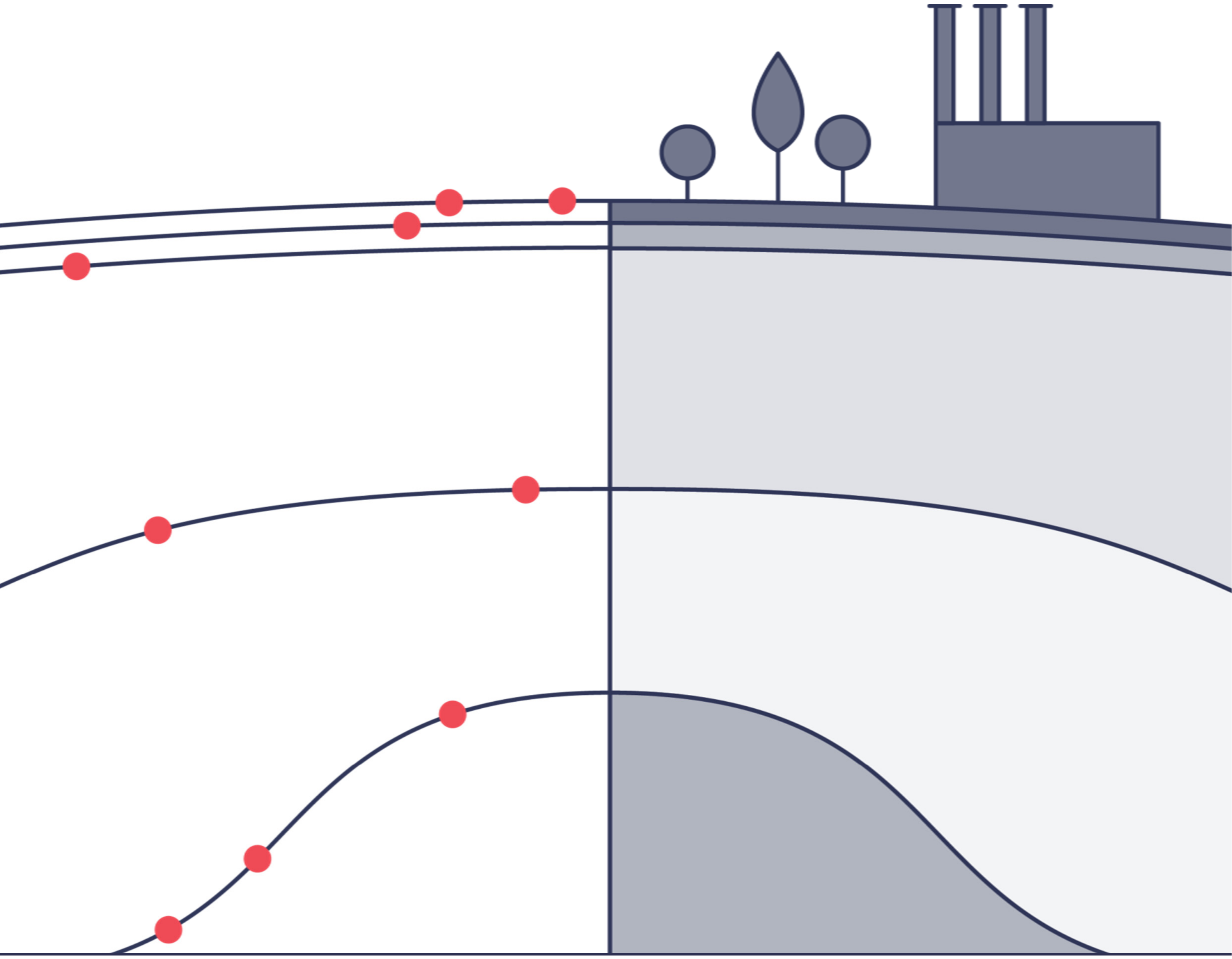
How to price carbon to reach net-zero emissions in the UK

Joshua Burke, Rebecca Byrnes and Sam Fankhauser

Policy report

May 2019



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About the authors

Joshua Burke is a Policy Fellow and Rebecca Byrnes a Policy Officer at the Grantham Research Institute on Climate Change and the Environment. Sam Fankhauser is the Institute's Director and Co-Director of CCCEP.

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Contents

Glossary and abbreviations

Baseload technology: Baseload is the minimum level of demand on an electrical supply system over 24 hours. Baseload power sources are those plants that can generate immediately available power to consistently meet demand.

Carbon budgets: A rolling set of five-yearly emissions targets that provides a statutory cap on economy-wide greenhouse gas emissions in the UK, required under the Climate Change Act (2008).

Carbon capture and storage: A technology that captures carbon dioxide emitted from fossil fuel plants.

Carbon leakage: Where emissions occur in a new place due to businesses transferring production to other countries where constraints on carbon emissions are less stringent, to reduce their costs.

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA): By aiming to limit emissions to 2020 levels, this initiative set up by the International Civil Aviation Organization, effectively allows airlines to strategically increase their emissions until 2020.

Carbon Price Support and Carbon Price Floor: The Carbon Price Support was introduced by the UK government for the power sector to supplement the European carbon price, requiring UK power generators to pay a minimum carbon price, which is referred to as the Carbon Price Floor. The Government recently decided to cap the Carbon Price Floor at £18.08 per tonne of carbon dioxide-equivalent (€20.40) till 2021.

Circular economy: A system where resources are kept in use for as long as possible, with the aim to extract maximum value, then to recover and regenerate products and materials at the end of their useful life.

Clean Growth Strategy: The UK government's strategy for decarbonising all sectors of the UK economy through the 2020s, published in 2017.

Climate Change Act: Became law in the UK in 2008, setting a statutory long-term economy-wide target to reduce greenhouse gas emissions by at least 80 per cent on 1990 levels by 2050.

Climate Change Agreements: Voluntary agreements reached between UK industry and the Environment Agency to reduce energy use and carbon dioxide emissions. In return, operators receive a discount on the Climate Change Levy.

Climate Change Levy: A tax applying to electricity, gas, solid fuel and liquefied gases used for lighting, heating and power in the business and public sectors.

Clean Development Mechanism: A scheme that allows emission-reduction projects in developing countries to earn certified emission reduction credits. These saleable credits can be used by industrialised countries to meet a part of their emission reduction targets under the Kyoto Protocol.

Contracts for Difference: The Government's main mechanism for supporting low-carbon electricity generation.

Fuel duty: Included in the price consumers pay for petrol, diesel and other fuels used in vehicles or for heating, ranging from 10.70p/litre for 'fuel oil' burned in a furnace or used for heating to 57.95p/litre for petrol, diesel, biodiesel and bioethanol.

Gross-zero target: A target to reduce greenhouse gas emissions from all sources uniformly to zero.

Landfill tax: A tax applying to all waste disposed of at a licensed landfill site unless the waste is specifically exempt, charged by weight, with two rates, currently £91.35/tonne at standard rate and £2.90/tonne for the lower rate, to which inert or inactive waste is subjected.

Marginal abatement cost: The cost to abate one additional unit of pollution/carbon.

Negative emissions technology: A technology that removes carbon dioxide from the atmosphere and stores it on land, underground or in the ocean.

Net-zero emissions: Balancing carbon emissions with carbon removal, i.e. allows for some residual gross positive emissions as long as they are offset by gross negative emissions.

Peaking technology: Technologies that generate power only when there is a high demand for electricity, in order to balance supply and demand on the grid.

Renewable Heat Incentive: A UK government financial incentive to promote the use of renewable heat, with a domestic and a non-domestic scheme.

Renewable Transport Fuel Obligation: Obligates suppliers of fuel in the UK who supply at least 450,000 litres of fuel a year to show that a percentage of the fuel they supply comes from renewable and sustainable sources.

Shadow price of carbon: The basis for incorporating carbon in economic appraisal of public investments.

Steam methane reforming: A process through which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source such as natural gas.

Unabated gas: Gas from power plants built without carbon capture and storage.

List of abbreviations

BECCS: Bioenergy with carbon capture and storage

BEIS: Department for Business, Energy & Industrial Strategy

CAP: Common Agricultural Policy [of the EU]

CCC: Committee on Climate Change

CCS: Carbon capture and storage

CDM: Clean Development Mechanism

CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation

DAC: Direct air capture

DECC: [former] Department for Energy and Climate Change

Defra: Department for Environment, Food and Rural Affairs

EV: Electric vehicle

EU ETS: European Union emissions trading system

GGR: Greenhouse gas removal

GW: Gigawatt (one thousand million watts)

HGV: Heavy goods vehicle

ICE: Internal combustion engine

IMO: International Maritime Organisation

IPCC: Intergovernmental Panel on Climate Change

[M]tCO_2e: [Million] tonne of carbon dioxide equivalent

NIC: National Infrastructure Commission

R&D: Research and development

REDD+: Reducing emissions from deforestation and degradation

RHI: Renewable Heat Incentive

ULEV: Ultra low emissions vehicle

Executive summary

Key messages

- The UK government needs to reform its approach to carbon pricing if its new commitment to net-zero emissions by 2050 is to be credible.
- Pricing emissions ensures they are reduced as cheaply as possible, is easier to get right than regulation, and makes the polluter pay.
- It is sensible to implement a politically feasible 'medium-level' carbon price that is higher than today's price.
- Because a 'medium-level' price may not be high enough to ensure full decarbonisation, this carbon price must be complemented by regulation, technology support and incentives for negative emissions to remove residual carbon dioxide from the atmosphere.

High-level recommendations

- The move to a net-zero emissions target will require a higher shadow price than the current projections from the Department for Business, Energy & Industrial Strategy (BEIS). This is the government-internal carbon price that guides policy decisions.
- A shadow price consistent with a net-zero target would start at £50 per tonne of carbon dioxide (tCO_2) (with a range of £40–100) in 2020.
- Complete decarbonisation will require the use of negative emissions technology, which, at the scale required, could cost in the order of £160 (£125–300) per tCO_2 in 2050. The shadow carbon price should rise steadily towards this level.
- To be politically feasible, the carbon price imposed on emitters may have to be lower and it must be responsive to the sector context. In many sectors, a politically feasible carbon price could start at around £40 per tCO_2 in 2020, rising to £125 per tCO_2 or more in 2050.
- Negative emissions should be incentivised in sectors that can deliver them. The Government could set up a public procurement scheme where it purchases offsets in proportion to the residual carbon output (emissions that cannot be avoided), or establish a market for offsets that market participants buy in place of paying the carbon price.
- Any approach to negative emissions must have the highest levels of environmental integrity. Strong regulation for domestic and international accounting processes will be a necessary component of market design.

Accelerating climate action: the UK context

Across stakeholders and political parties in the UK consensus is growing on the need for greenhouse gas emissions to fall to 'net-zero'. This means balancing carbon emissions with carbon removal. Now the Government's independent advisory body, the Committee on Climate Change, has provided a compelling and comprehensive assessment of how the target can be met in its net-zero advice to Parliament, published in May 2019.

Reducing emissions to net-zero is in line with the latest evidence from the Intergovernmental Panel on Climate Change, which shows that to limit global temperature increase to 1.5°C – the most ambitious goal of the 2015 Paris Agreement – emissions will have to fall to net-zero globally by 2050.

Neither the UK's 2050 target under the 2008 Climate Change Act, nor its actual emissions performance, is consistent with achieving net-zero. However, strengthening the target is meaningless without a credible policy framework in place. Pricing carbon is a key component of any strategy to reach net-zero.

The importance of pricing carbon

It will be very difficult to achieve net-zero emissions in the UK without a proper price on carbon. Pricing carbon encourages emissions to be reduced where it is cheapest to do so, is easier to get right than regulation, and sends a clear signal that the polluter must pay.

The cost of achieving net-zero at the margin will be higher than the cost of the UK's current target of reducing emissions by 80 per cent on 1990 levels by 2050. This calls for higher carbon prices than those currently in place. Carbon has been under-priced in most sectors to date, stalling the development of low-carbon solutions, particularly in sectors that are more difficult to decarbonise.

Designing the right price

The Government will have to adjust the shadow price of carbon it uses internally to guide public-sector decisions. A shadow price that is consistent with net-zero would start at £50 (with a range of £40–100) per tonne of carbon dioxide (tCO_2) in 2020, reaching £75 (£60–140) in 2030 and £160 (£125–300) per tCO_2 in 2050, which reflects the likely cost of negative emissions technology. This cost serves as the new anchor of the shadow price trajectory.

It is doubtful that a carbon price at this level can be imposed on all emitters. A high carbon price results in a redistribution of incomes between low- and high-carbon producers, consumers and government that may stretch the political consensus. Political realities necessitate a balance between carbon pricing and complementary policies. We therefore call for a medium-level carbon price in the private sector that makes the polluter pay but may not lead to full decarbonisation. For most sectors, this price would start at around £40/tCO_2 in 2020 (the lower end of the shadow price range) and would typically rise to around £100–125/tCO_2 by 2050.

There may be differences in price levels between sectors to account for differing contexts (see next page). The carbon price may rise more slowly in sectors where full decarbonisation is cheap, and be higher in sectors where remaining emissions would otherwise be too high.

The new pricing schemes can build on existing measures (such as the Climate Change Levy), although this is also an opportunity to improve and simplify the policy landscape. Schemes will have to be designed carefully to ensure public buy-in. This includes targeting the recycling of carbon price revenues transparently and with sound communication.

If imposed through a tax or the auctioning of emissions allowances, the proposed price levels would raise public revenue of around £20 billion a year until the early 2030s, before falling gradually as emissions reduce to net-zero. This is equivalent to about two-thirds of the total revenue raised through fuel duty. If fully redistributed it would equate to a carbon dividend of about £300 per person and year.

To ensure a net-zero target is met, remaining emissions will have to be treated through complementary policies (such as regulation) or offset through negative emissions elsewhere. Carbon pricing is only one of several policy measures the Government must deploy. A net-zero target will probably move the balance between carbon pricing and complementary policies in favour of the latter.

An additional price incentive is needed to encourage negative emissions

A price on (positive) emissions discourages the release of greenhouse gases but on its own it does not encourage negative emissions. A complementary price mechanism must therefore be set up to encourage the development and use of negative emissions technology.

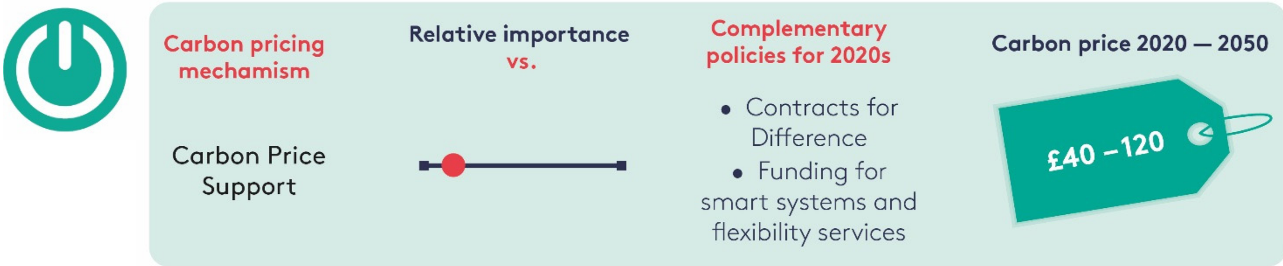
We identify two generic ways in which negative emissions may be rewarded:

- **The first possible mechanism is a public procurement scheme**, through which the Government would purchase negative emissions in proportion to the residual carbon output that its policies have not succeeded in avoiding. The Government could, in the first instance, use revenues raised from a carbon price to pay for negative emissions.

