KEEPING IT COOL

HOW THE UK CAN END ITS CONTRIBUTION TO CLIMATE CHANGE

November 2018
An analytical report by Vivid Economics

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FOREWORD BY WWF

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WWF's 2018 Living Planet Report shows just how stark the threat to nature from human activity is, demonstrating a 60% decline, on average, in populations of vertebrate species since 1970.

Habitat degradation, loss and over-exploitation are currently the biggest threats to nature with climate change a significant and growing threat. If we tackled all other threats, but failed to keep global warming to below 1.5°C, then nature and wildlife would still be under threat of continued decline. This century has already seen 17 of the 18 hottest years on record alongside more and more climate-related impacts. These are all warning signs from our planet and if we fail to tackle climate change we will face costs and consequences; which will only get worse.

The 2015 Paris Agreement marked a global milestone – the world committed to keeping global warming to well below 2°C, aiming for 1.5°C, working to strike a balance between greenhouse gas emissions by sources and removals by sinks. Following the publication of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C, the science is clear that it is vital to keep warming to 1.5°C in order to limit the risks of severe climate impacts to people and nature. The report also tells us how: rapid and deep cuts to global greenhouse gas emissions and ramping up removal of carbon dioxide from the atmosphere.

Therefore, as the UK celebrates 10-years of its world leading Climate Change Act, it is time to take stock of our current ambition, set to cut greenhouse gas emissions based on a 2°C world. This is an important opportunity for the UK to show leadership by setting an ambitious net-zero greenhouse gas emissions target which puts us on track to meet our commitments under the Paris Agreement and bring an end to the UK's contribution to climate change.

New analysis from Vivid Economics in this report does the crucially important job of demonstrating to us that it is technically feasible for the UK to reach net-zero greenhouse gas emissions by 2050. Further, it shows that, with international collaboration and innovation, the UK can achieve net-zero emissions by 2045. Both these scenarios are hugely challenging, but they demonstrate that it is possible.

The pathways set out here will, inevitably, be modified over time and the path taken will look different when we look back at it from 2045. Innovation and technology development can be swift and unpredictable – as the UK has demonstrated with offshore wind development, for example. So too is behaviour change – just recently, we discovered how fast people in this country are switching to plant-based diets. This, and other changes in how we live our lives will hasten progress towards net-zero. What is essential is that we confront this challenge head on.

Action to tackle climate change cannot be taken in isolation. In 2020, world leaders meet to do three crucial things. Shortly after the UN General Assembly marks its 75th anniversary, leaders come together to review and update the sustainable development goals. A few months later, they review the Aichi targets which were set to protect biodiversity against the decline that we see all too starkly now. At the end of the year, they must submit their nationally determined contributions to the Paris Agreement, to deliver climate action geared to a 1.5°C world. These major milestones – to protect people, wildlife and our planet – must work together to deliver a global deal for nature, to build a world in which people and nature can thrive. The first step for the UK is to commit to ending our contribution to climate change as soon as we possibly can. This report shows what is possible.

1. THE UK CAN REACH NET-ZERO GREENHOUSE GAS (GHG) EMISSIONS BY 2045

This will require strong action across all sectors, with commitment from government, business and society. Achieving net-zero GHG emissions by 2045 requires innovation, collaborative action and demand reduction. This report sets out two scenarios: to achieve net zero in 2050 and in 2045. The 2050 scenario (*UK2050*) includes action in key areas, which are then supplemented by additional actions around behaviour change and international collaboration for the 2045 scenario (*Collab2045*). Overall, we need to achieve:

1.

ZERO EMISSIONS IN SEVERAL SECTORS:

The power, surface transport and building sectors must reach zero, or near-zero, GHG emissions by 2050.

2.

DEEP CUTS IN 'HARD TO TREAT' SECTORS:

Industry, shipping and agriculture must significantly reduce their GHG emissions from current levels. Aviation must (at least) maintain emissions to current levels, which will likely require close to zero emissions from domestic aviation.

3.

INTERNATIONAL COLLABORATION:

To cut emissions from international aviation and shipping, as well as help accelerate innovation in technological solutions.

4.

BEHAVIOUR CHANGE:

Business and governments supporting individuals to make more sustainable choices, such as embracing more plant-based diets.

5.

LARGE-SCALE DEPLOYMENT OF GREENHOUSE GAS REMOVAL (GGR) OPTIONS:

The remaining emissions are compensated by removals using carbon sinks. These include forest growth, but also more technological options such as sustainable bioenergy coupled with carbon capture and storage (BECCS). The scenarios show that we need rapid deployment of GGR technologies at scale, including some (such as direct air-capture of carbon dioxide (DACCS) whose deployability is unclear, and others (BECCS) which come with other environmental risks.

By contrasting the two scenarios, this report highlights the value of driving behavioural change (such as reducing meat consumption) and international cooperation (for instance on aviation) in achieving net zero with the least risk and cost. More rapid and deeper emissions cuts in the short-term via these routes significantly reduce reliance on riskier carbon dioxide removal options and make it feasible to bring the date the UK can reach net zero forward.

2. WE NEED TO PRIORITISE RAPID AND DEEP EMISSION CUTS BEFORE IT'S TOO LATE

In order to achieve net-zero greenhouse gas emissions and limit global warming to 1.5°C we need urgent action to prioritise deep emissions cuts. Increasing action now – particularly in proven areas such as renewables and electric vehicles – is critical and offers a 'no-regrets' scenario.

The food system as a whole is responsible for a third of global greenhouse gas emissions – more than direct emissions from the transport sector - with the livestock system being responsible for nearly 15% of these. Dietary shifts, including a rebalance of protein consumption away from animal products, have the potential to contribute substantially to reducing emissions globally, and reducing pressure on land, seas and water (and therefore biodiversity). The multifaceted nature of food requires a systemic approach. We cannot, for example, focus solely on production if we are to reduce the pressure our current food system has on the planet. We need to focus on consumption as well in order to reduce demand for high-impact products, starting to make them unviable for producers, suppliers and retailers along the supply chain. Policymakers can deliver appropriate regulatory frameworks and incentives. Businesses can develop and market more sustainable products and services, 'nudging' consumers toward healthier and more sustainable choices. And individuals can act more responsibly and put pressure on policymakers and business to increase the availability of those sustainable choices.

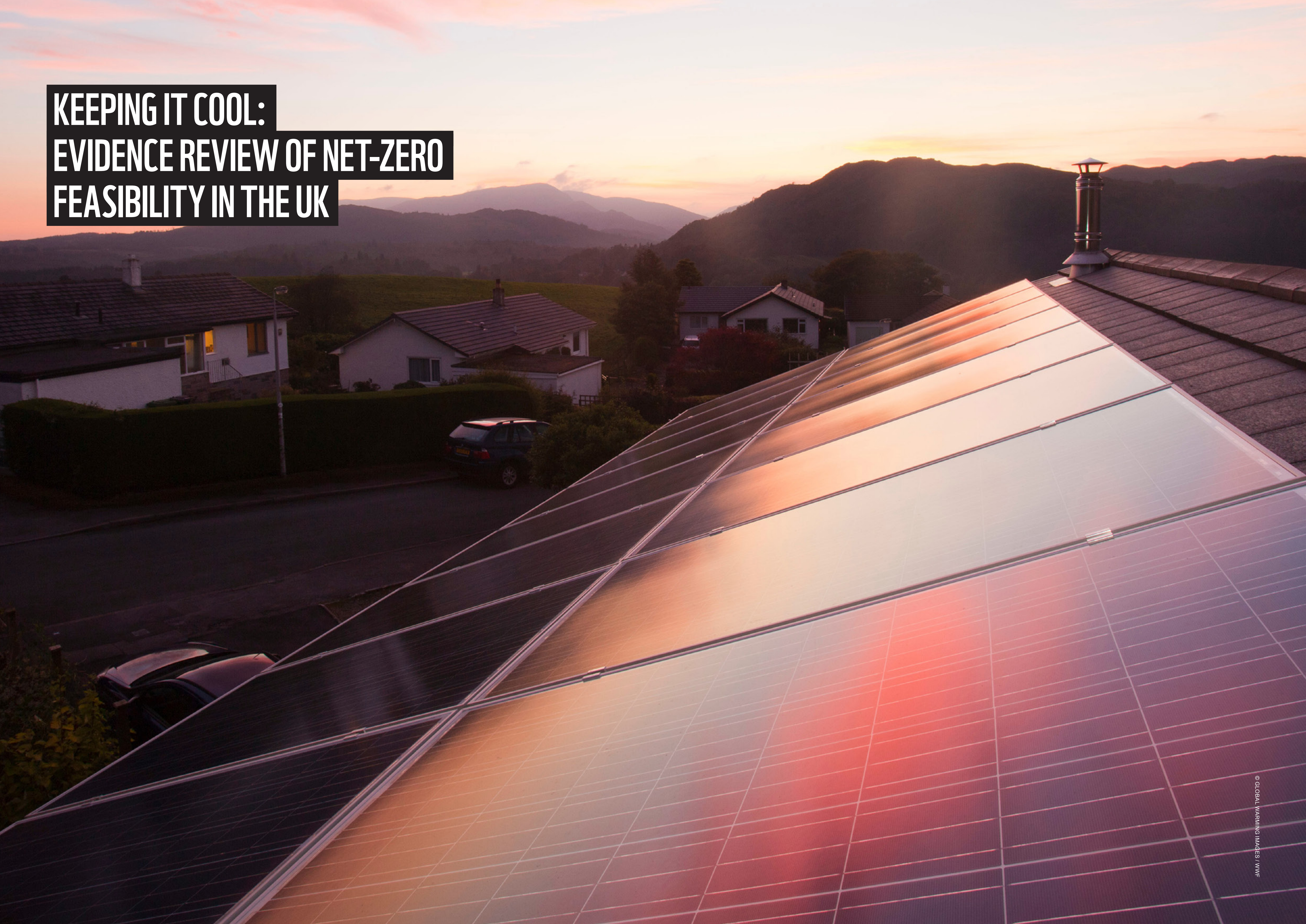
3. WE NEED COLLABORATIVE ACTION

Achieving net zero by 2045 relies on international collaboration. To reduce emissions from aviation significantly, a step change in the current ambition of international agreements is required. Innovation drives deployment of renewables; areas such as aviation and shipping require further technological innovation to achieve decarbonisation, such as for short haul European electric flights.

International collaboration on research, development and deployment of new technologies could accelerate the pathway to net-zero. DACCS, for instance, is currently an immature technology with only very small-scale demonstrations underway and no meaningful deployment feasible until 2030. The UK could achieve a 2045 net zero scenario from stronger investment in this technology.

Reducing the UK's net emissions to zero will end the UK's contribution to climate change. We have long known that the economic costs and benefits of tackling climate change far outweigh the costs of failing to do so. Achieving this within the next three decades puts the UK in a formidable position of global leadership on tackling climate change - able to unite others to protect future generations, restore nature, and enable us to live within planetary boundaries.

KEEPING IT COOL: EVIDENCE REVIEW OF NET-ZERO FEASIBILITY IN THE UK



1. INTRODUCTION

1.1 THE NEED FOR NET-ZERO EMISSIONS IN THE UK

The IPCC has concluded that the negative consequences of climate change will be significantly more severe under 2°C warming than 1.5°C (IPCC, 2018). For example, beyond 1.5°C, there will be substantial further increases in weather extremes such as heatwaves, droughts and storms, and in their associated impacts on crop yields, flood risk, and fresh water availability – all of which have significant negative effects on people and nature. The additional 0.5°C of warming will severely impact biodiversity and habitats. For example, twice as many species of plants and vertebrates – and three times as many insects – will lose over half of their climatically determined range at 2°C than at 1.5°C. Sea-ice-free summers in the Arctic are ten times more likely at 2°C, and while we may preserve around 30% of existing coral reefs at 1.5°C, we face their total loss at 2°C. Approximately 13%[1] of total land area is likely to undergo an ecosystem transformation with 2°C warming (IPCC, 2018).

Strong global action is necessary; as a G7 economy and a large historical emitter, the UK should be expected to do more than the global average, and achieve net-zero emissions for all greenhouse gases (GHGs) as early as is reasonable and practical. For no, or limited, temperature overshoot of the 1.5°C target, global CO2 emissions must reach net-zero around 2050, with deep cuts in non-CO2 gases as well (IPCC, 2018)[2]. It implies reducing net UK emissions by 160 MtCO2e beyond the current 80% target set in the Climate Change Act. Recent analysis from the Royal Society suggests this is possible through a combination of additional emission reductions and significant deployment of greenhouse gas removal (GGR) technologies (The Royal Society & Royal Academy of Engineering, 2018).

