Climate Change Committee (CCC) [47]	Further ambition	Significant decarbonisation along with roll out of new technologies reduces emissions in 2050 by 96% compared to 1990.
Advocacy groups		
Centre for Alternative Technology [48]	Central	Cross-sector and technically feasible scenario reduces emissions by 92% compared to 2020 by 2030.
Friends of the Earth [49]	Central	Utilises new technologies to achieve net zero emissions by 2045.
Greenpeace [50]	Central	Socially fair, government-driven strategy based on proven technologies that achieves net zero emissions by 2050.
Academic reports		
UK Fires [51]	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 (DDP) [52]	Decarbonise and expand	Near-term power decarbonisation with strong policy support, widespread electrification and CCS to reduce 2050 emissions 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.
Industry bodies		
National Grid (NG) [53]	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.

Some reports mentioned the merits of potential options but did not directly propose them, such as the 'speculative options' proposed by the Climate Change Committee [47]. 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. We merged options where the implementation or intent of the proposals were the same.

2.1.3. 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 reduction so are treated separately in the analysis.

2.2. Disruption metric

We quantify the disruption of mitigation options based on the proposed change in the associated market or activity. Following the definitions given in Table 1, technological disruption describes changes in the market share of a technology; behavioural disruption is changes in the behaviour share of a given activity.

Our disruption metric is based on the percentage change in the market or activity between 2020 and 2050. We take the absolute value since change is disruptive regardless of direction, and use 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:

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

We calculated the baseline using contemporary statistics for the technology or behaviour share in 2020, except in two cases. If an option related to efficiency, we indexed the baseline to 2020 and measured relative improvements. Similarly, when the relevant baseline was the size of the market rather than a market share, such as for reducing ceramics consumption or total distance travelled, we again indexed changes 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 we allocated a quantitative value proportional to the implied ambition. When the target did not match the identified market or activity in the baseline, we assumed 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 [55, 56, 57]. In such cases, a 0% baseline share was replaced by 0.0001% to enable calculation while still capturing the barriers to implementation.

2.2.1. 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 3 provides examples from different sectors to illustrate how we identified relevant markets and activities. Our examples describe the most disruptive options in each sector. Where relevant we include an example with both technological and behavioural disruption. Additional notes and the classifications for all 98 mitigation options are provided in the supplementary material.

2.2.2. Assessing the disruption metric

Our chosen metric is based on simple measures: the proposed change in market or activity share of a technology or behaviour. We considered several alternatives, including the readiness level of the technology, market concentration, and the social acceptability of the behaviour. These factors are important in disruption. However, we believe our chosen metric is the most transparent method to quantify disruption. Possible extensions to the metric are discussed in Section 2.5.1.

Assessing whether our results can, as we hope, be interpreted as disruption is difficult because no other studies perform similar analysis. However, we can take some guidance directly from the report produced by the Climate Change Committee (CCC). 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 [47, p. 155]. Using our classification, 9% of the CCC's mitigation options involve only behavioural disruption and 73% involve only technological disruption. The remaining 17% require a combination.

Our 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 our definitions. Although it does not explain the categorisation, we suspect that the discrepancy occurs because the CCC defines societal and behavioural changes more broadly than we do. 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, we would classify it as a solely technological disruption because it is a supply-side adjustment. We stand by our behavioural classification method as the best way to capture the demand-side disruption of mitigation options. However, adding a category of market disruption is a potential area for future research.

2.3. Estimating mitigation

Disruption can be thought of as the risk embodied in a decarbonisation scenario; mitigation is the return. Here we describe the process of estimating mitigation for the 98 proposed options. We distinguish 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.

2.3.1. Global emissions shares

The first step to calculate mitigation potential of decarbonisation options is to identify the emissions produced by the relevant market or activity. We calculate these emissions

Table 3
Classifying the market and activity of mitigation options in different sectors of the economy.