- **The second possible mechanism is a private but regulated offset market**, in which market participants would buy negative emissions in place of paying the carbon price. The cost of negative emissions is likely to be quite high in a free market, so the Government may have to subsidise negative emissions (using carbon tax revenues) to bring the cost of offsets in line with the politically acceptable carbon price.

Carbon pricing by sector

Electric power



The UK already has the institutional architecture to decarbonise the power sector, and the technologies exist to deliver a zero-emissions outcome. Indeed, the power sector may contribute to negative emissions through the deployment of 'bioenergy with carbon capture and storage' (BECCS).

A moderate carbon price starting at £40/tCO_2 in 2020 rising to £120/tCO_2 in 2050 (the anticipated cost of carbon capture and storage), complementing existing measures, should be sufficient to secure a net-zero power sector. This carbon price could be based on the existing Carbon Price Floor or a new scheme, depending on the UK's future participation in the EU emissions trading system.

By raising the price of gas, the carbon price will increase electricity prices. However, the impact on electricity bills should be small, since a higher carbon price will also reduce the payments that have to be made to clean energy producers under their 'Contracts for Difference'. Complementary policies will also need to focus on ensuring high system flexibility in a highly intermittent energy network.

Transport

Surface transport

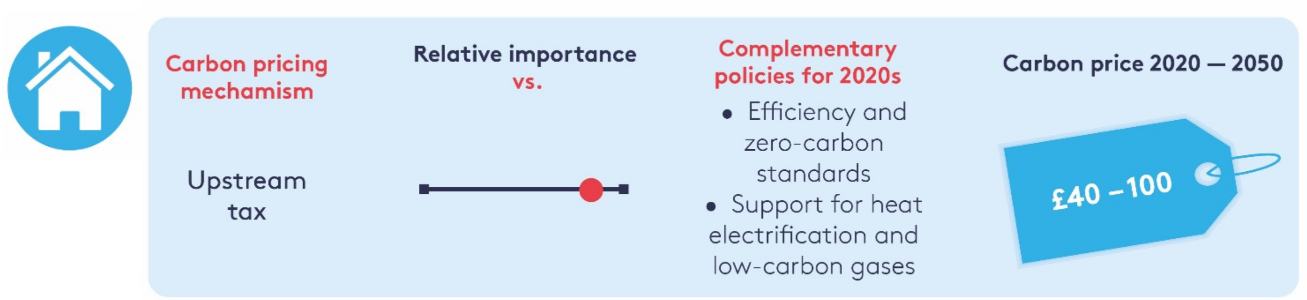
The technologies to decarbonise road transport are increasingly being deployed and falling in cost. A carbon tax is an effective way to support these trends. Transport fuels are already heavily taxed for both revenue-raising and environmental reasons, and raising them has proven difficult in the past. Nevertheless, the fuel duty accelerator should be reinstated to quicken the uptake of zero-emissions cars, incentivise fuel efficiency and discourage short journeys. The carbon price component of fuel duty could start at £40/tCO_2 in 2020, rising to £100/tCO_2 in 2050. Had the fuel duty escalator not been frozen, its level would already be aligned with this trajectory.

The uptake of zero-emissions vehicles could be further encouraged through an even stronger differentiation in vehicle excise duty and policy support for setting up a recharging infrastructure. These extra measures gain in importance the lower the political will to increase the price of transport fuels.

Aviation and shipping

Aviation and shipping are hard-to-treat sectors, which could have substantial demand for negative emissions. The carbon price on international transport fuels should therefore be aligned with the negative emissions price, starting at around £50/tCO_2 in 2020 and rising to £160/tCO_2 (the likely cost of negative emissions) by 2050. This price incentive may have to be complemented by regulatory measures such as increasingly stringent targets for synthetic fuels and internationally coordinated measures such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

Buildings

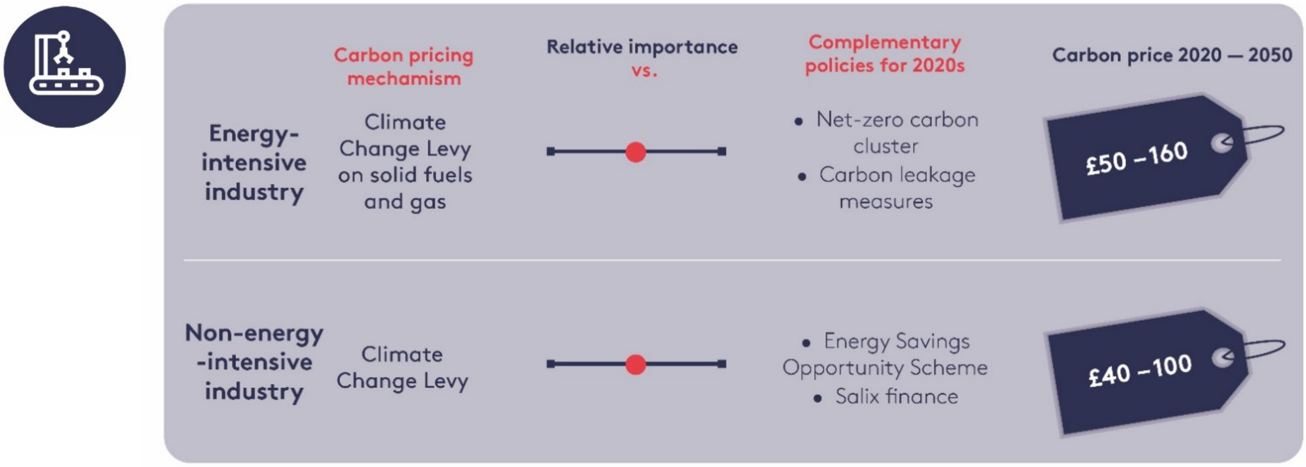


Progress in reducing emissions from buildings has been hampered by an insufficient and uneven carbon price, which discourages zero-carbon solutions. Domestic energy consumption, of natural gas in particular, needs to face a higher carbon price. This will create a level playing field with clean electricity.

A carbon price on its own will not be enough. Carbon pricing has to be complemented by regulation, including energy efficiency standards on appliances and building standards for new and refurbished homes. The roll-out of zero-carbon heating solutions may also need government support.

A carbon price on domestic energy use will be difficult politically and there are genuine fuel poverty concerns. Energy efficiency improvements can help to keep bills stable by reducing the amount of energy required. We propose a starting price of £40/tCO_2 by 2020, rising to £100/tCO_2 by 2050, when few emitters will still be paying the price.

Industry

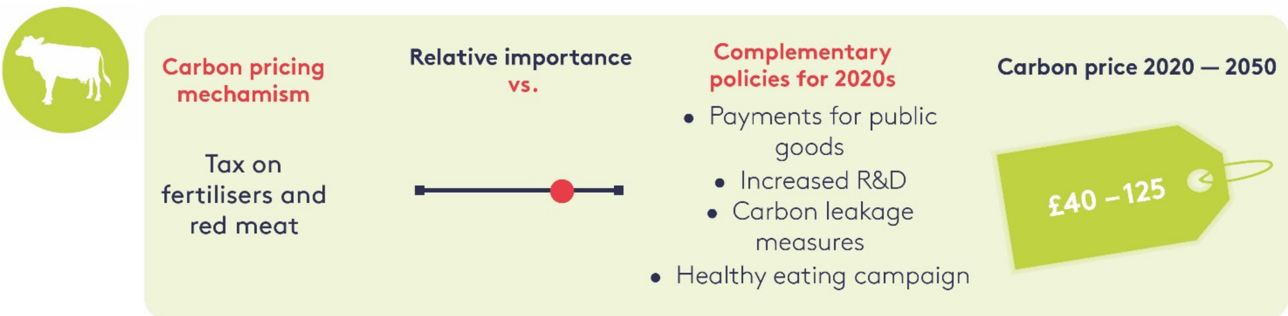


The carbon price faced by industry must become broader and more uniform. For non-energy-intensive industry, energy use is a relatively minor cost and a rising carbon price in the order of £40/tCO_2 by 2020, rising to £100 by 2050 would ensure a zero-carbon outcome. This carbon price could be levied by reforming the existing Climate Change Levy, raising its level and charging it according to the carbon content of fuels. Exemptions through Climate Change Agreements should be phased out or made consistent with a net-zero target. There should be no further levy on electricity or transport fuels, which are subject to their own carbon price.

In energy-intensive sectors, such as steel and cement, zero emissions will often be very costly and the technological solutions are not available yet. Regulatory measures and technology support may be more effective to complete their decarbonisation than the very high carbon price that would be required. A carbon price is still warranted to make the biggest polluters pay. A price starting at £50/tCO_2 by 2020, rising to £160/tCO_2 by 2050 would ensure equivalence between positive and negative emissions, on which the sector will depend.

For selected trade-exposed sectors support measures may have to be strengthened to protect their international competitiveness, including perhaps border carbon adjustment. However, competitiveness concerns will abate as more and more countries move to a net-zero trajectory.

Agriculture and land use

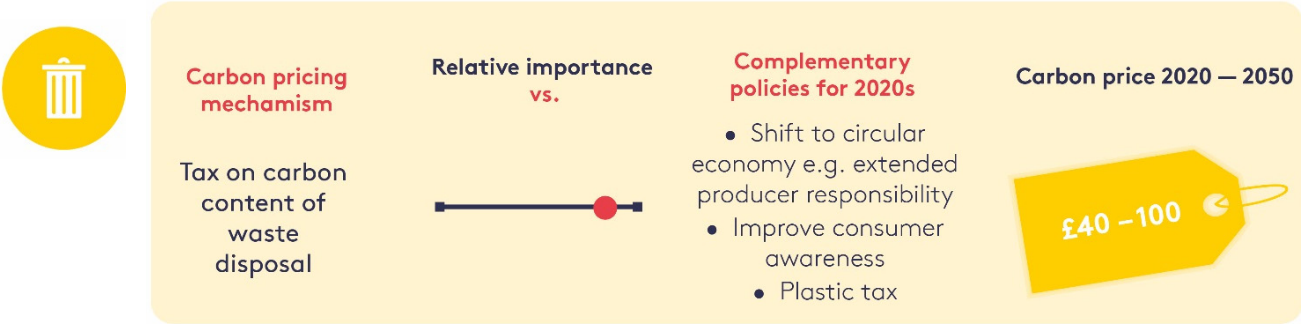


The reform of the agricultural support system that must happen after Brexit will provide an opportunity to create a more environmentally sustainable and zero-carbon sector. Land use measures can also deliver some of the domestically-sourced negative emissions that a net-zero target will require.

Greenhouse gas emissions in agriculture and land use are currently under-regulated. However, policy interventions need to be holistic and deliver a wider set of environmental and societal objectives (e.g. related to nature conservation, health and food security). A carbon price could be administered on selected emissions sources (such as red meat), complemented by a new payment-for-ecosystem-services approach in a reformed domestic agricultural policy.

A rising carbon price starting at £40/tCO_2 by 2020 would incentivise many of the key mitigation actions. More expensive measures, such as grain legume rotations, may need complementary regulation or financial support.

Waste



Carbon pricing in the waste sector needs to be embedded into a wider strategy to discourage waste and promote a circular economy. There needs to be awareness of potential environmental trade-offs, for example in waste-to-energy solutions.

The existing landfill tax has been successful in discouraging landfilling and associated greenhouse gas emissions. However, the waste sector now needs a broader-based carbon price, starting at around £40/tCO_2 by 2020, reaching £100/tCO_2 by 2050, to discourage greenhouse gas emissions in other aspects of waste management (e.g. related to recycling and waste incineration).

The price signal must be structured to specifically disincentivise greenhouse gas emissions, rather than to reduce the weight or volume of waste.

The strategic move towards carbon-based recycling targets may offer an effective framework with which to measure and reduce greenhouse gas emissions. Assuming this accounting framework provides a robust measure of embedded carbon within products, this may provide the basis to apply a carbon price to those products.

Conclusions

The Committee on Climate Change has outlined one of the most ambitious emissions reduction targets in the world to date. It should be legislated as soon as possible. To be credible the new target must be accompanied by an equally rigorous and stringent policy framework.

This report argues that a strong carbon price should be at the core of this framework. Imposing a carbon price at the proposed levels will generate revenues of approximately £20 billion per year for at least the next decade. This creates enough fiscal headroom to enhance the public acceptability of carbon pricing through appropriate redistribution of the revenues, and will help fund research into and the development of negative emissions technologies or other low-carbon projects.

Although the core technologies are known, much about the UK's pathway to net-zero remains uncertain. The numbers presented in this report present a static representation of cost and must be revised over time, allowing for behaviour change and technological and process innovation.

Part A. The importance of pricing carbon

1. Introduction

The dangers of inaction on climate change are stark and call for accelerated action. This is as much the case in the United Kingdom as anywhere, even though the UK's greenhouse gas emissions have fallen substantially since 1990.

Under the 2015 Paris Agreement nearly 200 countries committed to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C". The latest evidence from the Intergovernmental Panel on Climate Change shows that for the latter target, global greenhouse gas emissions will have to fall to 'net-zero' levels by 2050 (IPCC, 2018). This means balancing carbon emissions with carbon removal (see below and Burke [2019] for further explanation of what achieving net-zero involves).

Neither the UK's statutory greenhouse targets, nor its actual emissions performance, are consistent with this latest scientific advice, despite the fact that the UK has signed up to the Paris Agreement. Recognising this, in October 2017 Energy and Clean Growth Minister Claire Perry wrote to the Committee on Climate Change, an independent advisory body on climate targets, asking for advice on a net-zero target for the UK, which would replace or complement the existing 2050 target of cutting emissions by at least 80 per cent relative to 1990 levels.

In its response, published in May 2019, the Committee on Climate Change (CCC) recommended that "the UK should set and vigorously pursue an ambitious target to reduce greenhouse gas emissions … to 'net-zero' by 2050, ending the UK's contribution to global warming within 30 years" (CCC, 2019a).

Carbon pricing under a net-zero target

Determined yet thoughtful and equitable policy design is essential to deliver on this ambitious new goal and realise the boost to clean growth this could bring. Such policy design includes – but it is not limited to – the more forceful use of carbon pricing, which is an indispensable part of any strategy to induce emissions reductions in an efficient way. This report explores the role of carbon pricing in achieving net-zero emissions.