The UK is well placed to lead the global mitigation effort; however, in common with almost all Parties to the Paris Agreement, it must urgently ramp up its climate action. The UK has been a leader in climate change action and is well placed to continue to lead the global transition, both through policy ambition, and through the development of green business opportunities in, for example, renewables, smart technology, and carbon dioxide capture and storage (CCS). The UK will however have to raise its ambition to remain consistent with scientific consensus. Existing UK commitments are based on a pre-Paris Agreement global warming limit of 2°C, but analysis by the Committee on Climate Change (CCC) suggests current UK action does not suffice to reach even the *less ambitious* 80% reduction target in 2050[3]. To achieve emission levels compatible with 1.5°C, the UK will first need to get back on track to achieving existing targets, and subsequently redouble efforts to exceed them as soon as possible.

1 Compared to 4% with 1.5˚C global warming

2 Note, CO2 concentrations are a cumulative problem. That is, the stock rather than the annual emissions of CO2 matter. Achieving net zero by 2050 is thus important for two reasons: to stop adding to the CO2 stock by 2050, and the rapid decrease of emissions necessary to reach net zero by 2050 means much less CO2 is added to the atmospheric stock in the years to 2050.

3 Compared to 1990 levels, as set out in the 2008 Climate Change Act.

WWF GLOBAL DEAL FOR NATURE

Climate action cannot be taken in isolation - we need a global deal for nature. The IPCC report is clear that the threats to nature are greater at 2°C than at 1.5°C. WWF's 2018 Living Planet Report shows just how stark the threat to nature from human activity is, demonstrating a 60% decline, on average, in populations of vertebrate species since 1970. On track for that number to reach 67% in 2020, the need for action is urgent. Pollution, over-exploitation and consumption are having the biggest impacts on nature, but climate change is a significant and growing threat; if we tackled all other threats, but failed to keep global temperature rises to 1.5°C, then we would still likely be facing the sixth mass extinction of species on our planet. In 2020, world leaders convene to commit to nationally determined contributions (NDCs) under the Paris Agreement - which need to be sufficient to keep warming to well below 2°C - preferably to 1.5°C. But 2020 also sees revision of the Sustainable Development Goals and an overhaul of the Aichi Targets, set under the UN Convention on Biodiversity. Climate action must go hand in hand with action to protect, and restore biodiversity, and to deliver sustainable development, capable of enabling a growing world population to live in harmony with wildlife and nature. A global deal for nature in 2020 must unite action for climate, nature and people.

1.2 OBJECTIVE AND SCOPE OF THIS STUDY

In the context of the IPCC Special Report on Global Warming of 1.5°C, this study sets out ambitious pathways for the UK to achieve net-zero greenhouse gas (GHG) emissions by or before 2050, supplementing existing scenarios with the latest evidence on mitigation and greenhouse gas removal (GGR) opportunities. Existing scenarios by the CCC and Royal Society suggest it is feasible for the UK to achieve net-zero GHG emissions in 2050 through a combination of ambitious mitigation[4] and rapid ramp up of greenhouse gas removal (GGR) options (CCC, 2016, The Royal Society & Royal Academy of Engineering, 2018). This review of techno-economic feasibility provides a high-level review of this conclusion and contributes new insights on opportunities for GHG reductions, risks, and policy needs. It makes several contributions beyond the existing evidence base including:

- *Identification of promising further mitigation opportunities, particularly in industry.* Recent contributions to the evidence base allow a series of innovative potential emissions savings, including zero-carbon steelmaking and the reduction of coke manufacture in the UK.
- *Identification of key policy areas for GGR.* To achieve net-zero emissions, deploying GGR techniques is vital. Beyond 2050 GGR may come to dominate climate policy if large negative emissions need to be achieved. However, policy development to support GGR is in its infancy, particularly compared to the well-established suite of policies to support emission reduction. This report gives attention to both, identifying areas where GGR policy requires urgent development.
- *Demonstration of the value of behavioural change and international cooperation.* By contrasting two scenarios, we highlight the importance of behavioural change and international cooperation to the UK in achieving net-zero. It can significantly reduce the reliance on more risky technologies such as bioenergy with CCS (BECCS), and potentially bring the date the UK can reach net zero forward to 2045.

60%

DECLINE IN WILDLIFE POPULATIONS SINCE 1970

4 Taking the CCC's most ambitious max scenario and the Royal Society's GGR deployment scenario for the UK.

- *Identification of urgent next steps.* Urgent policy decisions are needed around certain key technologies and support for their development and roll-out For example, the viability of large direct air carbon capture and storage (DACCS) and the possible speed of its roll out remain poorly understood; it also remains unclear which options are most likely to be pursued to decarbonise heat, for instance.

Our objective is to illustrate that net-zero emissions by 2050 is not constrained by fundamental techno-economic barriers. As an evidence review, this study does not consider all dimensions of feasibility in detail, but instead builds on existing evidence. Where possible, the study makes use of historical analogies, such as the roll out of gas-fired power plants and offshore wind in the UK to understand the possible rate of an ambitious roll out. Box 1 provides detail on how we operationalise feasibility considerations within our scenarios. Further work is necessary to identify, per sector, detailed road-maps to net zero. In particular, a bottom-up study to understand associated costs, and the implications of the trade-offs associated with paying these costs across society, is required to fully judge feasibility.

BOX 1:
FEASIBILITY CONSIDERATIONS

A judgement on the feasibility of an emissions pathway cannot be distilled into a simple 'yes' or 'no' (IPCC, 2018). As discussed in the IPCC Special Report on Global Warming of 1.5°C[5], there are at least six dimensions to feasibility: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional. These six dimensions interact in complex ways, and a complete assessment of the feasibility of an ambitious net-zero goal requires a full assessment of all dimensions and their interactions.

Recognising the complexity within feasibility, our scenario operationalises the IPPC's feasibility considerations by applying 'tests' to the measures included in our scenario. Focussing on fundamental techno-economic elements of feasibility, we test the following:

- ***Test 1:*** Deployment at the predicted scale can occur given physical and technological constraints, including constraints on land use and credible technological readiness of new technologies.
- ***Test 2:*** Ramp up and roll out rates of new technologies are within historical precedents or close analogues exist.
- ***Test 3:*** Deployment of the mitigation option would not result in large scale asset stranding or extensive scrappage before the end of the viable lifetime[6] of the asset.

Where possible, we include further feasibility considerations. In particular, this report touches upon enforcement considerations (including carbon leakage risk), environmental feasibility of certain GGR options, and socio-political or institutional feasibility. In the spirit of the IPCC special report, this study aims to provide a picture of the conditions required to meet a net-zero pathway, instead of a binary judgement on feasibility. As such it highlights risks and challenges to the feasibility of included options, but does not necessarily exclude options if the above three tests are passed.

5 See Cross-Chapter Box 3 in Chapter 1

6 As a rule of thumb, we assume the majority of investments in the economy are done on the basis of approximately a 10-year payback period. This implies that measures which create scrappage within this period impose significant costs and hence are unlikely to be economically feasible.

2045

DATE BY WHICH IT IS POSSIBLE FOR THE UK TO GET TO NET-ZERO

1.3 KEY CONCLUSIONS

It is possible for the UK to reach net-zero GHG emissions by 2050, without the use of international offsets and with the UK's share of international aviation and shipping included. There are three key requirements for the UK to do so:

1. *Zero emissions in several sectors*[7]*:* The power, surface transport and building sectors must reach zero, or near-zero, GHG emissions by 2050. This is possible with established technologies, but nonetheless requires a significant increase in ambition to achieve the required deployment rates. For example, sales of internal combustion vehicles must be phased out by 2030.
2. *Deep cuts in 'hard to treat' sectors:* Despite expected demand increases and the technical challenge of reducing emissions, industry, shipping and agriculture must significantly reduce their GHG emissions from current levels (by approx. 90%, 70% and 40% respectively). Furthermore, aviation must (at least) maintain emissions to current levels in the face of strong demand growth, which will likely require net-zero emissions from domestic aviation.
3. *Large scale deployment of greenhouse gas removal (GGR) options:* The required GGR scale (~100 MtCO2e) implies a significant programme of afforestation as well as that the majority of UK agricultural land is utilised (alongside continued food production) for at least one form of GGR (e.g. increasing carbon storage in soils). Assuming deployment of BECCS is required on the scale modelled here, then around 6% of agricultural land would need to switch from food to bioenergy crop production; this can be delivered without adversely affecting UK food security. To achieve this, ramp up of mature GGR options must start now, complemented by further demonstration and preparation for the ramp up of less mature (but required) options.

We identify two scenarios compatible with reaching net-zero emissions

- ***UK action*** *to achieve net-zero GHG by 2050 (UK2050):* In keeping with CCC and other scenarios, this scenario is anchored in supply-side action[8], incentivised and driven by UK government. It assumes the maximum feasible emission reductions and GGR deployments are achieved in virtually all UK sectors[9]. There is little margin for error, and rapid, large-scale GGR deployment implies risks for the environment if not carefully managed, or displaced by greater delivery elsewhere. (Figure 1).
- ***Collaborative action*** *to achieve net-zero GHG by 2045 (Collab2045):* This scenario includes additional abatement that is contingent on international collaboration and behavioural change by consumers. For example, additional progress in internationally traded sectors, such as international aviation, is possible with international collaboration. Also, diet change in the UK could lead to significant reduction in agricultural emissions. Finally, extensive international collaboration on particular technologies, such as direct air capture with carbon storage (DACCS), unlocks lower costs and enables a faster ramp up of this technology in the UK (Figure 2).

7 This report defines sectors using UK Government definitions.

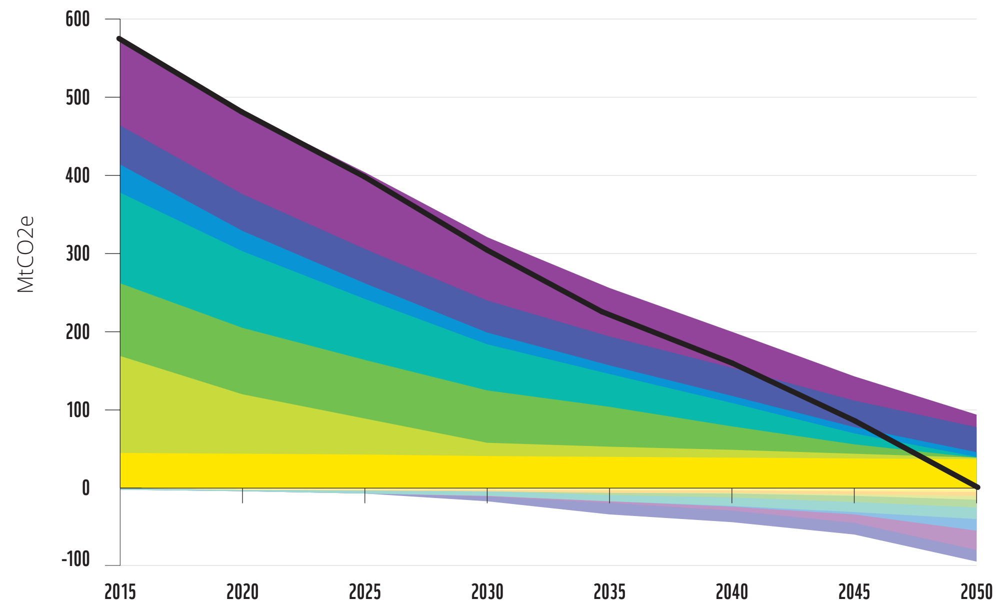
8 Some behavioural change, such as increased recycling, is included, but there are no major changes to behaviours assumed.

9 A notable exception is the relatively conservative deployment of ~15 MtCO2 of BECCS. This is to minimise the risk of UK biomass imports creating unsustainable practices abroad.

The collaborative action scenario (Collab2045) relies on measures which are not fully within the control of UK government, but illustrates the value of collaboration and behaviour change. The feasibility of the additional actions required to achieve the 2045 scenario is difficult to assess. However, the pathway is included to highlight the potential impact of behavioural change and international collaboration: it enhanced the likelihood of reaching net zero by 2050, and raises the possibility of an earlier date. International collaboration could also reduce reliance on less developed and higher-risk GGR options such as BECCS, reducing the associated environmental and biodiversity threats. With international collaboration and behaviour change, the UK could reach net-zero by 2050 without BECCS.