Sector	Option	Technological market or behavioural activity (and 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)
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)

(1) Where changes are made to new homes, we assume that the responsibility for meeting building standards falls on the construction industry and individual decisions (house purchasing) are not affected. (2) We estimate this based on home occupancy factors and an estimation of the heating season [58, 59]. (3) Retrofits require both technological deployment in the construction market, and behaviour change by homeowners. (4) We assume the behavioural decision to install low carbon heating is the same across modes (electric and hydrogen). (5) We benchmark 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. We assume 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 we 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, we benchmark to 2020. (8) Restoring peatland and afforestation affects individuals by reducing space for building, while potentially creating more recreational space.

shares using the global emissions Sankey diagram in Bajželj et al. [60]. Their study traces emissions from final services, such personal travel, thermal comfort, construction of buildings and so on, through sector, equipment, device, final energy, fuel and emissions. Differences between the UK and global economies means we over- or under-estimate true mitigation for some options. However, no such analysis exists for the UK. BEIS [31] provides emissions data for some categories but not for final uses, and attributing emissions to final uses is extremely challenging. Existing UK Sankey diagrams are produced only for energies and exclude end uses. The Bajželj et al. [60] framework offers an internally consistent method to estimate mitigation for options acting at different points of the supply chain and across different markets.

The mitigation potential for each option depends on the existing emissions intensity of the market or activity. To estimate this we locate the option within a relevant *class* in the emissions Sankey diagram [60] 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. We then multiply the category's share of global emissions by the UK's influenceable emissions.

2.3.2. 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 [31]. We estimate imported emissions based on Davis et al.'s [61] 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 [31] to include the effect of radiative forcing that increases the global warming potential of air travel [62], based on conversion factors provided for organisational greenhouse gas reporting [63]. These three emissions sources give an estimate of $780MtCO_{2e}$.

2.3.3. Maximum potential mitigation

Mitigation options may not affect all emissions arising from a market or activity. We determine scaling factors for each option based on the share of category emissions that an option can reduce. Technology scaling factors reflect the maximum practicable deployment. For behavioural options, maximum mitigation relates to what Dietz et al. [35] call 'plasticity': the maximum potential adoption of effective instruments. Scaling factors therefore ensure realism in our mitigation calculations.

Multiplying UK category emissions by the scaling factor yields maximum potential mitigation. Our scaling assumptions over the electricity and hydrogen supply are particularly important.[2] Mitigation from electrification depends on the availability of non-emitting electricity. We assume an unlimited supply of renewable generation. Similarly, we assume 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.

2.3.4. Estimating mitigation ambition

Mitigation ambition relates the mitigation potential to the target scale in a given scenario. To calculate ambition we first define a maximum possible share 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. We then calculate the ambition ratio 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 and behavioural change, we take the higher ambition across the two disruption types to capture the dominant effect. Mitigation ambition is given by:

$$\text{Mitigation ambition}_{i,p} = \text{Maximum potential mitigation}_i \times \text{Ambition}_{i,p}$$

2.4. Illustrating our method with examples

We clarify our method further with example calculations of disruption and mitigation for three options proposed by the Centre for Alternative Technology (CAT) [48]. 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 4 provides the information necessary to calculate technological and behavioural disruption, using the method described in Section 2.2. Table 5 illustrates the calculations described in Section 2.3 to calculate the mitigation ambition for each option. These tables are drawn from our supplementary material, which provides these data and assumptions for all proposed mitigation options.

2.5. Evaluating our method

Our method 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. Here we discuss assumptions and possible limitations.

[2] These are strong assumptions. 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 this assumption are intended as technical maxima.

Table 4
Example disruption calculations for options proposed by the Centre for Alternative Technology [48].

Technological factors		Behavioural factors		Centre for Alternative Technology			
Market	2020 baseline	Activity	2020 baseline	Market share	Technological disruption	Behaviour share	Behavioural disruption
Reduce beef and lamb consumption							
		Eating (red meat share of adult diet by energy intake) [58]	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) [64] (2)	94%			100%	1.8	N/A	0
Electrify road passenger transport							
Passenger vehicles (share of car stock that is electric or hybrid) [65]	2.3%	Car purchasing (share of car sales that are electric or hybrid) [66]	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
Example mitigation calculations.

Global emissions share			UK maximum mitigation			Centre for Alternative Technology	
Class	Category	Activity or 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) We make several assumptions to allocate enteric fermentation and land use emissions to cattle and sheep stock: see supplementary Table 14. (2) We assume that an energy efficient home produces 24% less emissions than average home [67]. In 2050, 21.5% of housing stock in 2050 will be new [51, 68, 69, 70] (3) We calculate technical maxima so assume non-emitting electricity.