It is important to be clear about the difference between *gross-zero* and *net-zero* emissions: a gross-zero target would reduce emissions from all sources uniformly to zero. Net-zero allows for some residual gross positive emissions – produced by hard-to-treat sectors where emissions abatement is prohibitively expensive – as long as they are offset by gross *negative* emissions, which could come from natural or engineered sinks. Net-zero emissions occur when the gross negative emissions match the gross positive emissions.

To achieve a net-zero outcome, a price on positive emissions will have to be combined with an incentive scheme to deliver negative emissions. A penalty on positive emissions will, if high enough, reduce these emissions to zero, but there is no incentive to go beyond. To deliver negative emissions an additional incentive is needed that specifically rewards carbon sinks.

Objectives of this report

1. Reinforcing the strategic long-term rationale for carbon pricing

The decision to move towards net-zero presents an opportunity to reinforce the rationale for carbon pricing. The importance of a strong, predictable carbon price is worth reiterating in light of recent government statements. In its plans for a no-deal Brexit, the Government indicated that it "will seek to reduce the [Carbon Price Support] rate if the Total Carbon Price remains high".[1] While defining 'high' remains an arbitrary exercise, subject to political wrangling, the statement suggests

[1] See Glossary, p2, for definitions of technical terms such as Carbon Price Support.

a potential disconnect between the Government's Brexit plans and its net-zero ambitions. With the phase-out of coal now pledged for completion by 2025, carbon pricing could also lose some of its political legitimacy. A key objective of existing pricing schemes has been to discourage coal. This report reiterates the case of carbon pricing as an essential policy tool and articulates the need for clear long-term visibility over the level of the price, its purpose and its interaction with other policy interventions.

2. **Making the case for a target-consistent approach to carbon pricing that reflects the UK's new climate ambitions**

In 2009, the UK moved from a social cost of carbon or damage cost approach for valuing carbon to a target-consistent approach, where the government-internal carbon price reflects the marginal costs of meeting the statutory 80 per cent reduction target for 2050. The Government must now move to net-zero emissions by 2050 as the new target in its carbon pricing approach. This is vital in order to ensure that government takes full account of climate change in appraising and evaluating public policies.

3. **Presenting a robust but politically feasible approach to carbon pricing**

The carbon price clearly has to rise. Carbon has been under-priced in many sectors, stalling the development of effective low-carbon solutions (Energy Transition Commission, 2018). However, the price levels required to ensure full decarbonisation in hard-to-treat sectors like agriculture and heavy industry may be difficult to achieve politically. What is required, therefore, is the pragmatic combination of carefully designed pricing schemes with complementary policies, including regulation, technology subsidies and incentives for negative emissions.

Structure of the report

- **Part A (Sections 1–3) acts as an overview of the main arguments in favour of carbon pricing** and how a net-zero target may change the UK's approach to carbon pricing. It also discusses the role of negative emissions and how they might be incentivised.
- **Part B (Sections 4–9) follows with a more detailed review of carbon pricing, sector by sector**. We have taken this approach because while getting to net-zero requires all sectors of the UK economy to make drastic emissions cuts, the appropriate policy mix and the level of carbon pricing may differ across them. Part B covers the six main UK emissions sectors: power, transport, buildings, industry, agriculture/land use and waste.

2. A higher, but pragmatic, carbon price

Why carbon pricing?

The case for carbon pricing has been made compellingly by Bowen (2011), who shows that it is an ideal tool to reduce greenhouse gases in a cost-effective manner. A strong carbon price is arguably even more important for meeting a net-zero ambition than for the current carbon target of an 80 per cent cut. Net-zero will be very hard to achieve without a proper price on carbon. Carbon pricing has to be part of a broader set of policy interventions, dealing with a variety of barriers and externalities that hold back decarbonisation. However, a policy strategy with a carbon price at its core is more likely to be efficient and fair than one without.

Carbon pricing is both fair and efficient

The *fairness argument* in favour of pricing carbon rests on a key principle of environmental law, which states that polluters must pay for the damage they cause or for its abatement. A carbon price is the most explicit way to ensure this. This does not mean that carbon pricing will not hit some socioeconomic groups that society would otherwise like to protect. It does. The use of carbon is so far-reaching in a modern economy that any attempt at net-zero emissions, through whatever policy instrument, will affect some firms and households disproportionately.

However, carbon pricing has the advantage that it can be designed to compensate those groups, not least through the judicious use of revenues from carbon taxation or allowance auctions. Compensation payments can be made visible and explicit, for example through a 'citizen dividend'. In other words, carbon pricing provides a progressive means to allow a 'just transition' away from fossil fuels. Research in the power sector has also shown that the distributional effects of climate policy are lower under carbon pricing than under any other policy intervention (Doda and Fankhauser, 2017).

The *efficiency argument* for putting a price on carbon follows directly from basic welfare economics. Policy intervention is needed when markets do not work perfectly, and a price on carbon would correct the fundamental market failure that is at the core of the climate problem. The emitters of greenhouse gases are not confronted with the economic, social or environmental risks associated with greenhouse gas emissions. Climate change impacts are an 'externality' that is not factored into decision-making.

The expectation is that once emitters are confronted with the full cost of their actions through a carbon price they will find ways to reduce their carbon output. How exactly they do this is left to them, rather than prescribed by a regulator. This flexibility is associated with economic efficiencies in the form of lower overall abatement costs. Emissions are reduced wherever and however it is cheapest to do so. There are also regulatory efficiencies: regulators require much less information about the abatement potential in regulated firms. Faced with massive technological uncertainties, they are less likely to get it wrong. Pricing carbon is therefore a cost-effective way of addressing climate change.

Carbon pricing is part of a broader set of policy interventions

The failure to 'internalise' the climate externality is not the only barrier holding back low-carbon activity. Fankhauser and Stern (2019) point to a long list of additional problems, including failures in capital markets, externalities related to low-carbon innovation, network issues, barriers preventing the uptake of energy efficiency measures, and market failures associated with other societal benefits such as better air quality and healthier lifestyles. There are also policy distortions, not least the subsidisation of fossil fuels and the under-pricing of energy (chiefly through a lower rate of value-added tax [Advani et al., 2013]).

Carbon pricing works better if it is accompanied by complementary policies that address these additional market or policy failures. The supply-and-demand response to a given carbon price signal will be more pronounced if associated barriers have been removed. For example, the carbon price needed to encourage the uptake of electric cars will be lower if complementary policies have removed potential constraints such as an insufficient vehicle recharging infrastructure.

Carbon pricing and other interventions are therefore complements. Each plays its role in addressing a particular market failure – the climate change externality in the case of carbon pricing and the removal of associated barriers in the case of complementary policies. However, there is flexibility in the way the different policies interact. A sufficiently high carbon price would in principle be capable of overcoming almost any related market failures. Conversely, generous support for energy efficiency and clean technology can compensate for a low or absent carbon price. Political economy considerations in particular may dictate a different balance of measures than economic principles might suggest. Technology support often comes in the form of subsidies, for example, which tend to be more acceptable to voters than a corrective carbon price (Carattini et al., 2018).

A 'net-zero' target will probably move the balance between carbon pricing and complementary policies in favour of the latter. Cleaning up the last remaining emissions sources is inherently difficult. It requires action in hard-to-treat sectors like agriculture, aviation and heavy industry. In the absence of obvious decarbonisation solutions, the supply response to a price signal may be minimal. The price level that would trigger changes in products and production processes may be unfeasibly high, causing price shocks and potentially a sharp reduction in demand. This suggests that regulatory measures and subsidies that explicitly target innovation may play a greater role than a stronger carbon price signal in abating residual emissions.

A higher carbon price

The carbon price required to achieve net-zero emissions is considerably higher than that currently applied, for two reasons. First, carbon is already under-priced. The current policy mix (carbon prices and complementary policies) is insufficient to secure the existing carbon targets. Second, the cost of achieving net-zero by 2050 is higher at the margin than the cost of the current 80 per cent emissions reduction target. This means that a target-consistent carbon price anchored on net-zero will also have to be higher. For both reasons the carbon price needs to rise, although it may not have to reach the level required for full decarbonisation.

In exploring the appropriate price level, we distinguish between the shadow price of carbon – the government internal carbon price used for policy guidance – and the actual carbon prices levied on emitters (for example in the form of the Climate Change Levy).

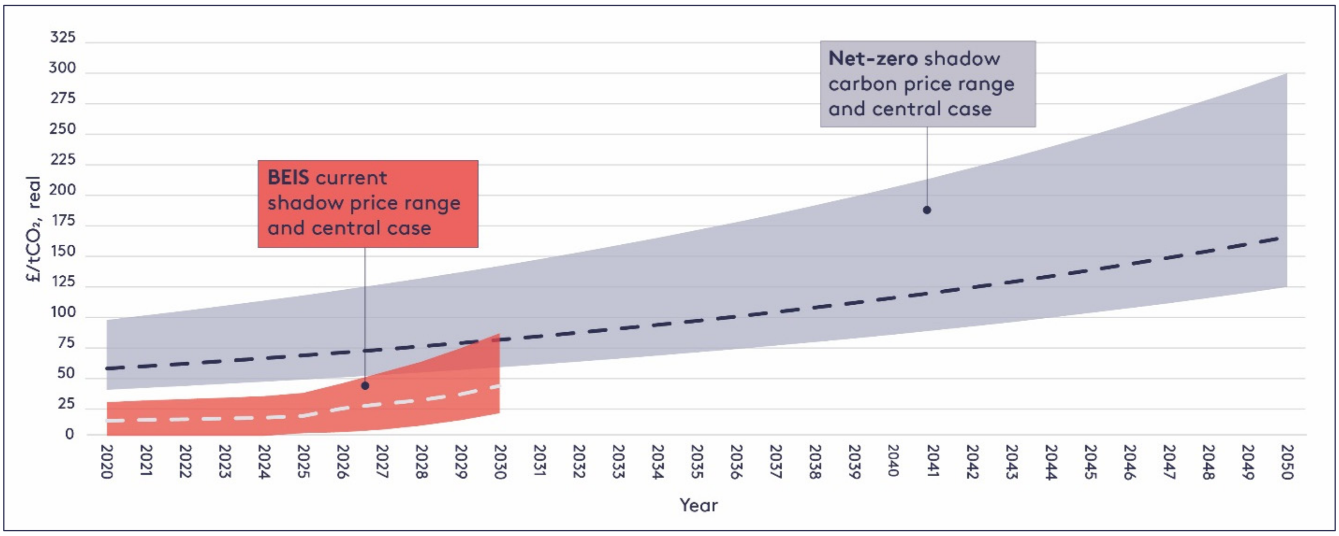
The shadow price of carbon

The *shadow price of carbon* provides policy guidance and is applied in the appraisal of all government projects with carbon implications (BEIS, 2018a). It is used, for example, when analysing the economic merit of airport expansion or the electrification of railway lines. The shadow price also guides the policy mix that is put in place to meet the statutory carbon targets. Measures that cost more than the shadow price are only justified if they bring additional benefits. For example, the initially high price paid for renewable energy was justified by the learning and cost-reduction benefits related to early deployment.

The shadow price is currently set at a level that allows the statutory carbon objective of the Climate Change Act to be met: that is, emissions are cut by at least 80 per cent from 1990 levels by 2050 (see Fankhauser et al., 2018). In the current central price trajectory the shadow price of carbon for modelling purposes grows from £14 (£0–28) per tonne of CO_2 in 2020 to £43 (£19–85) per tonne in 2030 (see Figure 1). In comparison, an international expert commission led by Joseph Stiglitz and Nicholas Stern recommended a global carbon price of US$40–80 (£30–60)/t$CO_2$ by 2020 and US$50–100 (£38–76)/t$CO_2$ by 2030 (Carbon Pricing Leadership Council, 2017).

The move to a net-zero target will require a shadow price that is at the upper end of the Stiglitz-Stern range and well above the current BEIS projections (Figure 1). Complete decarbonisation necessitates the use of negative emissions technology, which at the scale required could cost in the order of £125–300/tCO_2 in 2050, with a potential central value of £160/tCO_2 in 2050 (see Section 3 below). This switch price serves as the new anchor of the shadow price trajectory. The shadow price should rise steadily towards this level, so that emitters have an incentive to bring emissions cuts forward and by 2050 they prefer purchasing negative emissions over paying the carbon price. This suggests a new shadow price of around £50 (£40–100)/tCO_2 in 2020, reaching £75 (£60–140)/tCO_2 in 2030 and £160 (£125–300)/tCO_2 in 2050.

Figure 1. BEIS* short-term modelled values versus new net-zero shadow carbon price, 2020–50



*Notes: *BEIS = Department for Business, Energy & Industrial Strategy. The shadow price follows the Hotelling rule, rising at the rate of interest (assumed to be the 3.8% used by BEIS) to reach the price of the backstop (negative emissions) technology by 2050. Source: BEIS (2019a) and authors' calculations*

There is a wide confidence range around these numbers, which reflects the high level of uncertainty about the cost of negative emissions technology. The shadow price trajectory should therefore be reviewed from time to time as new information becomes available.

Because it is a guide price to inform policy interventions, this shadow price must be applied uniformly across sectors and to all policy decisions. This will ensure that policymakers find the right balance of reduction efforts across sectors.

The carbon price faced by emitters

In principle, the same uniform carbon price should be levied across firms and fuels in the form of a carbon tax or generated through an emissions trading scheme (Advani et al., 2013; Bowen, 2011). This is a fundamental recommendation of environmental economics and underpins the efficiency argument in favour of carbon pricing. However, it is doubtful that such a pricing scheme, at the required level, would be politically feasible at this point. There are important practical barriers that are hard to address in a political context where central government is preoccupied with Brexit.

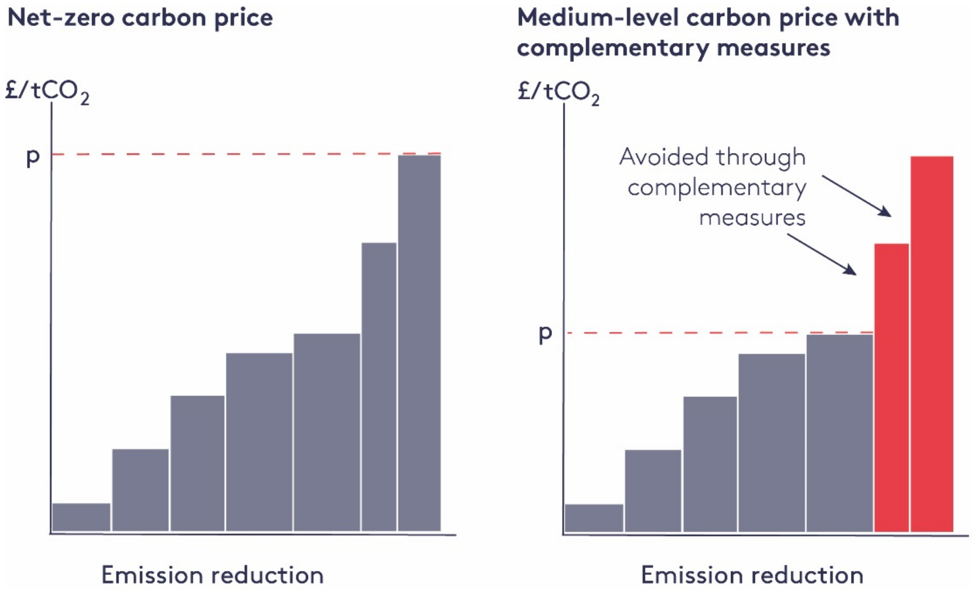
Voters are mistrustful of carbon pricing schemes, not just in the UK but across the industrialised world (Carattini et al., 2018). Carbon pricing is viewed as mostly fiscally motivated (a way to raise government revenue) rather than environmentally motivated (a way to reduce emissions). Voters also doubt whether pricing schemes work, despite clear evidence to show they do. They also feel that pricing schemes are too hard on poor households – a concern that is more supported by evidence than the others. These objections can be overcome through a combination of proactive communication and thoughtful mechanism design.