To achieve net-zero GHG emissions is highly challenging and requires a strong role for government to set policy that leverages the ability of business to invest in and deploy the options needed, across all sectors (Box 2). Nearly all feasible emissions reductions must be realised across all sectors, with little scope for delay. In the long term, emission reductions will likely be increasingly difficult as relatively easy mitigation opportunities are exhausted. To maintain momentum, continuous government support will be required, across all sectors. Furthermore, GGR options must be deployed at rates emulating the largest sector transformations seen in recent history. In some cases, such as afforestation, yearly tree planting rates must reach levels never before seen in the UK (but levels which have been achieved internationally).

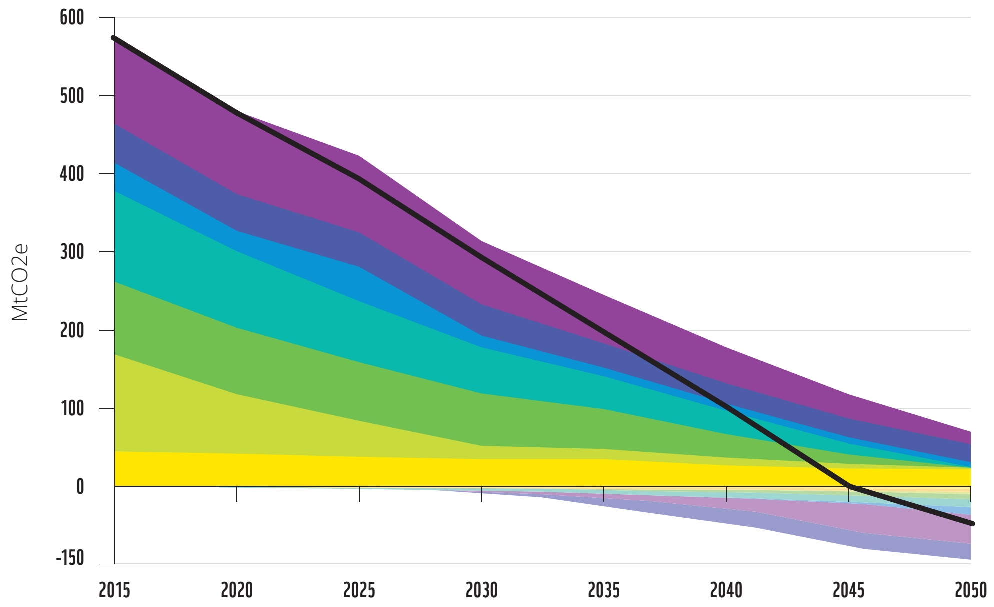
FIGURE 1:
EMISSION REDUCTIONS AND INCREASING REMOVALS IN THE UK2050 SCENARIO: A HIGHLY AMBITIOUS, BUT FEASIBLE PATHWAY FOR THE UK TO REACH NET-ZERO EMISSIONS



Note: *See Figure 4 for more detail on the split between land based GGR options*
Source: *Vivid Economics*

FIGURE 2:
EMISSIONS REDUCTIONS AND INCREASING REMOVALS IN THE COLLAB2045 SCENARIO: INTERNATIONAL COLLABORATION AND BEHAVIOURAL CHANGES COULD HELP BRING THE UK'S NET-ZERO EMISSIONS DATE FORWARD

- Industry
- Agriculture
- Other non-CO2
- Transport
- Buildings
- Power
- Aviation and shipping
- Wood in construction
- Habitat restoration
- Biochar
- Soil carbon sequestration
- Afforestation
- Enhanced weathering
- DACS
- BECCS
- Net Emissions



Note: *See Figure 4 for more detail on the split between land based GGR options*
Source: *Vivid Economics*

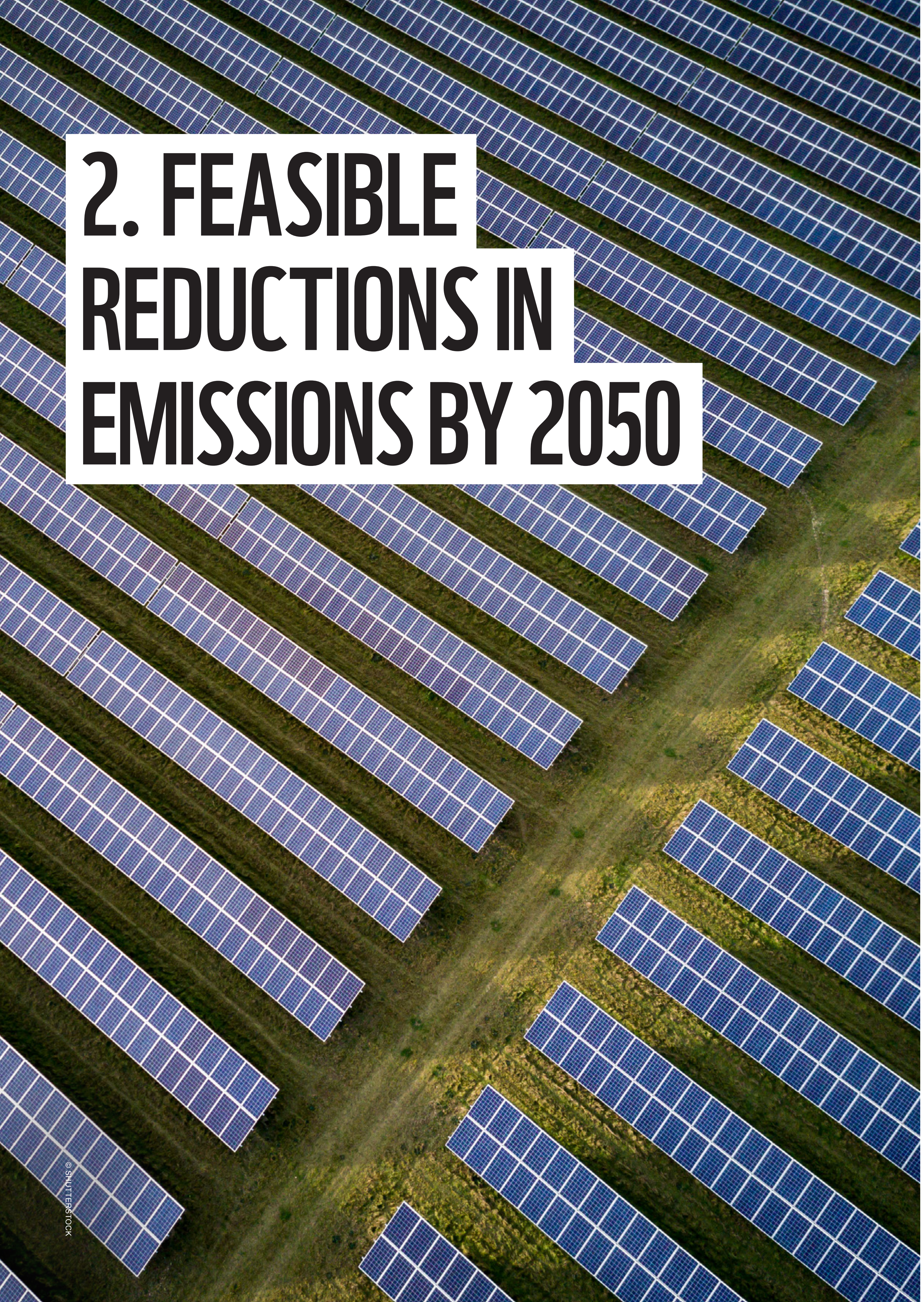
BOX 2:
KEY POLICY RECOMMENDATIONS

- More ambitious policies and targets in sectors where the move to net-zero is already underway, for example the phase out of internal combustion engine vehicles, would need to occur in 2030.
- Carbon capture and storage (CCS) is on the critical path to achieving net zero. It is essential for industrial abatement, bioenergy and CCS (BECCS), and the transport and storage component is crucial to direct air capture and carbon storage (DACCS). Policy is needed to support and manage CCS deployment for both emission reductions and greenhouse gas removal (GGR), as soon as possible.
- Implement a rigorous monitoring regime for the sustainability of the biomass and bioenergy supply to the UK, ideally through an international framework.
- Comprehensively embed both emission reduction and GGR incentives in agricultural policy, according to the "public money for public good" principle.

BOX 3:
KEY AREAS FOR FURTHER EVIDENCE DEVELOPMENT

Based on our rapid review, we have identified several areas where the evidence base is particularly thin, and we believe further research is urgently needed.

- A roadmap for deeper industrial decarbonisation, compatible with net-zero emissions. This includes the identification of opportunities for early CCS demonstration, and the implications of a net-zero steel industry.
- A reassessment of the policy tools for action in light of a more stringent target. This is particularly urgent in sectors where current action was judged insufficient to meet the existing 80% target. Key areas are CCS, buildings, and agriculture.
- Early development of the business model for DACCS to create an understanding of the requirements for commercialisation of DACCS.
- An in-depth calculation of the benefits and costs of a net-zero pathway to appropriately prioritise public funds and develop a cost-effective climate strategy. This should include potential feedback effects, such as the benefits to business of establishing early green competitive advantage, and a deep assessment of risks associated with different strategies.

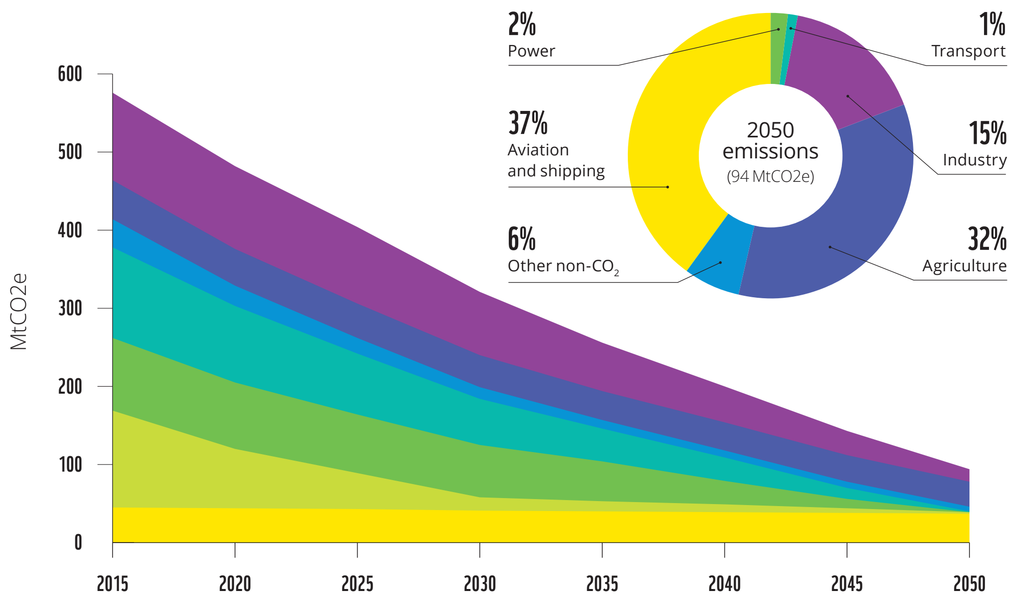


2. FEASIBLE REDUCTIONS IN EMISSIONS BY 2050

BOX 4:
KEY MESSAGES

- Achieving net-zero emissions will require more ambitious emission reductions, moving significantly beyond those required to achieve the current 80% target.
- The required reductions are feasible. We identify a pathway to reduce emissions to below 100 MtCO2ee (94 MtCO2e). This is sufficiently low to be compensated for by GGR and achieve net-zero emissions.
- This includes significant additional reductions – 37 MtCO2e beyond the most ambitious CCC – mostly from industry (see Appendix 1). If implemented, it provides the opportunity to achieve net zero by 2050 and significantly reduces the risk of overshooting a net-zero target.
- Achieving the level of decarbonisation required for net zero requires urgent and ambitious policy change, while ensuring that the burden and reward of the energy transition are equitably shared.