2.5.1. Assumptions of the disruption metric

Our 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 explicit consideration 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 most effect.

Disruption depends on time: the same change over a shorter period of time will be more disruptive to markets and behaviours. Our metric does not take into account the effect of different proposed timescales across scenarios. This means that our calculations underestimate the disruption embodied in the scenarios from CAT and Friends of the Earth, which aim to achieve net zero before 2050 [48, 49]. However, net zero has been legislated for 2050 in the UK. We focus 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.

We apply our disruption metric to a descriptive analysis of decarbonisation reports. The dearth of quantitative reports on behavioural mitigation options limits our analysis. Studies on the potential for socially-driven decarbonisation [e.g., 71] would yield a more behaviourally disruptive scenario, but have yet to provide a quantitative pathway to net zero. They were therefore not included in our review. Moreover, we may have overlooked a set of particularly disruptive interventions, such as geoengineering, by focusing on relatively mainstream sources. While our analysis considers policies that are perhaps most politically realistic, a wider net may provide a more complete picture.

2.5.2. Assumptions in estimating mitigation

We chose to estimate the UK's influenceable emissions by combining territorial emissions with estimated emissions from imports, aviation and shipping. Two alternative calculations were considered. The first calculates imported emissions using the share of emissions embedded in trade [72, 73, 74]. This method yields an estimate of 710$MtCO_{2e}$, 9% less than our central estimate. The second combines consumption-based emissions [75] with estimates of land-use emissions [31] and export emissions [61]. This gives emissions of 830$MtCO_{2e}$, 6.1% higher than our central estimate. From these two alternatives, we take the higher discrepancy of 9% as the uncertainty in mitigation potential.

Our mitigation estimates provide a signal for each 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; 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 all electricity is non-emitting, these measures do not reduce emissions. This interdependence means the mitigation potential across all options will sum to more than current UK emissions. Our mitigation estimates should not be treated as integrated projections of scenario emissions. Instead, they can be used to compare mitigation options.

3. Results

Our survey yields a set of 98 mitigation options and 538 proposed policies across the 12 decarbonisation scenarios. Here we present the disruption and mitigation results. The analysis depends on our classification of options and the disruption metric itself. Further detail on each individual option is given in the supplementary material.

Table 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.

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.

3.1. 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 current emitting practices. The disruption and mitigation associated with the maximum ambition scenario are presented in Figure 2. Bubble size indicates how each option compares in environmental efficacy. For clarity, we label only some of the mitigation options.

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.

Table 6
Summary statistics for the 538 proposed decarbonisation options collected in this study, 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