However, the challenge increases significantly if the objective is a net-zero carbon price rather than a more moderate cut in emissions. In hard-to-treat sectors like aviation, the price signal would have to be quite high to trigger the hoped-for responses on the supply side. Without substantial changes in aviation technology and fuel production processes, the main price response would be a reduction in demand. This and the associated level of income redistribution might raise political challenges. In the energy sector, clean low-cost producers (e.g. existing nuclear and onshore wind installations) would enjoy windfall profits. Government revenues would rise at the expense of business profits and household incomes. Some of these flows are desirable and the reason why pricing is an effective way to change behaviour. However, in political economy terms, they could become problematic.

It therefore seems sensible to implement a politically feasible 'medium-level' carbon price, which must clearly be higher than today, but may not be high enough to ensure full decarbonisation. Such a price would incentivise the majority of emission reductions, including in areas where pricing has so far been too low. However, it would leave a residual of 'difficult to abate' emissions that will have to be addressed through different instruments, including the use of negative emissions elsewhere (see Figure 2).

It is important to note that this approach does not change the economic cost of achieving net-zero in the UK, which the CCC estimates to be in the order of 1–2 per cent of GDP (CCC, 2019a). The cost of decarbonising the hard-to-treat sectors cannot be reduced through a more lenient carbon price. In the absence of the economic and administrative efficiency provided by price signals they may in fact be higher. However, this approach would reduce political frictions and avoid potentially controversial distributional implications.

Figure 2. Carbon price and marginal abatement costs



Note: The chart depicts a stylised marginal abatement cost curve. Each bar represents a particular emission reduction option (e.g. installing air source heat pumps). The width of the bar measures the amount of carbon that this option could save, the height of the bar measures the typical cost per tonne of CO_2. A carbon price of p will make it attractive to realise all emission reduction options that cost less than p. The price therefore has to be higher the more emission reduction options need to be realised.

Source: Authors

A pragmatic approach to carbon pricing

The level of carbon pricing that is required and the pricing schemes that are politically feasible are likely to differ from one sector to the next. The availability of zero-carbon solutions, their costs, their public acceptability and the political economy background in which they are proposed will vary. In sectors like electric power and transport it also makes sense to embed pricing schemes into the existing policy landscape – although the move to a net-zero target is an opportunity to strengthen and streamline the UK's carbon policy landscape, which is often complex and ineffectual.

Departing from the uniform carbon price across firms and fuels advocated by economic theory (Advani et al., 2013; Bowen, 2011) is a major concession to pragmatism. However, there are good reasons to do so.

There are likely to be major differences in the costs of removing the final emissions in each sector. While decarbonisation is ongoing, there seems little reason to burden a sector like electric power, which can decarbonise relatively cheaply, with the carbon price needed in a hard-to-treat sector like aviation. It would only exacerbate the redistribution effects between clean and dirty producers, consumers and government. (Once decarbonisation is complete, the carbon price becomes irrelevant, of course.) Similar arguments have recently been put forward by Vogt-Schilb, et al. (2018).

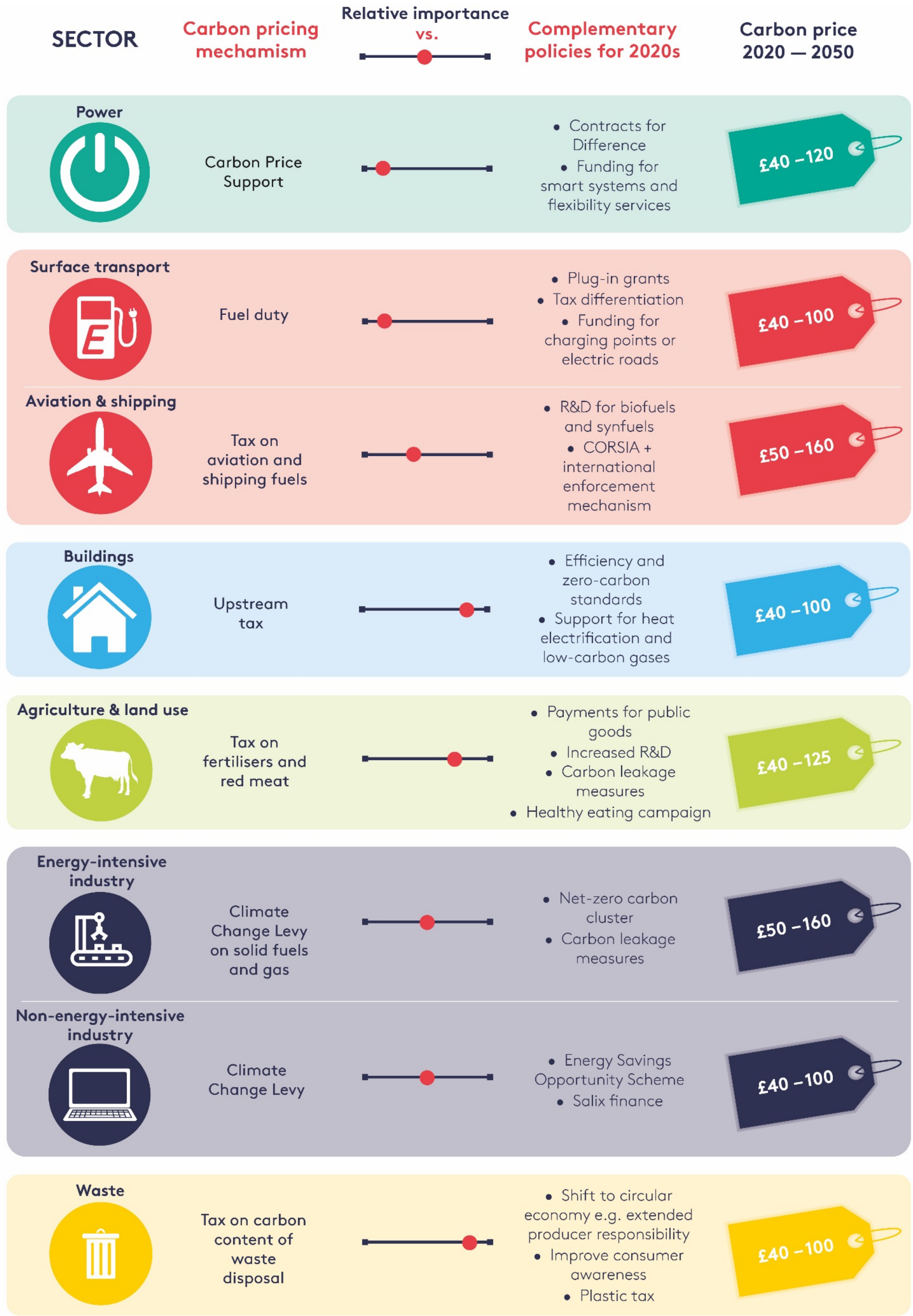
We examine the carbon pricing strategy in each sector and the right combination of pricing and complementary policies in Part B of this report (Sections 4–9). The assessments take into account the likely costs of full decarbonisation; the existing policy landscape, that is, the measures the price mechanism needs to complement; and any wider socioeconomic consequences, for example related to fuel poverty or industrial competitiveness, and potential political economy issues. The main insights are summarised in Figure 3 (next page).

The importance of carbon pricing in the policy mix differs, depending on the need to address complementary market failures (for example, the need for technological innovation in sectors like industry and aviation). The proposed carbon price levels generally follow the lower bound of the shadow price trajectory, either because this appears sufficient, in conjunction with other policies, for full decarbonisation (as is the case in surface transport and electric power) or because political economy constraints may prevent higher levels initially (as in the case of domestic heating, where fuel poverty is a major concern). However, in sectors with high residual emissions it is important to bring the carbon price signal in line with the likely cost of negative emissions, on which they will rely. These sectors should therefore face a higher carbon price, calibrated on the likely costs of negative emissions by 2050.

Even at these medium levels, carbon pricing can generate substantial government revenues, which can either be used to compensate the worst-affected households and businesses or finance additional emission-reduction measures. During the 3rd carbon budget period (2018–22) the average emissions cap is 509 MtCO_2 a year. At a carbon price of £40/tCO_2 in 2020 this equates to revenues of about £20 billion a year, or about £300 for every adult and child.

Revenues remain constant at this level until the early 2030s, as the rise in carbon prices and the fall in emissions cancel each other out. For example, during the 5th carbon budget (2028–32) expected annual emissions are down to 345 MtCO_2 a year, while the typical carbon price has risen to £60/tCO_2, keeping annual government revenues at about £20 billion. Only after this point does the fall in emissions outpace the rise in the carbon price and government revenues gradually begin to fall.

Figure 3. Differentiated carbon prices and the relative importance of carbon pricing versus complementary policies by sector



Source: Authors

3. Incentives for negative emissions technology

The role of negative emissions in reaching net-zero

While every effort needs to be made to reduce greenhouse gas emissions in all sectors, a net-zero target will require some greenhouse gas removal: that is, 'negative emissions'. For example, while aviation and industry have the capacity to reduce most of the emissions they produce, complete elimination is either too expensive or impossible, so residual emissions will remain. To offset this, domestic sectors – such as land use and power – that have the potential to deploy greenhouse gas removal technologies will need to offset residual emissions in order to achieve net-zero across the UK economy. The UK will also have access to internationally produced negative emissions, although the Committee on Climate Change (CCC) has advised against this option.

The CCC considers that even in its 'Further Ambition' scenario – its pathway to net-zero – there will be around 90 $MtCO_2e$ a year of residual emissions that negative emission technologies will have to remove. Of the residual 90$MtCO_2e$, aviation accounts for 35 per cent and agriculture for 29 per cent. There may also be small residual emissions in industry (11 per cent of the total), waste (8 per cent), buildings (5 per cent), power generation (3 per cent, excluding BECCS), surface transport (3 per cent), hydrogen production (3 per cent), F-gases (3 per cent) and shipping (1 per cent). While the UK has the potential to sequester 90 $MtCO_2e$ of carbon a year, the production of these negative emissions will have to be rewarded and incentivised. In practice, the pool of negative emissions will act as a form of cross-sector backstop to be used by any sector with residual emissions.

Negative emissions technologies

The development of negative emissions technologies in the UK is in its infancy, and there is a paucity of substantial research and development or regulatory support in this area (Geden et al., 2019). Nevertheless, a picture is starting to emerge of the scope and potential of different greenhouse gas removal technologies. Figure 4 provides an overview (see also Table 1).

Figure 4. Taxonomy of negative emissions technologies

NATURAL Forestry/Agriculture	COMBINED Natural + Technological	TECHNOLOGICAL Energy/Industry
Afforestation/reforestation Tree growth takes up CO_2 from the atmosphere **Biochar** Partly burnt biomass is added to soil absorbing additional CO_2 **Soil carbon sequestration** Land management changes increase the soil carbon content, resulting in a net removal of CO_2 from the atmosphere **Other land use/wetlands** Restoration or construction of high carbon density, anaerobic ecosystems	**Bioenergy with Carbon Capture and Storage (BECCS)** Plants turn CO_2 into biomass that fuels energy systems; CO_2 from conversion is stored underground	**Accelerated weathering** Natural minerals react with CO_2 and bind them in new minerals **Direct air capture** CO_2 is removed from ambient air and stored underground **Ocean alkalinity enhancement** Alkaline materials are added to the ocean to enhance atmospheric drawdown and negate acidification **CO_2 to durable carbon** CO_2 is removed from the atmosphere and bound in long-lived materials

Source: Reproduced from UNEP (2017)

An important distinction is between natural (land-based) solutions, such as afforestation and biochar, and technological options, such as direct air capture (DAC). The former tend to be more established solutions and proven in practice, but they are subject to tangible environmental integrity and sustainability concerns. Technological options are still mainly on the drawing board. One of the most technology-ready options for greenhouse gas removal in the UK is bioenergy with carbon capture and storage (BECCS), which combines both natural and technological features.

Negative emissions technology needs to be distinguished from traditional carbon offsets, such as those available in the voluntary carbon market or, in its time, under the Clean Development Mechanism – a scheme not without flaws. The important distinguishing feature is that negative emissions technologies reduce emissions relative to a zero-emissions baseline, which is essential to ensure a net-zero outcome, whereas many traditional offsets do not achieve this. A fuel-switching project, for example, that replaces diesel generators with solar panels, can be used to offset the air travel emissions of a voluntary offset buyer. However, the combined emissions of the two activities remains greater than zero. A net-zero outcome requires the offsets to be genuinely negative emissions relative to a zero baseline.

Environmental integrity and public acceptability

Negative emissions technologies raise considerable risks. Environmental integrity needs to be ensured in both the capture and storage of greenhouse gases to ensure genuine and permanent emissions reductions. Greenhouse gas removal therefore raises important considerations for regulation and temporal governance in relation to monitoring, reporting and evaluation (Cox et al., 2018). Incorporating negative emissions into existing frameworks is particularly challenging for natural removal options, due to the need to protect stocks of vegetation over substantial periods of time (Gough et al., 2011). A key consideration going forward will be how to account for these emissions and how governance frameworks can deal with non-permanence, should any negative emissions be reversed once a credit has been issued (ibid.). Restricting the production of negative emissions to engineered removals may help to overcome issues of permanence.

Adding an international dimension to the creation of negative emissions may also exacerbate issues surrounding environmental integrity, particularly as carbon capture and feedstock expansion in the case of BECCS is expected to occur primarily in tropical countries with high biodiversity value, weak forest governance and a chequered history of land-use planning (Chatham House, 2018). With regard to natural offset solutions and BECCS a precautionary approach must be taken. As Heck et al. (2018) discuss, over-reliance on BECCS could steer the Earth system closer to planetary boundaries for freshwater use and lead to further transgression of planetary boundaries for land-system change, biosphere integrity and biogeochemical flow (pathways by which elements or compounds flow between living organisms and the environment). Transparency, strong regulation and governance measures are necessary and essential, although they will inevitably increase the price of negative emissions.