FIGURE 3:
A FEASIBLE EMISSION REDUCTION PATHWAY COMPATIBLE WITH NET-ZERO EMISSIONS BY 2050 (UK2050 SCENARIO)



Note: See Figure 4 for more detail on the split between land based GGR options
Source: Vivid Economics

BOX 5:
THE COMMITTEE ON CLIMATE CHANGE (CCC) MAX SCENARIO

- The CCC provides three scenarios (Barriers, Central and Max) for each sector. The CCC Max Scenario represents "deployment towards the maximum limits that are likely to be feasible, acceptable and sustainable (CCC, 2016)."
- The CCC Max Scenario represents a highly ambitious mitigation pathway, with little room for delay or failure in any sector.
- The CCC Max scenario still retains an element of cost optimisation for a pathway towards 80% reduction by 2050, with all abatement measures "potentially cost effective" (CCC, 2012).
- Our scenario goes beyond the mitigation measures proposed in the CCC Max Scenario by reflecting the latest evidence on emission reduction technologies and costs, and slackening the cost effectiveness requirement by focussing on feasibility[10].

10 See Box 1 for a discussion of feasibility. Note, given our scenario is designed for a different target (100% rather than 80% reduction by 2050) our additional measures are not necessarily suboptimal from a cost point of view. Our objective is to establish the fastest feasible pathway to net zero, rather than a cost optimal pathway. Further work is necessary to achieve which measures required to get to net zero are cost optimal.

2.1 POWER, BUILDINGS AND TRANSPORT

Power, buildings and transport sectors must each rapidly decarbonise and reach near-zero emissions for the UK to reach net zero by or before 2050. In 2015, emissions from power (122 MtCO2), buildings (85 MtCO2) and transport (118 MtCO2) represent around 60% of total UK emissions (CCC, 2015). By 2050, this can be reduced to around 3 MtCO2 in total, a 99% decrease. In each of these sectors, there are established zero-emissions technologies which can be rolled out. However, particularly in the case of heat for buildings, there are significant policy decisions to be made by government, in consultation with industry, about what mix of technologies to pursue. Key technologies such as on- and off-shore wind, solar power, heat pumps and electric vehicles are all proven at scale, with quickly growing supply chains and reducing costs. It is particularly important to ensure a route to market for tested and cost-effective technologies – particularly solar and onshore wind – to ensure that they get quickly to the point of being able to be routinely deployed without subsidy.

Decarbonising the power sector while increasing its capacity is crucial, as it enables other sectors to decarbonise. In a net-zero energy system, the power sector must be virtually zero emissions to enable decarbonisation in other sectors (by switching to electricity). New modelling, taking into account electricity demand increases compatible with a net-zero energy system, suggest this is possible (Aurora Energy Research, 2018; Imperial College London, 2018; Vivid Economics, 2018). In conjunction with a broad-based roll out of flexibility options such as demand side response (including vehicle to grid), most electricity can be generated through renewables, although nuclear and CCS- enabled plants, to ensure peak demand cover in winter, may be required[11]. With abundant green electricity, and with energy efficiency measures, buildings can cut their energy needs substantially, and become emission free by using heat pumps[12] instead of boilers, and our transport system can switch from combustion engines to zero-emission electric motors powered by electricity from batteries or fuel cells. As wind and solar continue to decrease in cost, support for their deployment can be reduced. However, government may need to support the retrofitting of gas power stations with CCS, or BECCS, see section 3.3. Furthermore, regulatory and financial support will be essential to enable the grid to become smart and robust to highly variable supply and demand.

It may be technically possible to reach zero emissions in buildings and transport, although 100% enforcement of take-up is likely to be difficult. Our scenario reduces annual emissions from buildings to zero, through extensive deployment of energy efficiency measures such as home insulation, followed by deployment of electric and/or hydrogen fuelled heating. Although technically possible and beneficial in terms of cost savings, incentivising broad based efficiency improvements and other mitigation measures in buildings has proven difficult historically, and progress is nowhere near to being on course to reach existing targets (Committee on Climate Change, 2018). In surface transport, emissions are reduced to 1MtCO2, through a near complete phase out of internal combustion engines. The emission reductions in both sectors will require an ambitious regime of strict enforcement and incentives. Key policy changes include an earlier phase out date of internal combustion vehicle sales, e.g. by 2030. To account for slow adopters, regulation[13] of such standards that prohibit the sale of some emitting technologies[14] may be required.

60%

CUMULATIVE TOTAL OF UK EMISSIONS FROM POWER, TRANSPORT AND BUILDINGS

11 The 2 MtCO2 of remaining power sector emissions account for non-captured CO2 from CCS enabled gas plants.

12 Or other zero emissions technologies such as electric heaters or hydrogen boilers.

13 These may require the government to compensate those adversely affected by bans.

14 Our scenario includes a 2030 phase out date (ban on internal combustion engine sales). If this is delayed, a more disruptive ban on the use of internal combustion engine vehicles may be required by 2050.

2.2 INDUSTRIAL AND OTHER ENERGY EMISSIONS

It is feasible for industry to reduce annual emissions to around 15 MtCO2e by 2050, from the 113 MtCO2e in 2015. These reductions are achieved through increased efficiency, CCS rollout wherever feasible, and (where possible) use of hydrogen and electricity for industrial heat. The remaining industrial emissions are associated with particularly hard to treat areas including: combustion emissions not captured by CCS (around 8 MtCO2)[15], some emissions from remaining refining and other oil and gas industry (3 MtCO2e), emissions from chemical processes (1 MtCO2e) and off-road construction and waste[16] (3 MtCO2e).

Reducing industrial emissions to 15 MtCO2 can be achieved while maintaining productive capacity, but industries such as steel will require a complete rebuild of key assets. This rebuild includes essential elements of the production process, such as blast furnaces for steel and kilns for cement production. To effect this change, government will likely need to support investment in these risky, capital intensive and long-lived assets. Our scenario includes both net-zero furnaces in the UK steel industry and zero-emissions kilns in the cement industry, eliminating the need for coking coal in these sectors(Energy Transitions Commission, 2018a, 2018b). This would reduce annual emissions by approximately 10 MtCO2 compared to maintaining fossil fuel use in these industries (even with CCS fitted). Net-zero steel can be achieved through a process which first uses hydrogen as a fuel to reduce iron ore before feeding it into an electric arc furnace. Several pilots by established steelmakers are currently ongoing and suggest this is feasible although economically challenging (Swedish Energy Agency, SSAB, LKAB, & Vattenfall, 2017; Verbund et al., 2018). If sufficient scrap steel were available, net-zero steel can also be created using electric arc furnaces to repurpose existing steel.

Industrial decarbonisation, and policy to support it, must ensure the UK maintains international competitiveness, to minimise adverse economic effects and prevent carbon emissions 'leaking'. An ambitious low carbon transition presents opportunities for UK industry, providing a potential competitive edge in low carbon production. However, policies designed to encourage decarbonisation must mitigate the risk of carbon leakage or significant loss of economic activity. Proven policy options, such as the linking of emission trading schemes, exist to minimise this risk.

15 CCS cannot capture all CO2 emitted. The precise capture rate depend on the composition of the exhaust gas and the type of CCS applied, however rates of 80-90% are thought to be the max feasible.

16 This emissions category includes off road mobile machinery such as cranes, diggers etc.

2.3 AGRICULTURE

10%

PROPORTION OF UK EMISSIONS FROM AGRICULTURE

Emissions from agriculture, 46 MtCO2e[17] in 2015, currently make up 10% of the UK's overall greenhouse gas emissions. Key gases and sources include:

- Methane (CH4): 50% of emissions, largely from enteric fermentation, which occurs in the digestive system of ruminant animals (e.g. cattle and sheep) and waste and manure management.
- Nitrous oxide (N2O): 41% of emissions, arising from the application of nitrogen fertiliser (organic and chemical) and returns from animal grazing and crop residues incorporated into soils.
- Carbon dioxide (CO2): 9% of emissions come from the use of fossil fuels to power farming equipment and heat farm buildings (Committee on Climate Change, 2015).

Without dietary change, agriculture will likely continue to emit significant amounts by 2050, representing roughly a third (32 MtCO2e) of total emissions, despite extensive action to reduce emissions. Virtually all (over 200,000) farm holdings will need to implement a range of changes to achieve the envisioned emission reductions. On top of various mitigation measures, farmers will also be expected to participate in GGR measures (see Section 3). The number and complexity of changes, and the limited progress to date[18], suggest this is a significant challenge. Table 1 groups key agricultural emission reduction measures.

Achieving the required behavioural change by farmers may be challenging and is likely to require sophisticated policy including strong incentives, training and awareness programmes, and robust enforcement where possible. Given the heterogeneity of farms in the UK, there are challenges to ensuring that all farmers implement the required mitigation measures. There are varied and complex reasons for this; for example, many farmers operate with limited spare capital, creating understandable risk aversion as changes (and associated risk) can significantly impact the financial standing of a farm. Consequently, monetary incentives may not be as effective as in other sectors, and may need to be bespoke to farm types, regions and other relevant characteristics. Furthermore, measurement and monitoring of mitigation measures is likely to be resource intensive and difficult, complicating the provision of results-based incentives.

The UK's exit from the European Union and the Common Agricultural Policy (CAP) provides an opportunity to embed climate incentives into agricultural policy. The CAP provides generous subsidies based on the amount of land farmed, providing little incentive for farmers to take environmental factors into account (Jeffrey, 2003). In the past the CAP has led to overproduction and environmentally damaging intensive farming through the commitment to guarantee prices. The creation of a new agricultural policy and a new environmental land management system, with a focus on providing "public money for public goods", could prioritise environmental standards and incentives for climate change mitigation and adaptation (UK Department for Environment Food and Rural Affairs, 2018).

17 Note, these are all emissions. Agricultural emissions are often reported together with LULUCF in which case net emissions are lower given LULUCF provides net negative emissions. Given this report's focus on GGRs, LULUCF is accounted for there.

18 Since 2008 there has been virtually no change in agricultural emissions.

TABLE 1:
CATEGORIES OF KEY AGRICULTURAL MITIGATION MEASURES

Mitigation measure	2030 (CCC Max)	2050 (CCC Max)	Additional feasible action included in *UK2050*
Measures to reduce emissions from enteric fermentation	Animal diet change, selective breeding	Precision livestock farming, genetically modified livestock	Inoculations and radical diet change such as seaweed
Reduced fertiliser use through crops and soil measures	Use of cover crops and improved management practices	Novel crops, nitrification inhibitors (limited), improving and upgrading existing drainage systems (limited)	Nitrification inhibitors (full potential),improving and upgrading existing drainage systems (full potential)
Waste and manure management	Anaerobic digestion	No further action	No further action
Reduced emissions from fuel combustion	Improvements in the fuel efficiency of stationary machinery	Full electrification	No further action
Behavioural changes	None	Small diet changes due to carbon prices in food,	No further action (but included in *Collab2045*)

Note: *The categories in this table are a summary of dozens of mitigation measures from Eory et al. (2015). The table includes the timing of the measures envisioned by CCC and the additional measures we include.*

Source: *Vivid Economics based on (Committee on Climate Change, 2015) and (Eory et al., 2015).*

BOX 6:

SIGNIFICANT BEHAVIOURAL CHANGES COULD HELP TO REDUCE AGRICULTURAL EMISSIONS

Halving UK meat consumption, to approximately WHO recommended levels,[19] could save roughly 10 MtCO2e (Audsley et al., 2011). This would significantly reduce the implementation challenge for farmers. A concerted approach from industry, government, NGOs and other stakeholders, using policy levers but also highlighting ethical, health and climate benefits is likely required. As highlighted in Garnett, et al.(2015), successful policy should move beyond a focus on individual behaviour and target changing broader societal norms. There are several practical challenges:

1. *Achieving behavioural changes:* Interventions such as carbon labelling and taxes will likely have limited impacts, as demand for meat is strongly driven by norms and habits and not very responsive to price[20]. Furthermore, the implementation of high taxes may be politically challenging given their regressive nature. Across the expert interviews conducted for this work, one of the most promising options is thought to be to focus on the health benefits of reduced meat consumption.
2. *Reduced consumption does not necessarily imply reduced production:* Changes in consumption might not have the desired impact on UK production as farmers could export[21] their products.
3. *Environmental impacts of fruit and vegetable production:* In most cases, meat and dairy production is more intensive than alternatives in terms of CO2 emissions, land use, and fresh water consumption and quality(Poore & Nemecek, 2018). But alternatives do not always have fewer environmental impacts as this is dependent on the type of production system. For example, plantations used to grow food can have higher water requirements than non-irrigated pastures for grazing animals (Eory et al., 2015).