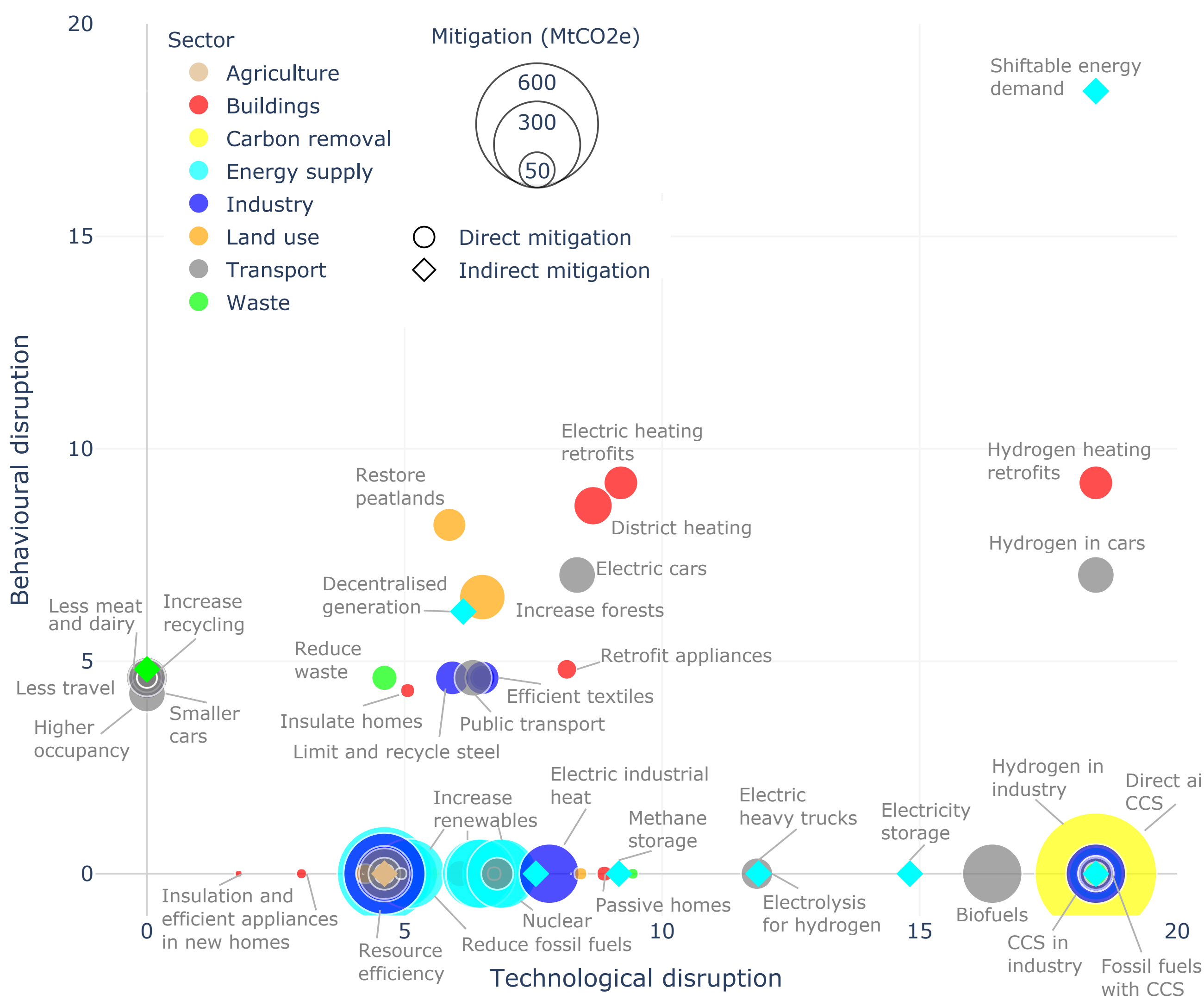

Figure 2: The maximum disruption and abatement for all mitigation options. The size of the bubble gives the relative mitigation potential.

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 [53]. 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 share.

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 our methodology. For the maximum ambition scenario we assume 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% [76], all else remaining 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 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 are not captured in our 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.

The behavioural options in our analysis 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, our analysis focuses on the mitigation option itself, and is confined to what is suggested in the surveyed reports. Deeper inspection of the options is warranted and welcome. Our intention in this high-level analysis is to highlight the many interesting questions that we face in the next three decades of disruptive decarbonisation.

3.2. 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. We perform cluster analysis on the 538 proposed mitigation options to identify groups with similar characteristics.[3] This allows us to assess the scenarios more generally. Figure 3 shows the results. Each cluster is labelled with a summary of the grouped options.

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 iteration of direct air CCS has not yet progressed beyond proof-of-concept [56]. Hydrogen can be effective in transport and energy, but faces high barriers to scale due to large carbon-free energy requirements [55]. 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; we use 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. Our 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 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 12 proposals. The cluster of options utilising hydrogen in buildings and cars is a translation along the technological axis of electrifying and retrofitting homes.

[3] We use k-means clustering and determine 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.