Costs and scale

Knowing all of this, it is important to present the major strategies for negative emissions, their mitigation potential and costs. Table 1 below outlines a range of greenhouse gas removal methods and the amounts of carbon they might be able to remove, domestically and internationally.

Table 1. Greenhouse gas removal (GGR) methods, costs and scales

GGR method [1]	Cost/tCO_2 (US$)	Readiness of technology	Domestic (UK) scale ($MtCO_2$)	International availability ($GtCO_2$)
Increased biological uptake				
Afforestation, reforestation and forest management	3–30	Between active commissioning and operations	15	100–300
Wetland, peatland and coastal habitat restoration	10–100	Between pilot scale and large scale	5	10–20
Soil carbon sequestration	-3–10	Between active commissioning and operations	10	20–100
Biochar	0–200	Between proof of concept, bench scale research, pilot scale and large scale	5	100–200
Bioenergy with carbon capture and storage (BECCS)	100–300	Bioenergy: between inactive commissioning, active commissioning and operations CCS: between bench scale research, pilot scale, large scale and inactive commissioning	50	300
Ocean fertilisation	10–500	Between basic principles, invention and research, proof of concept, bench scale research and pilot scale	*	
Building with biomass	0	Between active commissioning and operations	4	20–50
Natural inorganic reactions				
Enhanced terrestrial weathering	50–500	Between basic principles, invention and research, proof of concept, bench scale research and pilot scale	15	100
Mineral carbonation	50–300 (ex-situ) 20 (in-situ)	Between basic principles, invention and research, proof of concept, bench scale research, pilot scale, large scale, inactive commissioning and active commissioning	*	
Ocean alkalinity	70–200	Between invention and research, proof of concept and bench scale research	*	
Engineered removal				
Direct air capture	200–600 (early stage) 100 (longer term)	Between bench scale research, pilot scale, large scale and inactive commissioning	25	200–500
Low-carbon concrete	50–300 (mineral carbonation	Between large scale and inactive commissioning	1	Uncertain

*Notes: [1] See Figure 4 for definitions. *Technology not yet advanced enough for costs to be estimated. Sequestration scale based on 130 $MtCO_2$ pa by 2050. Source: Adapted from Royal Society (2018).*

The table shows that the costs of negative emissions technology vary significantly. For example, engineered removals such as BECCS and DAC are much more costly options than land-based options such as afforestation, biochar or soil carbon sequestration. Luckow et al. (2010) find that a price incentive above US$150/t$CO_2$ is needed to ensure over 90 per cent of biomass in the energy system is used in combination with CCS. At $160/t$CO_2$ BECCS could be cheaper than coal or gas (without capture).[2]

In contrast, nature-based solutions could be considerably cheaper, assuming environmental integrity concerns can be addressed. Van Winkle et al. suggest enhanced forest management may need an offset price of less than $60/t$CO_2$, which is more than the estimates above but still considerably less than the price of engineered solutions, while agricultural soils could have significant sequestration potential from about $15/t$CO_2$ (McGlynn and Chitkara, 2018).

As Table 1 outlines, there is potential for negative emissions technologies to remove up to 130 MtCO_2 a year of residual emissions. As mentioned above, the recent CCC report on achieving net-zero in the UK now suggests, under its 'Further Ambition' scenario, residual emissions in 2050 will be less than this, at a possible 90 MtCO_2e a year. About 51 MtCO_2e a year of this is to be removed via BECCS, of which the estimated cost is £8.6 billion per year. This is an increase of £6 billion compared with the cost of engineered removals consistent with the current 80 per cent reduction target. In addition a further 31 MtCO_2e are expected to be removed from the atmosphere via natural sequestration solutions such as peatland, woodland and wood used in construction.

Although the relative costs and scaling potential could suggest an innovation hierarchy for progressing with different technologies, this may imply picking technological winners. Instead, Anadon et al. (2016) emphasise diversification to manage risk; given that so many technologies are embryonic in terms of their development, such an approach seems appropriate.

It is also important to consider the rate of technology cost reduction. Table 1 above presents a range of costs for each technology. Generally, one expects the costs to move from high to low but the cost of some nature-based solutions could increase over time. For example, although land management options like soil carbon sequestration, biochar, afforestation and reforestation have a small-scale availability at low, zero, or even negative costs in some places, the marginal costs of abatement tend to increase with deployment, particularly for land management options (Fuss et al., 2018). This includes for afforestation and reforestation, where costs rise due to opportunity costs for land, and for soil carbon management, where costs rise due to the exhaustion of low-cost mitigation options. The implication is that these options could increase in cost beyond 2050.

On the other hand, engineered solutions such BECCS and DAC are comparatively costly ($100–300 and $200–600/t$CO_2$, respectively) – but they have the ability to be scaled up, especially DAC, as it can be designed to be modular. However, there is considerable uncertainty over the long-term cost of BECCS due to a combination of land use factors – opportunity costs for land and biomass – and technological factors. It may be that increases in land use costs negate any potential reduced costs via scaling and technological learning. DAC has the potential for longer-term cost reductions.

A price mechanism for negative emissions

To incentivise the production of negative emissions they need to have an economic value. Carbon pricing can play an important role in this respect as an economic enabler to create markets, drive deployment and generate revenues linked to technologies that remove and store greenhouse gases (Royal Society, 2018).

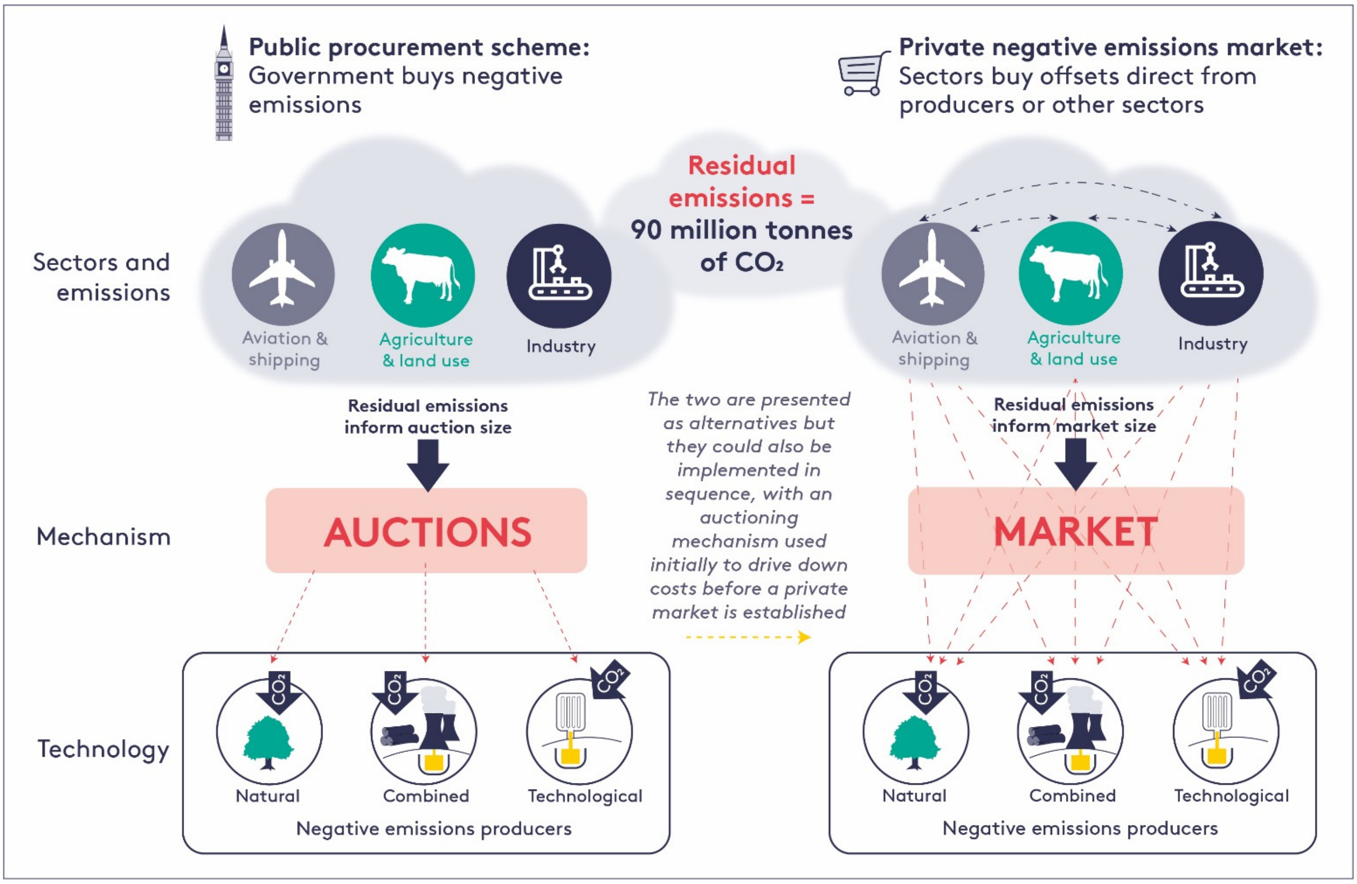
However, a penalty on positive emissions alone is not enough. A price on (positive) emissions discourages the release of greenhouse gases. If high enough, it will eventually reduce them to zero, but it does not encourage negative emissions. A complementary price mechanism must be set up to encourage the development and use of negative emissions technology.

2 BECCS could be competitive with coal or gas (without capture) at a carbon price of around $100/tC and cheaper at around $160/tC.

The way negative emissions are rewarded will have implications for the efficiency of the mechanism, its distributional impact and public support for greenhouse gas removal. Very little empirical evidence exists on how different forms of incentivisation impact on public perceptions of greenhouse gas removal technologies. In a recent study, Bellamy (2018) found that guarantees of higher prices for producers selling energy derived from BECCS were strongly opposed, owing to participants' knowledge of the high costs being imposed on taxpayers by this mechanism in order to support new nuclear energy provision (namely the construction of Hinkley Point C).

We identify two generic ways in which negative emissions may be rewarded, illustrated in Figure 5. The first entails government-led greenhouse gas removal auctions; the second involves the creation of a negative emissions market. The two are presented as alternatives, but they could also be implemented in sequence, with an auctioning mechanism used initially to drive down costs before a private market is established.

Figure 5. Pricing schemes for negative emissions



Source: Authors

A government procurement mechanism

Under a government-led public procurement scheme, the Government is the main source of UK demand for negative emissions. Based on an understanding of the efficacy of low-carbon policies, the Government would purchase negative emissions in proportion to the residual carbon output that its policies have not succeeded in avoiding.

Particularly in the early years, an important objective would be to stimulate learning and reduce the costs of greenhouse gas removal technologies. In this respect the Government can draw on the successful experience of promoting renewable energy sources like offshore wind. To encourage nascent technologies, the Government may, for example, choose to separate negative emissions technologies into different pots based on maturity, and ring-fence options that are considered to be strategically important. Funding for auctions could come in part through the recycling of carbon price revenues or from general taxation.

Public procurement through a competitive auction mechanism is preferred to a general subsidy for negative emissions where the Government would reward all producers with a fixed level of support (akin to feed-in tariffs), as an auction is more responsive to technological progress, the Government can gauge the quantities procured and it can help reduce the overall cost of the policy.

An advantage of the centralised model is that the Government has direct control over the environmental integrity of offsets and potential liabilities, including issues of permanency, the risk of leakage from geologically stored CO_2, or any other unwanted side-effects (Torvanger, 2019).

A private market for negative emissions

The second possible mechanism is a private but regulated offset market, in which market participants would buy negative emissions in place of paying the carbon price. Sectors with significant residual emissions – such as aviation – that require these offsets would then effectively fund technologies producing negative emissions.

Sectors that can produce genuine net negative emissions should be allowed to sell offsets to any other sector to enhance overall economic efficiency (Geden, 2019). This may include trade within sectors such as agriculture that are capable of producing negative emissions but that have residual emissions of their own.

The emitters of greenhouse gases would then face three compliance choices: abate remaining emissions, pay the carbon price or purchase negative emissions offsets. The preferred balance by emitters would be a commercial choice.

To ensure full decarbonisation, the carbon price on positive emissions would have to rise over time until emitting carbon and paying the price is no longer an attractive option. Therefore, the price level would have to be higher than either the costs of complete emissions abatement (a gross-zero outcome) or of negative emissions (a net-zero outcome). The required carbon price could be quite high as a result, and the Government may have to subsidise negative emissions (using carbon tax revenues) to bring the cost of offsets in line with the politically acceptable carbon price.

There is some precedence for how a market for emissions offsets might interact with carbon pricing schemes. Many emissions trading schemes, including the EU ETS in its early stages, permitted the use of carbon offsetting in place of emission permits. In the heyday of the Clean Development Mechanism (CDM), the EU ETS was an important source of demand for CDM offsets, known as certified emission reductions. It has been suggested that the Sustainable Development Mechanism under the Paris Agreement, a successor to the CDM, might usefully be expanded to analogously include international trades in negative emission offsets (Honegger and Reiner, 2018).

If the carbon price is levied through a tax rather than a trading scheme, the interaction with the greenhouse gas removal market would be slightly different. Installations may still have to pay the carbon tax on the emissions that have not been covered through purchasing negative emissions, but purchasing negative emission offsets could qualify for a tax deduction and reduce the total amount payable.

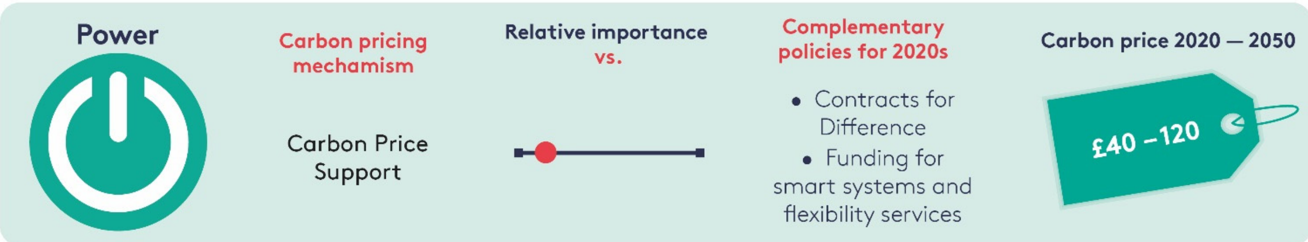
For a market in negative emissions to be credible it would have to be carefully regulated, with a governance system that ensures environmental integrity and provides absolute legal clarity over potential liabilities. It is worth reiterating that there has been mixed success for environmental safeguards under offsetting instruments such as REDD+ (Reducing Emissions from Deforestation and Degradation) (Pham et al., 2013), and so the formulation of a negative emissions market must be predicated on the highest levels of environmental integrity. Strong regulation for domestic and international accounting processes will be a necessary component of market design.