2.4 AVIATION AND SHIPPING

Emissions from aviation and shipping are difficult to reduce, with incremental rather than transformational reductions expected. The sector emitted 49 MtCO2 in 2015, of which the vast majority is emitted by international aviation (34 MtCO2) and international shipping (8 MtCO2). Without further action, emissions will likely increase significantly until 2050, with demand projected to double (Committee on Climate Change, 2009). Our scenario reduces emissions to 37 MtCO2. This requires aviation demand growth to be curbed to ~15%[22] and includes significant improvements in efficiency and biofuel use in aviation (1.5% yearly improvement in efficiency and 10% take-up of biofuels) as well as shipping[23]. Furthermore, we include aggressive UK policy[24] on domestic shipping and aviation, requiring domestic flights and shipping to be net zero by 2050. This could be achieved through a combination of relatively established methods such as biofuels, assuming these are sourced sustainably, and more experimental technologies such as electric flying, synthetic fuels or hydrogen (in ships). Achieving net zero domestic aviation and shipping would however be expensive, and only address approximately 3 MtCO2[25].

19 Daily average per capita meat consumption in the UK was 230g of meat per day in 2013, whereas the WHO recommended maximum is 90g per day (Chalabi, 2013).

20 Price elasticity of meat is estimated to be -0.8 (Tiffin, Balcombe, Salois, &Kehlbacher, 2011). For large quantity changes in demand this is likely to be significantly lower, meaning very large price changes (taxes) are likely required to significantly alter consumption.

21 50% of the UK's food production is already exported (DEFRA, 2017).

22 This would be a break from the growth trend, but would not require significant behavioural change.

23 These factors mirror CCC analysis.

24 The UK is already beginning to move in this direction, by supporting the development of greener technology. See https://www.gov.uk/government/news/lift-off-for-electric-planes-new-funding-for-green-revolution-in-uk-civil-aerospace

25 Beyond what could be achieved through continued use of fossil fuel with significant increases in efficiency.

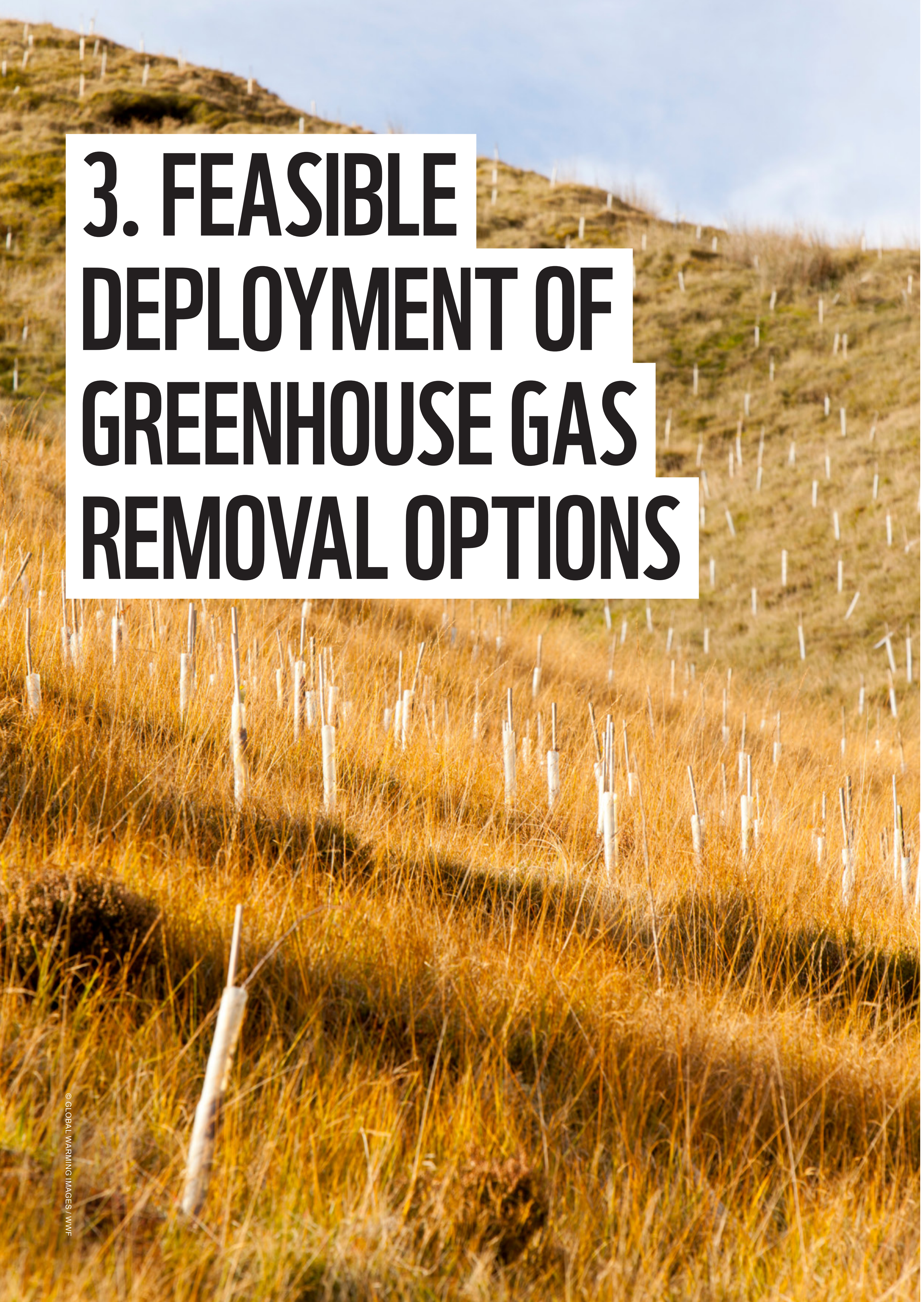
Incentivising behavioural change provides a potentially easier and cheaper alternative to achieve emissions reductions. We do not explicitly include this in our scenario, but for example, the reduction in domestic aviation emissions could to a large degree be achieved through modal shifts, such as shifting demand to high speed rail.

To achieve deep emissions reductions in aviation, ambitious international cooperation is required. International flights cause 95% of aviation emissions attributed to the UK. It is possible to target the emissions caused by international flights through domestic policies; however, in the highly competitive airline industry this could lead to carbon leakage. For example, any carbon-based restrictions imposed on aircraft landing in the UK could shift long haul flights to other aviation hubs in Europe, such as Paris or Amsterdam, and hence not make a meaningful impact on global emissions. As described in Box 7, international emissions reduction schemes are not very ambitious at present (they fall within the reductions in our scenario). With its strong aerospace and aviation sector, the UK is well placed to lead a push for more stringent international action standards on aviation emissions, possibly globally, but perhaps more realistically at the European level. International action can ensure emission reductions, through a combination of reductions in the number of flights, without the risk of carbon leakage, and accelerated innovation as airlines and manufacturers are incentivised to reduce their carbon footprint.

BOX 7:

INTERNATIONAL AMBITION FOR MITIGATION ACTION ON AVIATION AND SHIPPING IS NOT AMBITIOUS ENOUGH

- **International aviation** (current emissions attributed to UK: 32 MtCO2): From 2027 onwards, the International Civil Aviation Organization (ICAO) will implement the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which obliges all states with significant aviation activities reduce or offset their emissions to 2020 levels. The mandatory phase will be preceded by a voluntary compliance scheme from 2021 (International Civil Aviation Organization, 2018).
- **International shipping** (current emissions attributed to UK: 9 MtCO2). In 2018 the International Maritime Organization (IMO) adopted a target to reduce the total annual GHG emissions by at least 50 per cent by 2050 compared to 2008 levels. To facilitate this, the IMO has adopted mandatory energy efficiency requirements and is evaluating other options including a move to low-carbon and zero-carbon fuels or the use of market-based mechanisms (International Maritime Organisation, 2018).

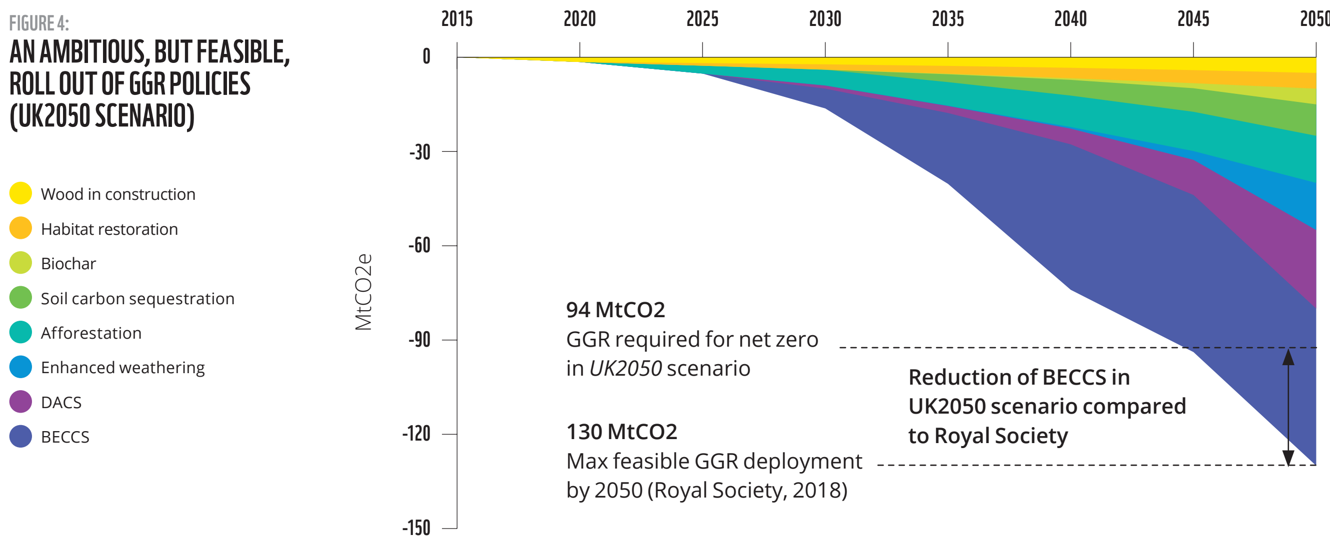


3. FEASIBLE DEPLOYMENT OF GREENHOUSE GAS REMOVAL OPTIONS

BOX 8:
KEY MESSAGES

- By 2050, the UK will require at least 94 $MtCO_2$ of GGR to reach net-zero emissions, which is within the ~130 $MtCO_2$ of feasible GGR available.
- A rapid ramp up of GGR will be required. The rate of change, particularly in the 2030s-2040s, is comparable to the fastest changes seen in the power and agricultural sectors in recent history.
- Immediate government support across the spectrum of GGR options is required. This includes large scale incentives for negative emission practises and sustainable bioenergy crops in agricultural policy, incentives and strong land-use policy to ensure afforestation and habitat restoration ramp up, and subsidies for demonstration and roll out of BECCS and DACCS.
- GGR options can have positive environmental benefits, but prudent policy is required to avoid unintended consequences, such as deforestation to provide biomass for BECCS.
- Achieving all emission reductions set out in Section 2 would reduce the scale at which environmentally risky GGRs, such as BECCS, need to be deployed to achieve net-zero emissions.

FIGURE 4:
AN AMBITIOUS, BUT FEASIBLE, ROLL OUT OF GGR POLICIES (UK2050 SCENARIO)



Note: *The 2050 GGR deployment levels for each GGR are based on The Royal Society & Royal Academy of Engineering (2018). Ramp up rates per GGR option are based on Vivid analysis of feasible changes in land use, earliest feasible deployment at scale, and past studies on the feasible deployment rate of CCS. For Collab2045 GGR deployment, see appendix.*

Source: *Vivid Economics*

3.1 GGR OPTIONS AND RISKS

By 2050, total feasible GGR deployment in the UK is approximately 130 MtCO2 per year. As most GGR options are technologically immature, there is significant uncertainty around the maximum feasible deployment of GGR options in the UK. However, the Royal Society's recent work estimates a total of 130 MtCO2 is feasible, taking into account the competing land use requirements of some GGRs (The Royal Society & Royal Academy of Engineering, 2018). Key options considered in this study are summarised in Table 4 in the Appendix.

Deployment of most GGR options is limited by physical constraints, except for DACCS, which can theoretically be ramped up beyond the 25 MtCO2 assumed by the Royal Society. The maximum amount of CO2 removed by different GGR options is typically governed by the availability of land or biomass (indirectly linked to land availability). DACCS is not limited[26] by either and could be deployed at large scale. However, DACCS is currently immature and costly; furthermore, it requires significant amounts of energy, CO2 transport and storage infrastructure, and the ease of ramp up of production of DACCS units is not yet well understood. We therefore limit the feasible level of DACCS deployment to the Royal Society's scenario in the UK2050 scenario. However, in the Collab2045 scenario, we assume deployment of 50 MtCO2 becomes feasible by 2045, helped by international collaboration to accelerate the production of DACCS units, reduce costs, and improve energy efficiency.