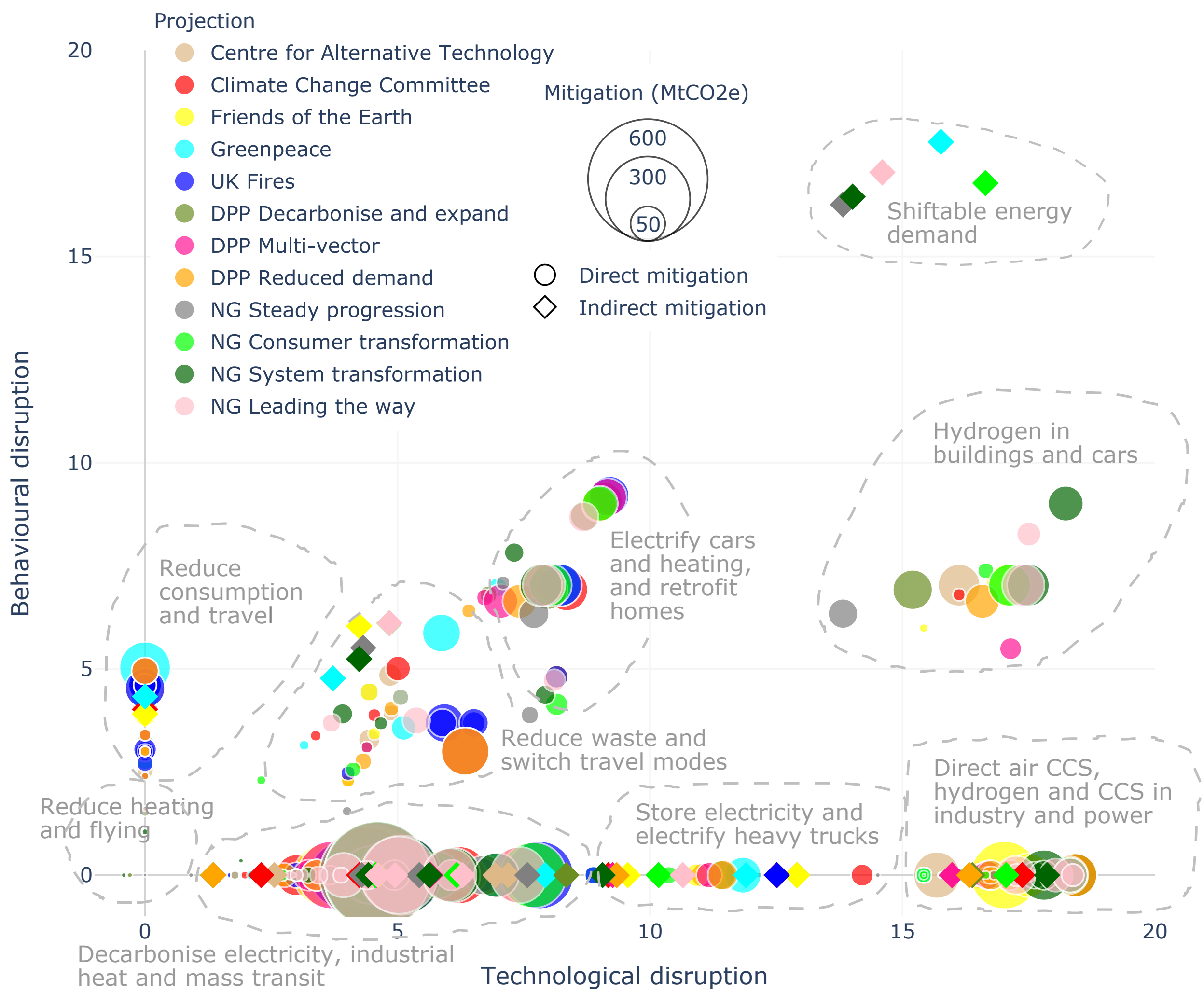

Figure 3: The technological and behavioural disruption for all mitigation options proposed in the scenarios. The size of the bubble gives the relative mitigation potential. Cluster analysis identifies different segments of decarbonisation strategies.

The 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.

3.3. 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 4 shows disruption in the 12 proposed scenarios. 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' [51, p. 1]. The outcome is a decarbonisation scenario that implies relatively little disruption to markets and lives.

Yet even the most technologically conservative report we surveyed provided less than half of mitigation through behaviour change. Figure 5 aggregates the results of Figure 4 to show the average disruption across all options in each scenario. Every proposal lies below the diagonal, indicating a greater reliance on technological over behavioural disruption.

4. Discussion

Our results illustrate an imbalance between technological and behavioural disruption in the net zero pathway. We discuss whether this constitutes a bias in climate policy, and why such a bias might arise. We then consider what it means for wider observations about disruption preferences, particularly in light of the Covid-19 pandemic.