Part B. Carbon pricing by sector

4. Electric power

Key points and recommendations

- The UK already has the institutional architecture to decarbonise the power sector, and the technologies exist to deliver a net-zero-emissions outcome. The ability to commercialise carbon capture and storage (CCS) and ensure system flexibility pose the greatest challenges to decarbonisation.
- The power sector should face the full cost of abatement, starting at £40/tCO_2e in 2020 and rising to £120/tCO_2e in 2050 to reflect the cost of CCS.
- This carbon price could be based on the existing Carbon Price Floor or a new scheme, depending on the UK's future participation in the EU emissions trading system.
- By raising the price of gas, the carbon price will increase electricity prices but to a small extent, since a higher carbon price will also reduce the payments that have to be made to clean energy producers under their Contracts for Difference.



Emissions performance of the electric power sector

At around 24 per cent of total emissions, the power sector still represents a significant portion of UK emissions (BEIS, 2019b). However, it is also the sector with the clearest pathway to achieving net-zero, with most technologies expected to be pivotal to decarbonising the sector having already progressed beyond the stage of R&D. The sector has made the greatest contribution to the UK's decrease in carbon dioxide emissions so far, falling 8 per cent between 2016 and 2017 alone to 112.6 million tonnes of CO_2, largely driven by a reduction in coal use and the closure of coal-fired power stations. This is attributed to an increase in the Carbon Price Support[3] in April 2015 from £9 to £18/tCO_2, which encouraged a reduction in coal generation of 26 per cent (ibid.). Emissions from the power sector overall have fallen 64 per cent since 1990 (CCC, 2019a).

The path to net-zero in power

A clear path to net-zero exists in the power sector, utilising mostly existing technologies. As previously discussed, the Committee on Climate Change's net-zero advice outlines two emissions reductions scenarios: a Core scenario, which represents low-cost options to meet a target of an 80 per cent reduction by 2050, and a Further Ambition scenario, which includes options that are more challenging and/or more expensive than the Core options, but all of which are likely to be needed to meet a net-zero target (CCC, 2019a). For the power sector, the key difference between the two scenarios lies in the scale of new energy capacity required by 2050.

Under an 80 per cent emissions reduction target National Grid has estimated that peak demand could be allowed to rise from around 61 gigawatts (GW) in 2017 to 79–83 GW in 2050 (National Grid

[3] For an explanation of the Carbon Price Support, see House of Commons Library (2018).

2018a, 2018b). However, a net-zero emissions target would force near-complete electrification, including in more challenging sub-sectors such as heat and heavy goods vehicles (as they switch from diesel to electric), with CCC estimates suggesting that peak electricity demand could increase significantly, up to 150 GW in 2050 (CCC, 2019b).[4]

The CCC projects that it is possible to meet this additional capacity while also reducing power sector emissions by 95 per cent from 1990 levels by increasing the share of clean energy generation from around an anticipated 50 per cent in 2019 to 95 per cent of the energy mix in 2050 (CCC, 2019b). This would require a quadrupling of variable or intermittent renewables, partly through a potential seven-fold increase in offshore wind, to achieve a 59 per cent share of the energy mix by 2050, abating around 130 $MtCO_2e$. Variable renewables would be complemented by up to 23 per cent generation from gas with CCS, some of which would provide peaking services and some of which would provide dispatchable low-carbon power (i.e. on demand when renewable energy is not available), around 4–10 per cent from nuclear energy, around 6 per cent from BECCS, and smaller amounts from bioenergy, hydro and peaking plant (power plants that generally run only when there is a high electricity demand) (CCC, 2019b).

At an abatement cost of £120/tCO_2e in 2050, CCS represents the most expensive abatement option. It is also the least commercially advanced, with no CCS plants currently operating in the UK. To achieve the scale required by 2050, 1–2 GW of CCS will need to be installed every year from 2020 to 2050, requiring significant and early government support to help commercialise the technology (CCC, 2019b).

'Flexibility services' – the ability of the electricity grid to respond rapidly to changes in electricity demand – will also be an essential part of the technology mix to integrate and manage the variability of renewable energy sources in a low-carbon power system.

The role of carbon pricing in the electric power sector

Based on a marginal abatement cost of £120 – representing CCS for peaking generation as the highest known cost technology – a carbon price set at £120 in 2050 could achieve a 95 per cent gross emissions reduction from the power sector by 2050.

A robust price signal in the power sector has the capability to change the order in which utilities dispatch technologies, shift consumer behaviours and stimulate private sector investment in sources of low-carbon or renewable power (Curran et al., 2017). This has been borne out as successive governments have demonstrated the political will to intervene in the marketplace through a robust carbon price. A modest carbon price has already seen significant coal to gas switching as the Carbon Price Floor raises the variable cost of plant with higher carbon intensities; hence a carbon price changes the merit order[5] from higher- to lower-carbon intensive plant (Newbery et al., 2018).

A carbon price can support an increasing share of subsidy-free renewable generation because, in addition to falling renewable energy technology costs, the carbon price will increase the cost of fossil fuel generation so that when generators bid into the market wholesale electricity prices are higher than they would be without a carbon price. On balance, this will counter the price-depressing effect of zero marginal cost renewable energy on the wholesale market. As all generators are paid the market price of the electricity sold by the highest-cost generator that is dispatched to the grid, renewable energy generators will benefit from higher profits resulting from the higher price of gas.

Raising domestic carbon prices does have the potential to create asymmetrical power prices with neighbouring EU countries, which could lead to opportunities for arbitrage through the development of additional interconnectors and see reduced domestic gas generation as greater quantities of power are imported from countries including Germany, Belgium and France. This

4 The CCC does not explain how it reached this figure. It also projects that electricity use in 2050 will be 594 TWh, up from 300 TWh in 2017.

5 Merit order is a way of ranking available sources of energy, such as electrical generation, based on ascending order of price.

raises carbon leakage concerns as although the UK's existing carbon tax has been successful in reducing domestic power sector emissions, the existence of interconnectors may favour cheaper imports from parts of the EU where power stations are on average older and less efficient than in the UK. Perversely, this means that although the UK's own carbon tax has reduced UK emissions, it may increase EU-wide emissions (Rooney et al., 2018). However, the extent to which this arbitrage can occur is limited to the amount of interconnection, which is often lengthy and costly to build, and may be offset by emissions reductions efforts in Europe.

Technology phase-out mandates – including the UK's mandated coal phase-out by 2025 – have been used to make up for lack of certainty around future carbon prices. Tvinnereim and Mehling (2018) highlight the prevalence of technology phase-out mandates – such as the UK's coal phase-out – as a reaction to the political economy constraints of carbon pricing, where prices are not sufficiently high and so prevent new investment in emitting technologies. Phasing out coal using carbon prices alone would require prices to increase to above £45/t by 2025 due to projected increases in the wholesale price of gas (Aurora Energy Research, 2018).

However, as we recommend a carbon price that would begin at £40 in 2020 and rise to £49 by 2025, the mandated 2025 phase-out would function more as a safety net in the event of unexpected increases in the wholesale price of gas.

Under a net-zero target, electricity will have an increased role as sectors such as heat and transport pursue this route to decarbonisation. This necessitates decarbonising electricity first, with other sectors following. New electricity capacity must therefore be clean and deployed at speed. Fiscal reform must encourage this transition. This justifies our call that the power sector should face a higher carbon price – relative to most other sectors – that reaches £120/tCO_2e, in 2050 in line with the full abatement cost of the most expensive technology, i.e. CCS.

Political economy issues around reducing emissions from electric power

The power sector faces few competitiveness concerns as it has limited trade exposure (Grover et al., 2016), although higher electricity prices can have flow-on effects to other sectors such as the industrial sector (see Section 7 on industry below).

In total, UK households and businesses currently pay around £7 million per year towards the roll-out of low-carbon power. Under a net-zero target, this cost is projected to rise to around £12 billion per year by 2030, then fall to around £4 billion by 2050 as low-cost renewable energy replaces existing generators without the need for further subsidies (CCC, 2019a). By contrast, the CCC's Core scenario would see a negative cost (i.e a cost saving) of -£2.4 billion in 2050.

Households have historically paid a smaller share of this cost compared with businesses: households faced an implicit carbon price of £5.92/tCO_2e in 2012, compared with £38.71, £51.53 and £69.17 for large energy-intensive firms, small- and medium-sized firms respectively (Advani et al., 2013). This is primarily due to the reduced rate VAT for households, which amounts to a subsidy of around £52.73/tCO_2e (ibid.). Of the costs that households do face (around £105 per household per year in 2016), these have been more than outweighed by savings from energy efficiency improvements, a trend projected to continue into the future (CCC, 2019a).

These costs and benefits are not spread uniformly among households. A carbon price on electricity is typically regressive for high-income countries like the UK, as low-income households spend proportionately more of their income on energy (Dorband et al., 2019). However, Kaufman and Krause (2016) found that the way in which carbon pricing revenue is recycled has the greatest overall distributional impact on households. A tax and dividend or other form of rebate scheme can mitigate equity implications arising from the regressive nature of the carbon price.

Given the high potential for a carbon price to be effective in the electricity sector, combined with the capacity to limit distributional impacts through energy efficiency measures and redistribution of carbon pricing revenues, we recommend that the electricity sector face the full cost of abatement in 2050 with a carbon price of £120, to align with the marginal abatement cost of CCS plant. This should be levied through the existing carbon pricing mechanism, the Carbon Price Support.

Complementary policies for electric power

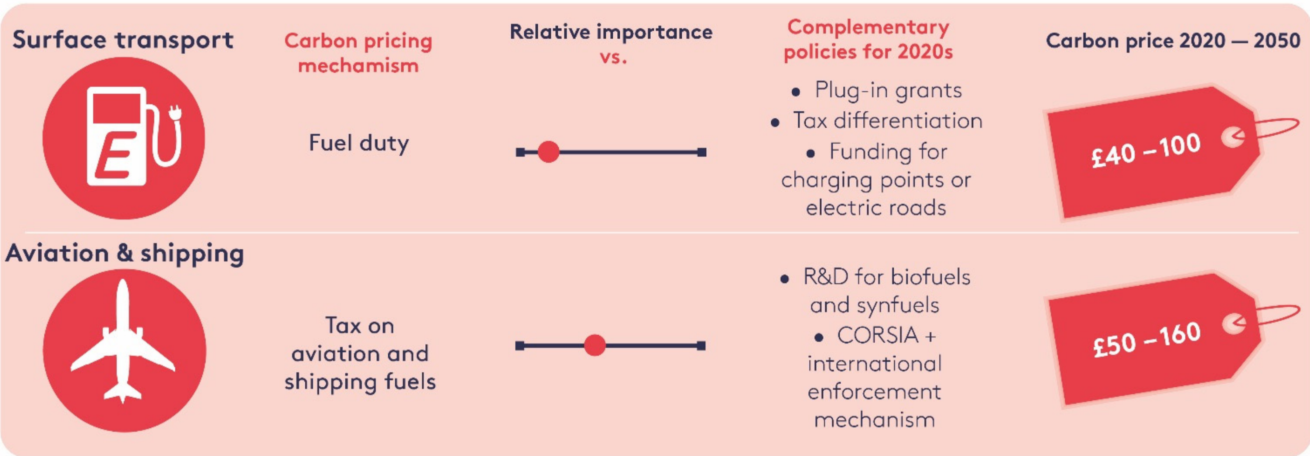
Carbon pricing can do much of the heavy lifting in decarbonising the power sector, but the CCC foresees that in order to achieve its projected abatement costs in 2050, government funding will be needed to support the continued scaling-up of offshore wind and the commercialisation of CCS (CCC, 2019a). The CCC projects that the Government's current commitment of £557 million per year in funding through the 2020s could achieve 57 per cent low-carbon generation by 2030, so more support will be needed to achieve the 75–85 per cent low-carbon generation needed to be on track to meet a net-zero target by 2050. This could occur through a scaling up of the Contracts for Difference programme, including extending the program to CCS plants. With innovations in the energy sector typically taking three to four decades to scale from early R&D to significant commercial deployment (Watson and Gross, 2018), significant and early commercialisation support is particularly critical for CCS to ensure sufficient capacity comes online in the lead-up to 2050.

In addition to support for low-carbon generation technology, government funding and policy will need to target system flexibility and security measures, and improvements to the distribution network. This is to ensure the future energy system can withstand the influx of variable renewable energy, increased demand and two-way energy flows through technologies such as vehicle-to-grid, whereby electric vehicles can export electricity stored in their batteries to the grid during peak demand. Work is already underway on this front – the Government has pledged £265 million in smart systems to reduce the cost of electricity storage as part of a wider innovation package targeted at the power system, and National Grid has announced plans to upgrade the current electricity network to enable it to operate safely with a zero-carbon energy mix by 2025 (Leslie, 2019). In addition to ensuring sufficient government funding is put behind the development of these services, the CCC also recommends electricity market reform to help ensure flexibility services such as storage, frequency and voltage control are always available.

5. Transport

Key points and recommendations

- Transport fuels are already heavily taxed for both revenue-raising and environmental reasons, and raising these taxes has proven difficult in the past. Nevertheless, the fuel duty accelerator should be reinstated to quicken the uptake of zero-emissions cars, incentivise fuel efficiency and discourage short journeys.
- The carbon tax for surface transport could start at £40/tCO_2 in 2020, rising to £100/tCO_2 in 2050.
- The uptake of zero-emissions vehicles could be further encouraged through an even stronger differentiation in vehicle excise duty and policy support for setting up a recharging infrastructure. These extra measures gain in importance the lower the political will to increase the price of transport fuels.
- Aviation and shipping are hard-to-treat sectors, which could have substantial demand for negative emissions. The carbon tax on international transport fuels should therefore be aligned with the negative emission price, starting at around £50/tCO_2 in 2020 and rising to £160/tCO_2 (the likely cost of negative emissions) by 2050. This price incentive may have to be complemented by regulatory and internationally coordinated measures.



Emissions performance of the transport sector

The transport sector – surface transport and aviation and shipping – is the largest contributor to greenhouse gas emissions in the UK, the sector as a whole responsible for 33 per cent in 2017 (CCC, 2019b).

Progress in cutting emissions from surface transport has been extremely slow. This sub-sector contributed 23 per cent of emissions in 2017, estimated at 117 MtCO_2e, 3.6 per cent more than in 1990. Emissions were constant from 2016 to 2017, after three consecutive years of emissions increases. Surface transport generally refers to cars, vans and heavy goods vehicles, which account for 94 per cent of surface transport emissions.

A further 10 per cent of the country's total emissions come from aviation and shipping. Aviation accounted for 7 per cent in 2017, the equivalent of 36.5 MtCO_2e, and shipping a further 3 per cent, or 13.8 MtCO_2e. Since 1990 emissions from aviation have more than doubled, while shipping emissions have fallen by 20 per cent (CCC, 2019b).