GGR options provide opportunities, but also involve risks, with potential environmental consequences and uncertainty around the maximum feasible deployment. If well managed, afforestation and wetland restoration could have significant positive environmental benefits. However, GGR options also include risks:

- *Environmental risks include biodiversity loss, and degradation of soil and water quality.* Large scale, largely uniform, land use could cause significant biodiversity loss. Furthermore, GGR options such as enhanced weathering and biochar may have unintended impacts on soil or water quality.
- *Technological immaturity means maximum feasible deployment may disappoint.* There are significant knowledge gaps around the practical implementation of GGR options. Furthermore, it is a scientific challenge to accurately understand life cycle emissions of GGR options, and the long-term behaviour of, for example, biochar buried in soils, is not yet fully understood. Current estimates of feasible GGR levels may hence be overoptimistic.

GGR options will be necessary to reach net-zero GHG emissions, but their deployment does not imply mitigation efforts can be reduced. Given the uncertainty around GGRs, emission reductions should be pushed as far as possible, to reduce the reliance on untested and potentially environmentally harmful GGR options. The additional ~40 MtCO2 emissions reductions identified in Section 2, provide essential flexibility in the GGR options deployed, and would allow the UK to reach net zero without pushing all GGR options to their feasible limit. Given the environmental risks associated with some GGR technologies, there needs to be a focus on identifying how mitigation and technological innovation over the next few years can help scale back reliance on GGR further, as well as looking to maximise natural climate solutions which do not carry the same scale of associated environmental risk – such as protecting and restoring forests and peatlands.

130 MtCO2

TOTAL FEASIBLE GGR DEPLOYMENT IN THE UK

26 CO2 storage limits are a key physical constraint, but the UK has large potential stores and this constraint is unlikely to become binding until the next century.

The feasible speed of the GGR roll out is key to determining a possible net zero date. Significant further work is required, together with the sectors involved, to establish action plans. The feasibility and resource required to roll out GGRs has received relatively little attention to date. Particularly when compared to, for example, high emission industries, where government has collaborated extensively with industry to establish roadmaps and action plans for reaching emission reduction targets. The following discusses the challenges with GGR roll out, and provides an initial assessment of the ambition and level of government support required.

3.2 THE RAMP UP CHALLENGE

To achieve net-zero GHG emissions by 2050, or before, GGR options will need to be rolled out rapidly. The scale required to offset remaining hard to treat emissions, ~100 MtCO2/a, implies rapid ramp ups across GGR options, which will require high rates of land-use change, rapid scale-up of supply chains, and large scale investment in relatively risky technologies, given the lack of track record.

Strong, persistent and predictable government support will be necessary to overcome key challenges associated with GGR deployment and roll out.

CHALLENGE 1: *Demonstration of immature technologies.* For DACCS, BECCS, biochar, and enhanced weathering, the technology needs to be demonstrated at scale in the early 2020s. This is feasible but will require strong regulatory and financial support from government. The demonstration plants will be crucial to build local skills, inform policy to support roll out, and create credibility for the private sector to invest in the roll out.

CHALLENGE 2: *Incentivising investment in complex, capital intensive, GGR options.* BECCS and DACCS require large scale infrastructure for CO2 transport and storage. Government will likely have to strongly support the development of this infrastructure, potentially through a public company (Parliamentary Advisory Group on Carbon Capture and Storage (CCS), 2016). BECCS - depending on the scale required - may also require large capital expenditure in required power stations. The Energy Technologies Institute estimates approximately £20 billion of investment in the plant and capture equipment (ignoring wider supporting infrastructure) would be required to build ~10GW of capacity to capture 50 MtCO2/a (Energy Technologies Institute, 2016). Although both our scenarios require only about half this investment level in BECCS[27], attracting billions of investment into a risky area will nonetheless require government to provide strong incentives and coordination across the supply chain, and actively help de-risk BECCS and DACCS.

27 15 MtCO2 of BECCS is required by 2050 in UK2050 and 31MtCO2 of BECCS is required by 2045 in Collab2045.

CHALLENGE 3:

Incentivising rapid land-use change. The scale of land-use change required is substantial. It is technically feasible but will require significant changes by farmers to deploy dual use[28] GGR techniques and grow crops for bioenergy. Furthermore, the required rate of afforestation (approximately 40,000 ha/a, roughly the size of the Isle of Wight each year) could face local opposition in areas most affected. Government will need to appropriately incentivise farmers to deploy GGR options, possibly directly including GGR incentives in agricultural policy, and ensure afforestation progresses through incentives and appropriate land use planning. Box 9 describes the challenges around land use in further detail, including the need to develop a reliable monitoring, reporting and verification system.

CHALLENGE 4:

Public acceptance and time requirements for due process. Several GGR options will likely require significant planning, and clear communication to stakeholders, before construction can begin. For example, CO2 transportation infrastructure required for BECCS and DACCS will require wayleaves from landowners and could face objection from affected communities. Sensitively managing objections adds significant time to project development, which must be taken into account. A comparable infrastructure project like the Beauly to Denny power line in the Scottish Highlands took 5 years[29] to be approved by the Scottish government, due mostly to the need to take local needs into account.

CHALLENGE 5:

Sourcing sustainable biomass and bioenergy inputs. The UK is a current net importer of biomass, and this is likely to continue given the need for biomass for BECCS and biochar, combined with any biofuel demand from other sectors (notably aviation and shipping). It is crucial the UK's bioenergy demand does not encourage unsustainable forestry and/or deforestation outside of the UK. This is very hard to ensure and will require rigorous international cooperation. Past experience of international agreements on, for example, the protection of migratory fish stocks suggests establishing rigorous agreements could take decades, which experts suggest is also true for bioenergy (UN Division for Ocean Affairs and the Law of the Sea, 2016).

28 For example, enhanced weathering enables agricultural land to be used for GGR, while maintaining food production.

29 The initial applications by SHETL and SPTL were submitted to the Scottish Government in 2005, with final approval granted in 2010 . (Scottish Government, 2009).

BOX 9:

THE IMPLICATIONS OF LARGE SCALE GGR DEPLOYMENT ON UK LAND USE

To support GGR, land use must change significantly across the UK, with two major changes in primary land use (The Royal Society & Royal Academy of Engineering, 2018):

- 1.5 million hectares (mha) (6% of total UK land area) increase in the land area dedicated to forests, a 50% increase compared to the current land area covered by forests. The majority (1.2 mha) of the required afforestation could use currently 'available' land[30]; and,
- Around 1 mha (4% of total UK land area) of land dedicated to biomass production for BECCS[31], requiring approximately 6% of agricultural land to change from food to biomass production.

Furthermore, large agricultural land areas must be treated with GGR options. Approximately ¾ of all agricultural land (14 mha) will need to be treated (The Royal Society & Royal Academy of Engineering, 2018). Although the primary purpose of this land will not change, farmers will need to be incentivised to deploy GGR options such as biochar, enhanced weathering and soil carbon sequestration (see Appendix 2 for a brief description). Similar to some agricultural mitigation options, monitoring, reporting and verification (MRV) is a key challenge for GGRs such as enhanced weathering. Any incentive framed in terms of £/tCO2 removed will require a reliable way to measure tCO2 removed, monitor the deployment per farmer, and reward farmers for verified removals.

Despite significant land-use change, the current UK trade balance for food and biomass can be maintained. The 6% reduction of land for food production is expected to be exceeded by efficiency increases. This would enable the UK to continue to supply 60% of its food demand.

Although challenging, there are past examples of rapid analogous roll outs suggesting GGR rollout on the required time scale is possible. Britain's recent experience with offshore wind shows the rate, from initial discussions in 1998[32] to 7 GW deployed 20 years later, at which the private sector can push immature and capital-intensive technology to scale deployment when strong government backing is provided (Wind Europe, 2017). There is also precedent for large land-use change and changes in farming practices, for example, British farmers rapidly responded to changes in price signals and switched approximately 1 mha of land from barley to wheat production between 1975-1985 (Zayed, 2016).

Combining feasible roll out rates of all GGR options in the coming decades suggest 90-100 MtCO2 per year of GGR can be achieved between 2045 and 2050, whilst limiting BECCS deployment. Royal Society suggests total GGR could be as much as 130 MtCO2. Our UK2050 matches GGR deployment for all GGR options, but as shown in Figure 4, requires 36 MtCO2 less BECCS to reach net zero. Table 2 below summarises the roll out rates assumed in this study. The cumulative impact on GGR deployment is summarised in Figure 3.

30 Defined as suitable for afforestation, currently not used for agriculture and not in any national parks, national scenic areas or areas of outstanding natural beauty.

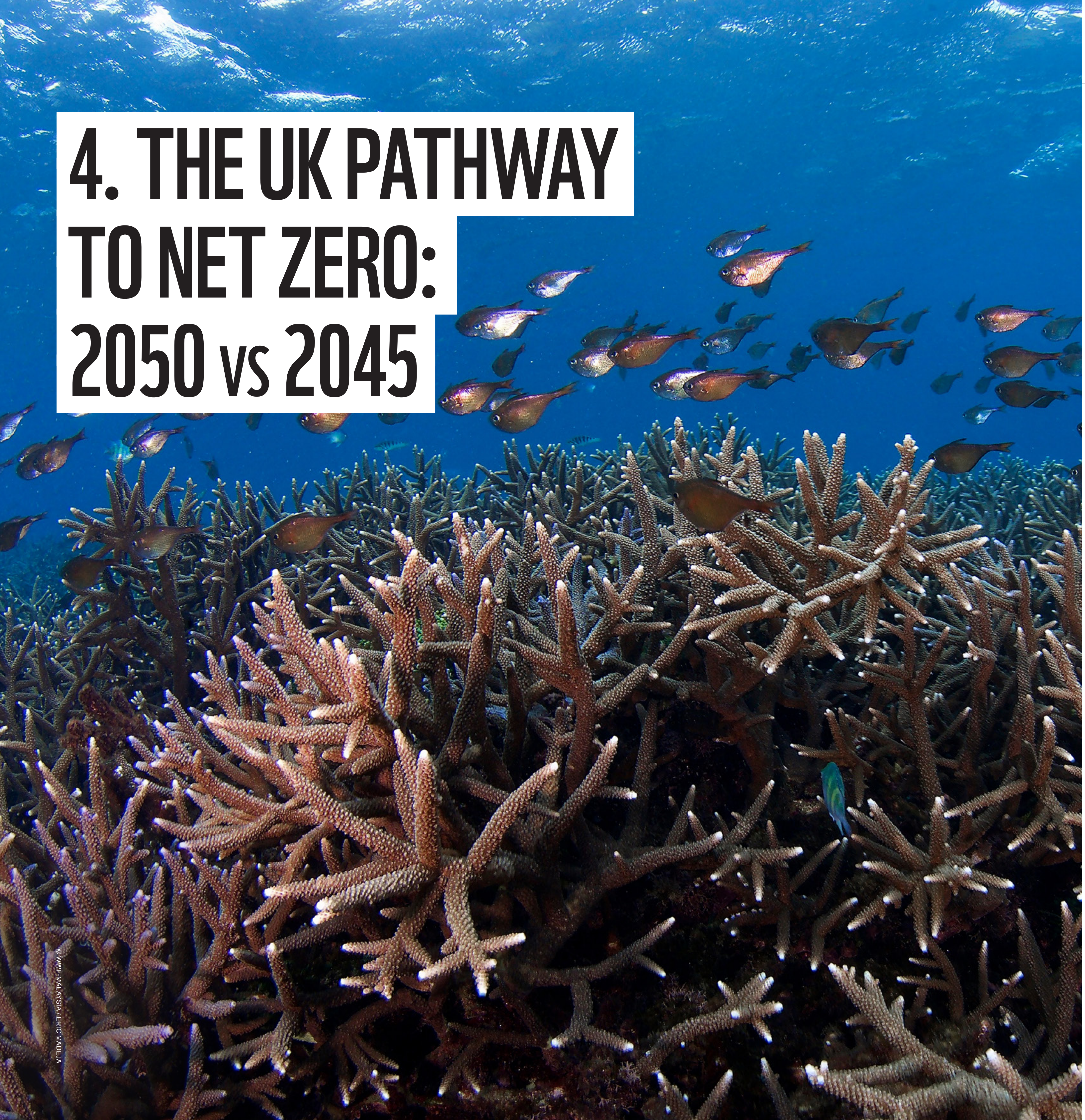
31 Sufficient for 25 MtCO2 annual sequestration through BECCS. The remainder would need to be imported if more BECCS is deployed at larger scale.