Figure 4: The technological and behavioural disruption of the mitigation options, for each of the 12 decarbonisation strategies reviewed. Our mitigation estimation considers the options in isolation. It cannot be used to describe the whole mitigation scenario as a sum of parts, as we note in Section 2.5.2. We therefore omit mitigation potential from this figure.

4.1. Is there a disruption bias in today's decarbonisation scenarios?

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 12 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.

Our results illustrate a bias towards technological dis-

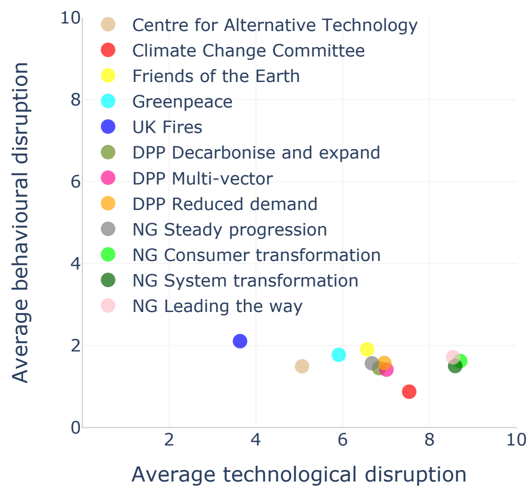

Figure 5: The embodied technological and behavioural disruption of decarbonisation proposals, averaged across all mitigation options.

ruption. 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 [2] and skills shortages [77] 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 [78]. 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.

Prudent future planning means treating speculative options—both technological and behavioural—with caution [79]. 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.

4.2. Why are some proposals more technologically biased than others?

All decarbonisation scenarios display some level of technological bias. However, some are far more technologically disruptive than others. The Climate Change Committee and National Grid are the most technologically disruptive. They are also 'closest' to government; the Committee is a statutory body and National Grid operates the UK's electricity system. Their proposals are likely 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 Climate Change Committee and National Grid, behavioural change has had a growing role in their climate proposals in recent years. The Climate Change Committee's updated 2020 policy proposal includes a *Balanced Net Zero* pathway in which 16% of emissions reductions are attributable to social or behavioural changes [80], up from 9% in 2019 [47]. Between 2019 and 2020, National Grid replaced decentralisation with societal change as a metric for estimating the speed of decarbonisation [53]. 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.

4.3. What can climate scenarios tell us about 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, we might conclude that the government would select the set of mitigation options which minimises disruption across both technology and behaviour. In Figure 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, as observed in our results.

Figure 5 supports the idea of a preference for technological disruption amongst climate decision makers. This preference would intensify the echo chamber effect of technological bias. Researchers might preemptively skew their proposal towards technological options to improve its reception with politicians [54]. As we discussed above, this is particularly pertinent for organisations closest to government.

A preference for technological disruption means policymakers might overlook potential behavioural mitigation opportunities. Our evidence suggests 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 [81]. 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.

Analysing climate proposals for other countries may produce interesting comparisons of national disruption preferences. Our study focuses on the UK. We believe this offers a sufficiently broad perspective on global mitigation options due to the similarity of national decarbonisation strategies. However, other countries may have different political contexts which allow for more interventionist policies. Identifying such differences could yield interesting insights on how disruption preferences affect the pace of decarbonisation.

5. Conclusion

The stakes of the climate challenge demand a careful balance between 'safe' mitigation and high risk, high reward strategies. Our results illustrate a bias towards technological disruption through 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. However, renewable energy and electrification are not sufficient to reach net zero. 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. However, we found that decarbonisation proposals tend to rely heavily on unproven technologies to meet the mitigation gap, such as CCS and hydrogen power. These technologies face significant and time-consuming barriers to scale. Disruptive behavioural interventions, such as regulating meat consumption, are off the table.

With less than three decades to reach net zero, climate policies should be prioritised for security and speed. Options that minimise disruption by relying on existing technology or accepted behaviours should be pursued at pace. Avoiding disruption entirely is impossible, however, and disruptive technologies should be matched by interventions to influence behaviour. Achieving net zero swiftly and with the least possible disruption means accepting that behaviour change is just as essential as technological change. Rebalancing the decarbonisation agenda will diversify climate policy and accelerate progress in the race to net zero emissions.

Policy recommendations:

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

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