Surface transport: road and rail

The path to net-zero in road transport

An important driver of decarbonisation to meet the legislated target of an 80 per cent reduction in emissions by 2050 has been to continue to increase the efficiency of conventional internal combustion engine (ICE) vehicles. This could reduce emissions by 22 $MtCO_2e$ by 2030 (CCC, 2019b). However, this option has limited long-term use given the CCC's recommendation that ICE vehicles should be completely phased out by 2035 in order to be able to decarbonise road transport by 2050. To reduce emissions by more than 22$MtCO_2e$ in 2030, 5 per cent of car miles will need to be shifted to walking, cycling and public transport.

Public transport will also need to be decarbonised, and could be made almost 100 per cent low-carbon by accelerating the rollout of both hydrogen and electric vehicles by 2050 (CCC, 2019b). In the short term, improvements to freight operations made, for example, through greater logistics efficiencies, will need to result in mileage being reduced by 6–8 per cent.

Switching from conventional vehicles to plug-in hybrid and electric vehicles (PHEVs) is the most cost-effective measure to abate road transport emissions up to 2050 (CCC, 2015b). Achieving full decarbonisation would also require phasing out PHEVs in favour of full battery-electric vehicles by 2050.

Table 3 shows the CCC's projected average abatement costs in 2050 for switching to battery electric and hydrogen vehicles. It should be noted that despite the CCC's projected cost of £34 for cars, more recent analysis suggests that the costs of electric vehicles are converging on ICE prices and that the cost of owning an ultra-low emission vehicle (ULEV) car is already cheaper over a four-year period than the cost of owning an ICE over the same duration (Howard et al., 2017; Wappelhorst et al., 2018).

Table 3. Marginal abatement costs for low-carbon road transport

Vehicle	2050 abatement cost, £/tCO_2e
Cars	-£39
Vans	-£64
Buses	£198
Heavy goods vehicles (HGVs)	-£39
Motorcycles	-£22
Aircraft support vehicles	£137

Source: CCC (2019b)

Under the 80 per cent reduction target, the combination of measures outlined above reduce road transport emissions from 117 $MtCO_2e$ in 2017 to 28 $MtCO_2e$ in 2050. Cars account for 9 $MtCO_2e$ and HGVs a further 15 $MtCO_2e$. But a net-zero target means deeper emissions cuts are essential. Under a net-zero pathway, emissions in surface transport must reduce from 117 $MtCO_2e$ in 2017 to 62.3 $MtCO_2e$ in 2030, with cars accounting for 53 per cent of this reduction. HGVs and vans make up a further 23 per cent and 16 per cent respectively. The remaining 8 per cent is split between motorcycles, buses, rail and aircraft support vehicles. Emissions must then be cut further from 62.3 $MtCO_2e$ in 2030 to only 2.1 $MtCO_2e$ in 2050 (CCC, 2019b). Cars, vans, motorcycles and aircraft support vehicles become gross-zero at this point. However, buses, HGVs and rail still have a small amount of residual emissions.

The extra technologies and measures required to get to net-zero by 2050 include the end of sales of conventional cars and vans, and of plug-in hybrids, being brought forward to 2035 at the latest. Under a net-zero pathway this is five years sooner for conventional vehicles and 15 years sooner for PHEVs compared with an 80 per cent reduction target. In addition, by 2040 almost 100 per cent of sales of HGVs must be zero-carbon, which can be achieved through a combination of electrification and the use of hydrogen fuel. However, electrification is more challenging for HGVs than for cars, as HGVs need to be able to travel longer distances and carry heavy loads – requiring more energy. Seventy-eight per cent of domestic freight in the UK between 1990 and 2017 was transported by road, so this is a significant challenge.

Under a net-zero pathway the CCC assumes that 54 per cent of the railway is electrified by 2040, compared with 40 per cent today. The Government previously committed to electrifying several additional routes, including for example the Midland Main Line north of Kettering, Cardiff to Swansea, and Oxenholme to Windermere, which would have resulted in 51 per cent of the network being electrified. However, these plans were cancelled in 2017 in favour of bi-mode, which can run on both electricity and diesel for sections of the track that are not electrified, on the basis of cost and lack of sufficient passenger benefit from electrification on the routes in question. The CCC assumes that hydrogen trains will be employed on all trains operating at speeds under 75 miles per hour on lines that are not electrified by 2040.

According to the CCC (2019b) the costs of the net-zero transition include a number of elements such as HGV refuelling infrastructure, which is likely to require capital investment of £3–16 billion to 2050, a rapid charging network for longer journeys, which would cost around £300 million to 2050, and a public electric refuelling infrastructure network for cars and vans, costing approximately £9.3 billion. However, overall, and unlike in other sectors, where achieving net-zero will incur costs, reaching net-zero in surface transport could result in a net annual saving of £5.1 billion, more than the annual cost saving of £2.6 billion under the 80 per cent emissions reduction target. This stems from new battery-electric vans and cars being cost-saving compared with a petrol or diesel car over the lifetime of the vehicle, due to a combination of reduced fuel costs and reduced capital costs. The saving is reflected in the average sector-wide abatement cost of £-35t/CO_2.

The role of carbon pricing for surface transport

The transport sector is already exposed to a carbon price through the application of fuel duty, which places a direct tax on the use of fossil fuels. All else being equal, tax receipts should decline as road transport is decarbonised. Carbon pricing can play a role in incentivising uptake of EVs by increasing the price difference between EVs and conventional vehicles. For example, in 2018 EVs in the UK were around 5 per cent cheaper than a diesel-powered engine, including purchase price, fuel and all taxes, while in Norway, where EV uptake is very high, they were 27 per cent cheaper (Wappelhorst et al., 2018).

That said, a carbon price in the road transport sector could have a delayed impact as demand is generally inelastic to changes in fuel prices in the short term, reflecting the fact that consumers typically own cars for long periods of time (the average age at scrappage is around 14 years). However, carbon pricing could play a key role in switching from ICEs to ULEVs by 2050 (SMMT, 2018). There will remain a need for investment in R&D to continue to improve battery technology, (Liimatainen et al., 2019); however, on the whole the technologies largely exist to decarbonise road transport. The balance between carbon taxes and complementary innovation policies therefore favours taxation.

A carbon tax is an effective way to support these trends. Transport fuels are already heavily taxed for both revenue-raising and environmental reasons, and raising them has proven difficult in the past. Nevertheless, the fuel duty accelerator should be reinstated to quicken the uptake of zero-emissions cars, incentivise fuel efficiency and discourage short car journeys.

For the purposes of simplicity and coherence, the carbon price could be implemented through a single measure such as the existing fuel duty. Fuel duty has been frozen since 2011/12 at 57.95 pence per litre. If a net-zero target-consistent carbon price of £40/t in 2020 were applied to fuel duty, this would raise the petrol duty price to 67.19p/litre in 2020 and the diesel duty price to 68.67p/litre (excluding VAT). Incidentally, if the fuel duty were not frozen in 2011/12 and rose in line with the original Fuel Duty Stabiliser,[6] the price in 2018 would already be higher than this, at 76.9p/litre. Applying a target-consistent price of £100/t in 2050 would raise petrol duty to 81p/litre and diesel duty to 84.7p/litre. Inflating the current fuel duty price by just 1 per cent per year would be sufficient to reach this target-consistent price in 2050.

With the implementation of an effective carbon price, climate policy for the road transport sector could be simplified. For example, under a tax high enough to incentivise the purchase of ULEVs

[6] The Fuel Duty Stabiliser was introduced by Alistair Darling when he was Chancellor of the Exchequer, and this was the mechanism to inflate fuel duty by 1 pence per litre over the rate of inflation.

there would be little need for the Renewable Transport Fuel Obligation (which regulates biofuels used for transport and non-road mobile machinery).

Political economy issues around carbon pricing for surface transport

A carbon price could be implemented through an increase in existing fuel duty, while recognising the potential distributional impacts of such a tax: opposition has manifested in major fuel protests, in the UK in 2000 (Cotton, 2012) and in France as recently as December 2018 (Chrisafis, 2018).

Some of the barriers to purchasing ULEVs are perceived rather than real. For example, Berkeley et al. (2018) found that a common concern among consumers was that they perceived the number of charging stations to be insufficient, despite the fact that there has been a substantial increase in their number in the UK since 2013, to around 10,000. Concerns around the length of time taken to offset the higher vehicle purchase price through fuel savings, and perceptions of limited battery range, might also reflect a lack of consumer awareness of recent technological advances and cost reductions. The high purchase price is the most commonly cited barrier, indicating that upfront capital costs can still pose a challenge.

Political economy considerations, combined with technology cost reductions in electric vehicles, suggest that a carbon price slightly lower than the shadow carbon price could be sufficient to get to net-zero in surface transport. The carbon tax for surface transport could start at £40/tCO_2 in 2020, rising to £100/tCO_2 in 2050.

Complementary policies for road transport

Policies complementary to a carbon tax should focus on providing funding to improve charging infrastructure, including upgrading local distribution networks that will supply electricity in locations where many trucks may need to charge simultaneously.

While vehicle standards have been effective to date and should be retained, policies should be targeted at encouraging a systemic shift away from ICEs to ULEVs, rather than incremental efficiency improvements. The current target of phasing out ICE vehicles by 2040 should be brought forward to 2035 at the latest, along with a minimum range electric drive requirement on electric and plug-in hybrid vehicles to ensure almost all trips can be completed without using the petrol or diesel engine (CCC, 2018a). Funding should be allocated to commercialise ULEV technology and increase consumer buy-in. This could be done through purchase subsidies or tax exemptions and consumer awareness campaigns (Long, 2017). The Government should also revisit its decision to cancel proposed rail electrification projects.

Aviation and shipping

The path to net-zero in aviation and shipping

In 2017, UK residents made 72.8 million trips overseas, 85 per cent of which were made by air (Department for Transport, 2019). International aviation emissions represent the greatest increase in emissions of all UK transport forms between 1990 and 2016, rising from 16 to 36.5 MtCO_2e (ibid.). Projections for increases in air travel demand range from 44 per cent from 2005 to 2035 (Nava et al., 2018) to 350 per cent from 2000 to 2050 (Markham et al., 2018); certainly the additional emissions from the growth in demand look set to far outstrip those offset by any efficiency improvements under a business-as-usual scenario. The increase in aviation emissions has been so pronounced that in 2018 Irish airline Ryanair became the first non-coal generator to enter the top 10 biggest carbon polluters in the EU (Cuff, 2019).

The main levers for emissions reduction for the aviation sector are reducing demand for flights, and long-term innovation with efficiency improvements in the short to medium term. Under an 80 per cent emissions reduction scenario, emissions from aviation increase to 37.5 MtCO_2e in 2050. This limits aviation emissions to 2005 levels by 2050, and uses carbon offsets from other economic sectors to address residual emissions (CCC, 2015b). This would require limiting demand growth to 60 per cent above 2005 levels in 2050, assuming a 0.9 per cent annual improvement until 2050 in fuel efficiency and a 10 per cent take-up of biofuels across the aviation sector.

Even under a net-zero pathway, the CCC finds little opportunity to drastically cut emissions. It finds that by 2050, emissions can only be reduced to 30 $MtCO_2e$, mainly through annual gains in fuel efficiency, which would increase from 0.9 per cent to 1.4 per cent but there is no scope to increase the use of biofuels beyond the 10 per cent take-up envisioned under an 80 per cent scenario.

The CCC's recommendations, are more ambitious than the global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) initiative, which aims to limit emissions to 2020 levels starting from 2021. CORSIA effectively allows airlines to strategically increase their emissions until 2020 to create a higher baseline for compliance. It is also voluntary for all states until 2026 (ICAO Assembly Resolution A39-3). There will be a need for carbon offsets for the residual emissions that remain in the aviation sector, whatever their extent, with estimates that CORSIA will generate demand for 1,600–3,700 $MtCO_2e$ of offsets from 2021 to 2035 globally (Hamrick and Gallant, 2018).

While the CCC estimates the overall average abatement cost for aviation to be negative (owing to measures such as limiting demand growth which have no resource cost), at -£10/tCO_2e (CCC, 2019a), individual measures are expected to incur a positive cost, e.g. the use of biofuel is estimated to cost £125/tCO_2e.

Options for reducing shipping emissions do exist. Under the current 80 per cent emissions reduction target, emissions need to decline to 4.4 $MtCO_2e$ by 2050, compared with 13.7 $MtCO_2e$ in 2017 (CCC, 2019b). This scenario aligns with the International Maritime Organization's agreed objective to reduce global international shipping emissions by at least 50 per cent below 2008 levels by 2050. The measures to achieve such cuts include greater uptake of energy efficiency measures and the deployment of ammonia fuel to replace three quarters of fuel demand by 2050. To get to net-zero, there must be a faster transition to the use of ammonia fuel, such that it represents nearly all of fuel demand by 2050. This would contribute to reducing emissions from shipping to less than 1 $MtCO_2e$ in 2050.

Shipping faces even higher emissions abatement costs than aviation. A switch to biofuel could cost around US$350/$tCO_2e$ (~£238) in 2050, increasing voyage costs by an average of 120 per cent. A switch to ammonia could cost around US$150/$tCO_2e$ (~£102), increasing voyage costs by around 50 per cent (Energy Transition Commission, 2018). The CCC suggests broadly similar abatement costs. It suggests an abatement cost of £200/tCO_2e for shipping, with limiting demand growth assumed to have no resource cost (CCC, 2019a).

The overall cost of a net-zero pathway to aviation and shipping is estimated by the CCC to be £5.4 billion per year, compared with £4.6 billion per year under an 80 per cent pathway.

The role of carbon pricing in aviation and shipping

Carbon pricing can play a key role in the aviation sector in helping to drive a reduction in demand (or at least stabilisation of demand) and an increase in innovation. The CCC's net-zero-consistent scenario allows for a 60 per cent growth in aviation passenger demand by 2050 compared with 2005 levels. This assumes that increased fuel efficiency offsets increases in emissions associated with larger passenger demand. However, growth must not exceed this figure. Carbon pricing is one potential lever to ensure that demand does not increase beyond 60 per cent.

To decarbonise aviation and shipping we propose a carbon price between £125 and £160. A high price is important to help bring forward more innovative technology. For example a carbon price of about £136/tCO_2 in 2050 is needed to encourage the use of synthetic fuels (such as hydrogen). This would add around 10–20 per cent to the price of an economy class ticket on a long-haul flight. While the Energy Transitions Commission (2018) states that this would not "have a material impact on overall standard of living or economic growth, and may simply need to be accepted as the unavoidable cost of decarbonising the aviation sector", the price will inevitably cause a larger cost burden for lower-income than for higher-income travellers. In the event that a carbon price aligned with this range cannot be implemented, as a minimum starting point aviation in the UK should be subject to VAT, as currently it is effectively subsidised compared with other sectors.