32 When the British Wind Energy Association formally began discussions with Government and Crown Estate to build offshore wind farms.

TABLE 2:
RAMP UP RATES OF KEY GGR OPTION

GGR options	Scale deployment period	Notes on scale up	Key constraints and risks to ramp up	Indicative yearly deployment
Afforestation	2020-2050	An average afforestation rate of 40,000 ha/a is required, ~400% increase from the current rate.*	• Land availability	~60,000 ha/a in 2030's to compensate for likely shortfall in 2020s
Soil carbon sequestration	2030-2050	After 20 years, there is a risk stored carbon is re-emitted if the soil is not maintained. We include a broadly linear ramp up rate between 2030 and 2050.	• Re-emission of stored carbon • Speed of adoption by farmers • Development of reliable MRV	~240,000 additional ha/a treated
Biochar	2025-2050	Requires the built up of pyrolysis facilities and sustainable biomass supply chains. To mitigate risks around soil quality etc., the rollout is likely to be slow to begin with, increasing exponentially as the risks are better understood.	• Speed of adoption by farmers • Risks to soil quality • Development of reliable MRV	Average of ~1mh/a additional land treated with biochar during the 2040s
Enhanced weathering	2025-2050	Requires the built up of silicate rock mining and crushing supply chains. To mitigate the risks on soil and water quality the rollout is likely to be slow to being with, growing exponentially.	• Ramp up of silicate rock supply • Speed of adoption by farmers • Risks to soil quality • Development of reliable MRV	~240,000 additional ha/a treated on average. Likely exponential pattern implies ramp ups of ~1 mha/a in 2040s
BECCS	2025- approx. 2041	Rollout based on most ambitious CCS roll out plans available for the UK***. This includes feasible but fast progression from planning, to final investment decisions, to construction and commissioning. The rate of construction and scale of plants are assumed to increase over time. Growth is capped in 2041 to limit total deployment at 50 MtCO2.	• Availability of sustainable biomass without crowding out other UK demand for bioenergy • Ramp up of CO2 transport and storage keeps pace with capture deployment	1 GW (~4MtCO2) of BECCS added per year by late 2030s
DACCS	2030	DACCS is currently immature, but once proven could be mass produced as each unit is relatively small and would be installed in DACC 'farms' similar to solar farms.	• Power demand from DACCS • Technological immaturity • Cost	3-4 MtCO2 additional capture capacity per year by 2045-2050. Based on 17% average yearly deployment increase (similar to solar ramp up)
Building materials	2020-2050	Approximately 200,000 houses a year would need to be constructed using wood and low carbon concrete. Up from ~50,000 at present.	-Total houses built (only ~170,000** in 2017)	~200,000 houses per year

Notes: **based on 9,000 newly planted forest in 2017-2018 (Forest Research, 2018). ** based on (ONS, 2017) ***based on (PÖYRY, 2016)*
Source: *Vivid Economics, based on The Royal Society & Royal Academy of Engineering (2018), expert interviews, Mclaren (2011), (CCC, 2016) and in house analysis*



4. THE UK PATHWAY TO NET ZERO: 2050 VS 2045

4.1 NET-ZERO EMISSION BY 2050 THROUGH UK ACTION

Achieving net-zero GHG emissions by 2050 (*UK2050 scenario*) is feasible if the UK achieves rapid progress in all sectors, including difficult to reduce sectors (Section 2) and rapid ramp up of GGR (Section 3). Achieving this in practice requires a high level of coordination, and an assumption of government and business working together to drive rapid deployment of technologies. The UK2050 scenario, Figure 5, also makes strong assumptions regarding the success of technologies that are yet to be deployed at scale, such as DACCS[33]. DACCS and BECCS represent large parts of the negative emissions potential, and both rely on the success of CCS, which has faced policy and other deployment barriers in the UK. With little room for error, if progress in any sector is delayed, the likelihood of achieving net-zero emissions by 2050 reduces significantly.

Significant international action and behavioural change would make achieving net zero easier and potentially eliminate the UK's reliance on GGR options with potential negative impacts such as BECCS. In our *UK2050* scenario, emissions reductions are constrained because we assume international progress does not keep pace with the UK, and behavioural change is limited. We apply these constraints to show a net-zero scenario is feasible without overly relying on parties, either international governments or UK consumers, over which government has no direct control. However, significant behavioural change and international cooperation could meaningfully reduce UK emissions. These reductions could help the UK to:

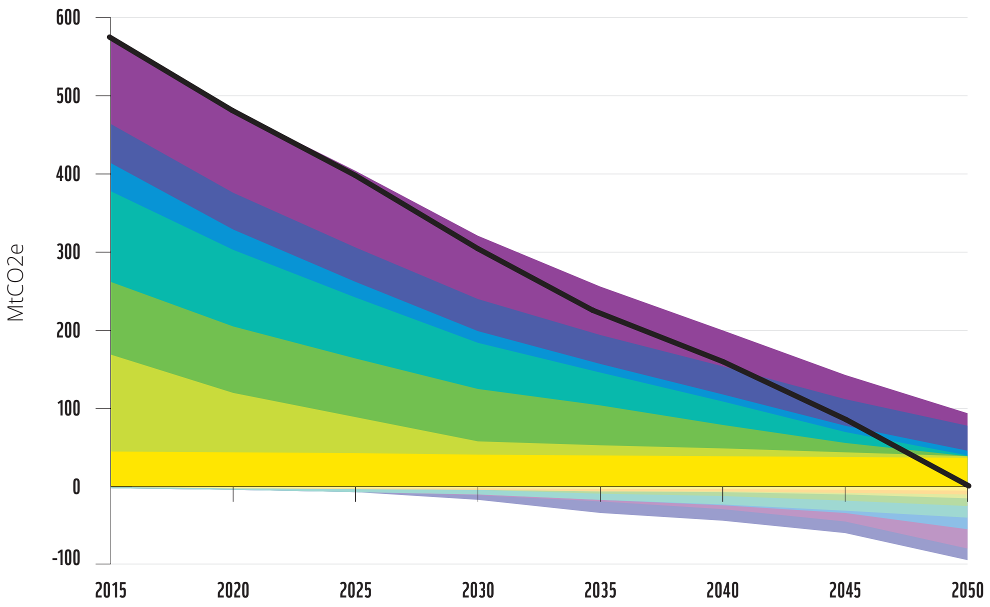
- *Eliminate the need for BECCS:* Our *UK2050* scenario includes 15MtCO2 of BECCS[34]. A 2050 net zero date, *without BECCS*, is achievable if the behavioural and international cooperation measure set out for the *Collab2045 scenario (set out below)* are achieved.
- *Reduce the risk of missing a net zero 2050 target.* Primarily relying on domestic supply side action to reach net-zero emissions is possible but leaves little room for error. Pushing international action, such as an ambitious aviation agreement, could achieve emissions reductions of the same order as a switch to net-zero steel and could, from an accounting perspective, absorb delays in the implementation of such measures.

A combination of behavioural change and international action could also allow the UK to achieve net zero emissions before 2050. In the next section, we construct a more ambitious scenario which considers the possibility of achieving net zero emissions even earlier, based on strong international action and behavioural change.

33 Research, development and policy commitment would be required to ensure this happens in practice.

34 This may need to increase in reaction to potential disappointing emissions reductions elsewhere. As per Royal Society estimates, 50 MtCO2 of BECCS is feasible.

FIGURE 5:
WITH STRONG ACTION ACROSS ALL UK SECTORS, INCLUDING DIFFICULT TO REDUCE EMISSIONS, AND GGR, NET ZERO EMISSIONS BY 2050 IS FEASIBLE *(UK2050 SCENARIO)*



Source: *Vivid Economics*

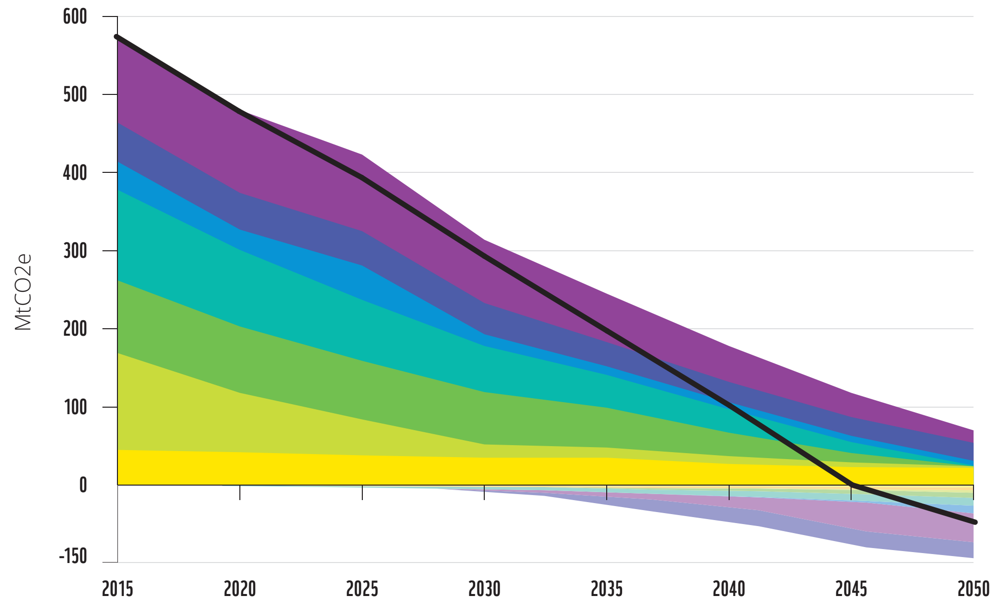
4.2 OPPORTUNITIES TO ACHIEVE NET ZERO GHG EMISSIONS BY 2045

Achieving net zero by 2045 is possible, but relies on international collaboration and behaviour change:

1. *International mechanisms to reduce aviation emissions:* To significantly reduce emissions from aviation, the ambition of international agreements on aviation needs to be increased. It is unlikely that such an ambitious agreement will be global, but it is conceivable that a coalition could be formed, for example, a regional agreement across Europe and agreements with Japan, the US and Australia could save 10-15 MtCO2 of UK emissions.
2. *International collaboration to achieve further technological advances:* International collaboration on research, development and deployment of new technologies could lead to a more rapid roll out than is currently regarded as feasible. One area where this is particularly pronounced is DACCS, currently an immature technology, with only very small-scale pilots currently deployed and no meaningful deployment feasible until 2030. Our *UK2050* scenario already includes an exponential ramp up from 2030, the UK could benefit from global production of this technology, significantly increasing the possible ramp up rate and likely reducing costs.
3. *Behaviour change to reduce emissions through even lower meat and dairy consumption:* For example, a 50% reduction in meat consumption could reduce UK agricultural emissions by approximately 10 MtCO2 (see Box 5).

Reaching net zero GHG emissions by 2045 would meaningfully reduce the cumulative emissions produced by the UK, but does require more deployment of environmentally risky BECCS. The difference in cumulative emissions, between 2045 and 2050 in our 2 scenarios is nearly 500 MtCO2e[35]. This is an important contribution, in the context of the remaining global carbon budget of 550GtCO2(IPCC, 2018), which will likely be nearly exhausted by the 2040s[36]. To achieve net zero by 2045 however, the UK will likely require around 30MtCO2 of BECCS, 15 MtCO2 more than the UK2050 scenario. This is in addition to the international measures and behavioural changes outlined above. The additional BECCS is necessary because the remaining emissions in 2045 from sectors such as transport are higher than 2050, as emitting technologies such as vehicles with combustion engines are still being replaced.

FIGURE 6:
INTERNATIONAL COLLABORATION AND BEHAVIOUR CHANGE COULD HELP BRING THE UK'S NET ZERO DATE FORWARD TO 2045 (*COLLAB2045* SCENARIO).



Note: *A 2045 net zero date would likely require more BECCS deployment than the UK2050 scenario, to compensate for the higher emissions levels in 2045.*
Source: *Vivid Economics*

35 Driven by both positive net emissions between 2045-2050 in the UK2050 scenario and negative net emissions in the Collab2045 scenario between 2045-2050.

36 Indeed, it may already be exceeded requiring global net negative emissions later in the century.

4.3 POLICY PRIORITIES FOR GREENHOUSE GAS REMOVAL

A broad portfolio of policies, across all sectors, will be required to achieve either of the scenarios described above. This study does not cover all policy needs in detail, rather we highlight **four key areas** where new policy intervention is required.

The development of CCS is on the critical path to achieving net zero by 2050. The GGRs with the biggest deployment potential – BECCs and DACCs – both assume CCS is available. To achieve this, new government policies are required. This includes providing a revenue stream for carbon capture. Deploying CCS also requires government to de-risk transport and storage infrastructure, where some risks are uninsurable and difficult for the private sector to accommodate. This could be achieved through a publicly owned company (Parliamentary Advisory Group on CCS, 2016).

In order to achieve genuine negative emissions from BECCs, close monitoring (including on imports) of biomass sourcing will be necessary. Particularly for imported biomass, it may prove very difficult to source sustainably produced biomass. Without sustainable biomass, BECCS could cause more climate and environmental problems than it solves. Complementary measures will also be required to ensure public and political acceptability thresholds continue to be satisfied for this potentially controversial technology.

A credible deployment schedule is required for DACCs in the UK. New research into the potential to reach DACCs deployment in line with the Royal Society (2018) is needed, including the timescales for pilot projects and gradual testing of full scale plant, a programme of deployment that is consistent with reasonable assumptions regarding supply chain development (what facilities would be required to support the at-scale deployment in the UK, where might these facilities be located and where could DACCs be deployed) and modelling of electricity demand and interactions with the energy system.

A further portfolio of policies to support the GGRs on the land, including:

- Agricultural policy will need to include sufficient financial incentives, potentially significantly exceeding the average £/tCO2 price in the economy, to make GGR worthwhile for farmers. To achieve the required rates of deployment, other subsidies may need to be made conditional on taking GGR steps. As discussed in Section 2.3, Brexit provides a potential opportunity given an alternative for the CAP has to be devised.
- Climate policy change could include the full inclusion of GGR options into emissions accounting, to enable negative emissions to be rewarded equally compared to mitigated emissions under a carbon tax or emissions trading scheme.
- Environmental and agricultural policy must ensure land based GGR options are not only incentivised, but also responsibly applied, and monitored minimising the risk of soil or water pollution, or CO_2 being re-emitted.
- Further areas where government's support is likely to be required include the acquisition of land for afforestation.

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ACHIEVING NET-ZERO WITHIN THE NEXT THREE DECADES PUTS THE UK IN A FORMIDABLE POSITION OF GLOBAL LEADERSHIP ON TACKLING CLIMATE CHANGE

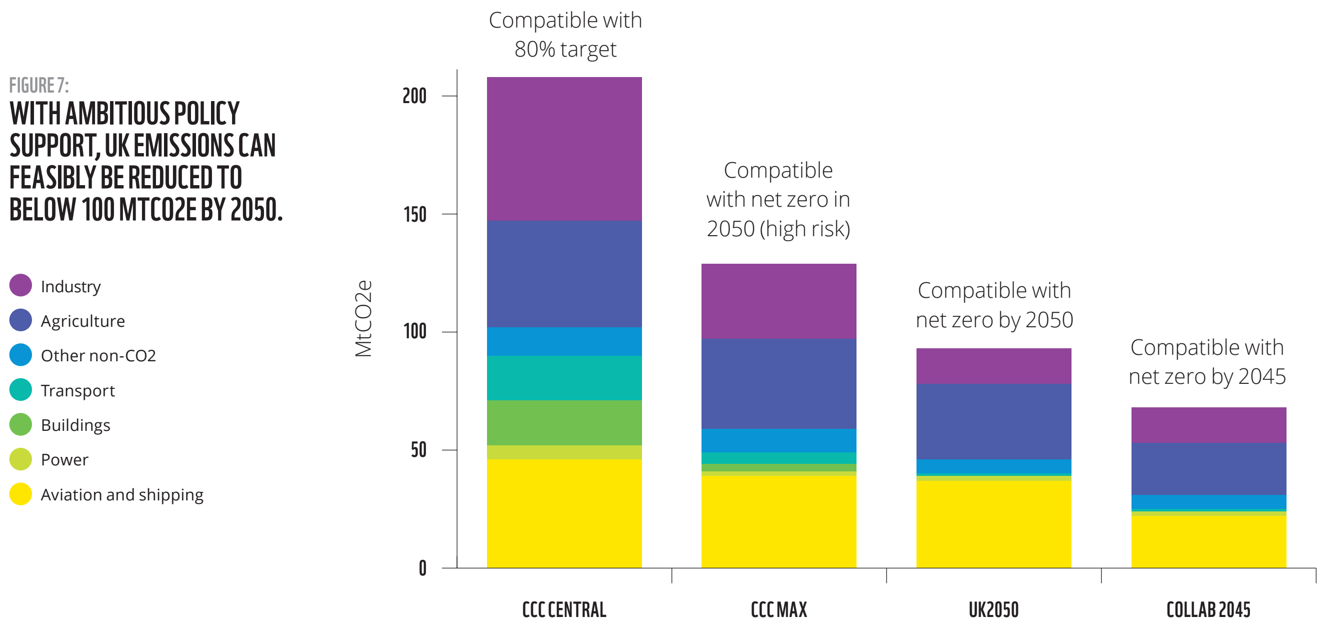
5. LIST OF ABBREVIATIONS

TABLE 3:
LIST OF ABBREVIATIONS

Acronym	Definition
BECCS	Bioenergy with carbon capture and storage
CAP	Common Agricultural Policy
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DACCS	Direct air capture and carbon storage
ETI	Energy Technologies Institute
GGR	Greenhouse gas removal
GHG	Greenhouse gas
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
NDC	Nationally determined contribution
NI	Nitrification Inhibitors

6. APPENDIX 1

FIGURE 7:
WITH AMBITIOUS POLICY SUPPORT, UK EMISSIONS CAN FEASIBLY BE REDUCED TO BELOW 100 MTCO2E BY 2050.



Note: *The CCC Max scenario includes around 130 MtCO2 of emissions, which could be compensated for through GGR as shown by The Royal Society & Royal Academy of Engineering (2018). This would however require deployment against feasible limits of nearly all GGR options, creating significant risk that net zero is not reached.*

Source: *Vivid Economics based on (CCC, 2016)*

Notes on differences between CCC Max Scenario and our *UK2050* scenario

Note, the emissions reductions in the *UK2050* and *Collab2045* scenarios are equivalent, with the exception of the additional collaborative measures described in Section 4.2.

2.1 POWER, BUILDINGS AND TRANSPORT

- In 2050, the CCC Max Scenario includes reductions to 3 MtCO2 (power), 4 MtCO2 (buildings) and 5 MtCO2 (transport).
- Our scenario reduces emissions further by:
  - Reducing emissions from buildings to 0 MtCO2, which requires all buildings to switch to electric or hydrogen-based heating. This would require strict regulation and enforcement to achieve.
  - Reducing emissions from transport to 1 MtCO2 as a result of an early internal combustion engine phase out (2030)

2.2 INDUSTRIAL AND OTHER ENERGY EMISSIONS

- The CCC Max Scenario includes 32 MtCO2 of emissions in 2050. We include further emissions reductions through:
  - Additional reductions in emissions from upstream oil and gas (3 MtCO2): We reduce expected emissions from oil and gas production by approximately (80%) in line with the expected decline in UK oil and gas production (Oil and Gas Authority, 2018).

- Additional reductions in emissions from refining (3 MtCO2): The CCC assumes CCS is used in refining in the UK, but does not reduce the UK's refining capacity. Our scenario reduces UK refining capacity, and consequently refining emissions, by half. This appears reasonable given the expected declines in domestic demand for petroleum products and the decline in UK oil and gas production.
- Reductions in emissions from steel making, cement production, and upstream coking (10 MtCO2): The CCC assumes steel and cement production follows the conventional process, with CCS fitted. Our scenario moves beyond this, electrifying the UK steel industry (possibly also using hydrogen) and using hydrogen to fire cement kilns. This eliminates the need for coke, a coal derivative and the fuel for high temperature blast furnaces and kilns. Several pilots by established steelmakers are currently ongoing and suggest this is feasible, although economically challenging (Swedish Energy Agency et al., 2017; Verbund et al., 2018). The ETI describes the industrial processes for low or zero carbon steel and cement making in detail (Energy Transitions Commission, 2018a, 2018b).

2.3 AGRICULTURE

- CCC Max scenario includes a 25 MtCO2e reduction from current levels by 2050, leaving 38 MtCO2e unmitigated.
- There are few further mitigation measures available, but we include the following:
  - *Further reductions in crop production:* by employing drainage and nitrification inhibitors up to their technical potential, which mitigates an additional 2 MtCO2e and 1 MtCO2e respectively. Advanced nitrification inhibitors and drainage are already applied successfully elsewhere in the world, and the largest uncertainties relate to costs rather than to technical potential (The Committee on Climate Change, 2012).
  - *Feed additives and use of inoculations*. The degree to which food additives interact to reduce emissions is not well established. We include the lower end of the range, 20% reduction in emissions from food additives beyond those included in the CCC's scenario (Mernit, 2018). The use of inoculations is feasible, but relatively unproven, and its effect reduces when used in conjunction with food additives. We take the low end of potential reductions to be prudent.

2.4 AVIATION AND SHIPPING

- We include an additional 3 MtCO2 mitigation through complete decarbonisation of domestic aviation and shipping. This will likely require a combination of modal shifts, biofuel use and electrification.

OTHER NON-CO2

- Our scenario includes 4 MtCO2e reductions beyond the CCC max Scenario. These are all knock on impacts from additional measures taken in other sectors.

7. APPENDIX 2

TABLE 4:
KEY GGR OPTIONS CONSIDERED

GGR option	Description	Maturity	Royal society scenario ($MtCO_2/a$)	Risks
Wood in construction	Increased use of wood in buildings to permanently store carbon	TRL ~ 9. Approximately 50,000 homes a year already constructed with wood frames in the UK	5	• Unsustainably sourced wood • Biodiversity risks (same as afforestation)
Afforestation/ forest management	Increasing forest area to increase CO2 absorption from atmosphere	TRL ~ 9. Already widely practiced throughout the world	15	• Biodiversity risks • Local precipitation and temperature changes
Magnesium silicate/oxide in cement	Replacement of carbonate in cement allows for potential absorption of CO2 over concrete lifecycle	TRL ~ 6. There are several start-ups attempting to implement this. Could scale quickly given significant interest from large established cement producers	1	• Net GGR over lifetime of concrete not fully understood. GGR may not be as large as expected.
Habitat restoration (wetland)	Rewetting and restoration of peatlands etc. to enhance natural carbon absorption	TLR ~ 5. Significant knowledge and readiness around habitat restoration, but not focussed on GGR	5	• No major risks
Biochar	Storing carbon through partially combusted organic matter (char) by burying it in topsoil	TRL ~ 5. Established GGR method, but not yet widely applied	5	• Potentially negative impacts on soil quality • Lifecycle emissions may be significant, reducing overall GGR
Soil carbon sequestration (changed agricultural practices)	'No-till' agriculture and organic soil management	TRL ~ 8. Ready for implementation and many of the practices are already used in some places	10	• After approx. 20 years soil becomes saturated, possibly requiring maintenance to avoid CO2 being re-emitted
BECCS	Carbon dioxide is captured and stored from combustion of biomass	TRL ~ 5. Bioenergy from biomass based power plants is a mature technology, while CCS is largely at the demonstration stage.	50	• Use of unsustainable feedstock • Leakage from CO2 stores
DACCs (amines or calcination)	Absorption of CO2 directly from the atmosphere using amines, suspended on a branched framework	TRL ~ 3. Only small scale DACCS currently piloted	25	• Waste treatment • Leakage from CO2 stores
Enhanced weathering	Spreading silicate minerals across soils to increase soil alkalinity, which increases absorption of acidic CO2	TRL ~3. Needs to be piloted in the field.	15	• Impact on soil and water quality • Environmental impacts due to large scale mining of required minerals

Note: TRL: Technological readiness level, method of estimating technology maturity. TRL are based on a scale from 1 to 9, with 9 being the most mature technology.

Source: Vivid Economics based on Royal Society & Royal Academy of Engineering (2018), Mclaren (2011), (CCC, 2016) and expert interviews.

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