As aviation and shipping are hard-to-treat sectors, which could have substantial demand for negative emissions, the carbon tax on international transport fuels should be aligned with the negative emission price, starting in line with the full shadow carbon price at around £50 per tCO_2 in 2020 and rising to £125–160/tCO_2 – the likely cost range for negative emissions and biofuels in 2050. This will lead to a 30 per cent increase in the price of jet fuel in 2020, rising from £1.596 per gallon in May 2019 to £2.075 per gallon, and a 96 per cent increase in the price of jet fuel under a £160/tCO_2 price in 2050, up to £3.13 per gallon. If the price is levied directly onto consumers, it will increase the price of an average flight from London to New York by 6.5 per cent in 2020, from £527 in May 2019 to £560, and rising by 21 per cent to £635 under a carbon price of £160/tCO_2 in 2050[7]. In addition to mobilising negative emissions, a price at this level will also help to mobilise abatement technologies such as synthetic fuels and biofuels at the margin.

Carbon leakage is a risk: in other words, there is a possibility that airlines that use UK airports as a stopover destination might choose to reroute elsewhere through Europe, and some travellers might choose alternative destinations if travelling to the UK becomes too expensive – so the emissions from those flights would simply occur elsewhere instead. We therefore recommend that in addition to implementing a UK aviation carbon price, the Government works through the International Civil Aviation Organisation to strengthen the CORSIA initiative and pursue a global carbon price on aviation.

As with the road transport sector, a carbon price could be implemented through a single measure: for aviation, either through the existing air passenger duty, or by replacing this with a carbon tax or emissions trading scheme; and for shipping by applying a tax directly to shipping fuels.

Political economy issues around carbon pricing for aviation and shipping

The extent to which a carbon price is passed through to consumers depends on the particular scheme. For example, modelling suggests that airlines covered by the EU ETS that were initially granted their allowances for free may have chosen not to pass through the price of allowances, in order to gain a competitive edge over new operators, who would have to pay the full cost of allowances (Nava et al., 2018). During the period of the carbon tax in Australia, from 2012 to 2014, airlines initially passed through the cost to consumers but then broader competitive pressures meant they eventually reduced the cost pass-through to zero (perhaps because of the two main airlines, Virgin and Qantas, competing for market share following the collapse of another airline [Markham et al., 2018]).

The shipping sector faces many of the same challenges as aviation, plus the additional challenge that ships may be able to avoid any UK-based carbon price on fuel simply by refuelling at a port in another country. However, given the minimal impact of a carbon price on consumers in the case of shipping, there may be fewer political feasibility concerns about a carbon price on this sector.

Complementary policies for aviation and shipping

Unlike the road transport sector, the technologies to fully decarbonise aviation and shipping do not exist yet. Technological strides have been made with regard to electrification, biofuels and hydrogen which could be used by both aviation and shipping sectors, but these remain in the very early stages of development. Innovation policy could be targeted at industry to develop fuel efficiency measures, in terms of the fuel itself, the design of the aircraft or pilot behaviour. In addition to complementary innovation policy a robust price signal to invoke substantial modal shift among consumers is necessary. This would result in consumers changing their behaviour by flying less.

In its 2019 Spring Statement the Government announced a planned call for evidence on offsetting transport emissions (HM Treasury, 2019) to investigate compulsory carbon offsets for the aviation sector. This is an important step to addressing residual emissions that cannot be abated, but there will still be significant demand for negative emissions across all sectors of the economy and offsetting should be a final resort only after abatement options are exhausted.

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7 Jet fuel prices are for Europe as of 15 May 2019, as expressed in the S&P Global Platts Jet Fuel index, converted from US dollars to pounds Sterling utilising the 15 May exchange rate from OANDA. Emissions per gallon are drawn from the ICAO (2019) Carbon Emissions Calculator methodology. Flight prices are calculated using the average price of a return flight over the May 2018–May 2019 period. CO_2e per passenger is derived from the ICAO Carbon Emissions Calculator.

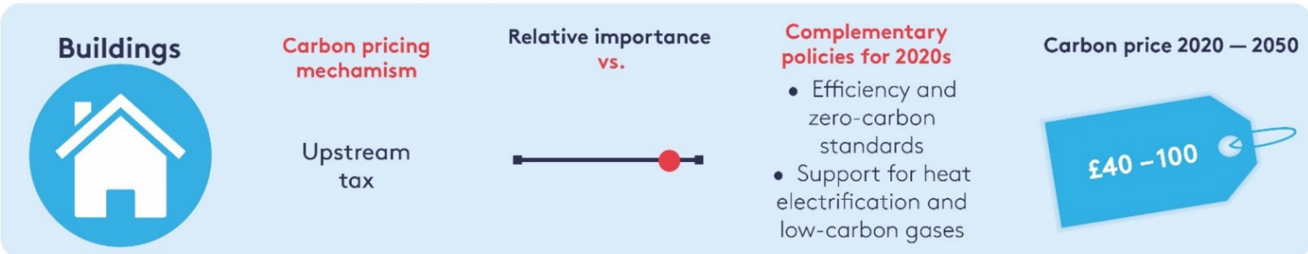
The Government should simultaneously fund R&D and commercialisation programmes to promote innovation in biofuels and synthetic fuels, particularly as emissions reduction in shipping are contingent on their deployment. As the average marginal abatement cost of these fuels is £200/t – and above the carbon price range we suggest – this suggests the need for complementary innovation policy to help reduce cost in the first instance, bringing them in line with a politically feasible carbon price.

Moreover, with abatement measures such as energy efficiency currently having negative cost measures (i.e. the measures pay for themselves even without a carbon price), with barriers relating to access to capital and lack of information, this suggests a complementary role for regulations to drive through these cost-effective options.

6. Buildings

Key points and recommendations

- Progress in reducing emissions from buildings has been slow, hampered by an insufficient and uneven carbon price that discourages zero-carbon solutions. This needs to be redressed.
- Domestic energy consumption, in particular of natural gas, needs to face a higher carbon price to create a level playing field with clean electricity.
- A carbon price on its own will not be enough in the buildings sector: it must be complemented by regulation, including energy efficiency standards on appliances and building standards for new and refurbished homes. The rollout of zero-carbon heating solutions may also need government support.
- A carbon price on domestic energy use will be difficult politically, partly because of genuine fuel poverty concerns. Energy efficiency improvements can help to keep bills stable by reducing the amount of energy required. We propose a starting price of £40/tCO_2 by 2020, rising to £100/tCO_2 by 2050, when fewer emitters will still be paying the price.
- For non-residential buildings (i.e. non-energy-intensive industry), energy use is a relatively minor cost and a carbon price in the order of £40/tCO_2 by 2020, rising to £100 by 2050, would ensure a zero-carbon outcome.



Emissions performance of the buildings sector

In 2017 buildings accounted for 17 per cent of the UK's total emissions, or 85 MtCO_2e (CCC, 2019b). Progress in reducing emissions from buildings has been extremely slow and it remains one of the thorniest issues in energy policy: they were reduced by an annual average of just 1 per cent between 2009 and 2014 (CCC, 2019a). This compares badly relative to other sectors: for example, while emissions in the power sector declined by 56.6 per cent from 1990–2017, over the same period residential emissions dropped by just 18.2 per cent (Policy Exchange, 2018). Only emissions in the transport sector decreased at a slower rate.

The challenge largely comes from decarbonising heat, much of which is still generated by gas, within residential buildings: homes make up three-quarters of direct emissions from the buildings sector (64 MtCO_2e) with non-residential buildings accounting for a quarter (CCC, 2016).

The path to a net-zero buildings sector

A pathway to net-zero in the buildings sector is beginning to emerge. Where previous strategies have pitted electrification *against* 'greener' gases to achieve decarbonisation targets, it is now recognised that this polarisation presents a false dichotomy. A number of options are now considered viable and complementary. These include:

- Repurposing the gas network for hydrogen or other low-carbon gases
- Electrifying heat using heat pumps (air source, ground source, water source and hybrid solar)

- Making greater use of hybrid systems that utilise both gas and electricity

Hydrogen has climbed up the political agenda over recent years and its potential recognised in several major reports (e.g. CCC, 2018c and Imperial College, 2018). Thus it is emerging as a credible solution to decarbonising hard-to-abate sectors.

Currently, the vast majority of hydrogen produced is carbon-intensive. Hydrogen produced by steam methane reforming has an emissions intensity of around 285 gCO_2/kWh, and coal gasification around 675 gCO_2/kWh (CCC, 2018c). For these processes to be low-carbon it is essential that CCS technology is deployed in the production of hydrogen. Unlike heat pumps, biomass and other biogases, hydrogen has little policy support, slowing down the ability for technologies that can produce sustainable hydrogen from deploying at scale. For example, it is not eligible for support under the Renewable Heat Incentive. Without sufficient funding, large-scale production and deployment in the 2020s may be optimistic.

Ambitious energy efficiency programmes are an important underpinning to all of these options, and can reduce overall system costs across all pathways by £0.9–6.2 billion per year (Imperial College, 2018). However, no solution is a silver bullet and many of technologies will need to be employed in conjunction to realise their full emissions reduction benefits (CCC, 2016).

A decarbonisation pathway that includes heat pumps, electrification and hydrogen conversion, or a combination of these, should be sufficient to achieve net-zero within the building sector. While they differ in technological maturity and cost, all options are within grasp, subject to political will, adequate financing and an understanding of consumer preferences.

Technologies under the CCC's Core scenario of meeting the existing target of an 80 per cent emissions reduction by 2050 consist of: energy efficiency measures such as greater insulation, which reduces energy demand by 21 per cent, installing conventional heat pumps in 17 million homes (23 million are currently connected to the gas grid), installing hybrid heat pumps for houses off the gas grid, and greater deployment of low-carbon heat networks. Combined, these measures are expected to reduce emissions by 65 $MtCO_2e$ – from 85 $MtCO_2e$ in 2017 to about 20 $MtCO_2e$ in 2050. The weighted average cost of decarbonisation for each group of homes in the Core scenario is under £250/tCO_2e (CCC, 2019a). But achieving net-zero requires much deeper emissions cuts.

In the CCC's Further Ambition scenario, the pathway to net-zero, buildings emissions are reduced to just 4 $MtCO_2e$. Achieving this deeper decarbonisation is contingent on converting residual gas demand to hydrogen, and achieving greater rates of energy efficiency to reduce energy demand by 25 per cent (4 per cent more than in an 80 per cent emissions reduction scenario). In this scenario the number of heat pumps in homes also increases, from 17 million (under the Core scenario) to 19 million. An alternative pathway that avoids electrification of heat but delivers similar levels of abatement may include the installation of 16 million hydrogen boilers.

The overall annual cost in 2050 to achieve a net-zero pathway that results in just 4 $MtCO_2e$ from the buildings sector is estimated to be £15 billion in 2050 (in real 2018 prices) (compared with £10.5 billion in 2050 for an 80 per cent emissions reduction pathway), with an average sector-wide abatement cost of £155/tCO_2 (CCC, 2019b). In terms of timing, low-regrets action (i.e. that is relatively low-cost and provides relatively large benefits) such as energy efficiency need to ramp up considerably from now. The rollout of heat pumps needs to begin between 2030 and 2035, with the precise timing depending on whether the heat pumps will be hybrid or installed on the basis of only providing electrified heat. The latter option would be sooner because the technology would not require changes to the gas grid that are required to fuel a hybrid heat pump.

The amount of emissions from non-residential buildings is considerably less than from the residential sector. Under the CCC's Core scenario, non-residential emissions need to be just 2.9 $MtCO_2e$ in 2050, declining to 0.6 $MtCO_2e$ under the Further Ambition scenario. Irrespective of how much emissions need to be reduced, the mitigation measures are broadly similar to those needed in the residential sector – increased energy efficiency, more deployment of heat pumps, and low-carbon heat networks. The latter will need to be fully deployed by 2050, while heat pumps must replace gas-fired heating in non-residential buildings by 2045. However, the CCC calculates a slightly lower cost for non-residential buildings of £95/tCO_2.

The role of carbon pricing in reducing emissions from the buildings sector

Electricity consumption is subject to a carbon price under the EU emissions trading system (ETS) and the Carbon Price Floor in the UK. But although the price of electricity reflects the carbon content of the fuel mix, this is not the case for households currently on fossil fuel-based heating systems. Energy use in the home also faces a reduced rate of VAT (5 per cent instead of 20 per cent), which is effectively a subsidy. Consequently, without an effective carbon price natural gas is artificially cheap (Oxford Energy, 2016).

Research conducted by the Energy Systems Catapult shows that the carbon policy costs for electricity are largely offset by this VAT subsidy, resulting in an effective carbon price of just £8/tCO_2, while for gas the size of the overall subsidy (i.e. the negative carbon price) is £-33/tCO_2. The amount varies by user group: households pay a combined carbon tax on gas equivalent to £-18.92/tCO_2. This compares with large energy-intensive firms paying £6.95/tCO_2, small firms paying £9.85/tCO_2 and medium-sized firms paying £21.77/tCO_2. Without the implicit VAT subsidy, current policy would result in an effective carbon price that is approximately equivalent to the targeted non-traded carbon price of £59/tCO_2e in 2013 (Advani et al., 2013).

One option is to impose VAT at its full rate on domestic gas fuel. There is a clear economic and environmental rationale for internalising the cost of carbon within gas – carbon prices help to incentivise efficiency, behavioural change and development of alternative technologies (Blyth, 2018). However, as highlighted below, there are political challenges to increasing VAT for gas. One alternative could be to flip the VAT rates, so that electricity faces VAT of 5 per cent and gas faces VAT of 20 per cent. The net impact on consumers would remain the same, but it would penalise high-carbon heat options, assuming the greater electrification of heat were powered by cleaner energy.

Carbon pricing can also play a role in reducing the levelised cost of low-carbon heat technologies such as heat pumps. Modelling by Chaudry et al. examines how a carbon price set at £50/tCO_2 and £100/tCO_2 impacts on technology cost. This work shows that the levelised cost for heat technologies dependent on fossil fuels will increase as the carbon price increases, and will fall as the carbon price drops.

For residential and non-residential buildings, we propose a starting price of £40/tCO_2 by 2020, rising to £100/tCO_2 by 2050, when fewer emitters will still be paying the price. This is below the anticipated net-zero target-consistent carbon price and the weighted average marginal abatement cost (£155/tCO_2) for residential building decarbonisation, but political economy constraints (see below) dictate that a medium-level carbon price that delivers the bulk of emission reductions, but not full decarbonisation, will be necessary. In contrast to residential buildings, fuel poverty concerns for non-residential buildings carry less weight and so the 2050 carbon price can accurately reflect the full average abatement cost of £100/tCO_2.

Political economy issues around reducing emissions from buildings

The reduced VAT rate for gas reflects a persistent and inherent tension between the economic interests of businesses, consumer welfare and decarbonisation policy. While wealthier households produce more carbon emissions in absolute terms (due to greater overall consumption [Jenkins, 2019]), carbon pricing on gas and electricity can have regressive impacts on low-income households as they spend proportionally more of their income on energy use – particularly for heating their homes – and often live in less energy-efficient housing than better-off people (Advani et al., 2013). A carbon price on domestic energy does therefore raise genuine fuel poverty concerns.

Until affordable low-carbon alternatives are available, gas suppliers can pass through the cost to consumers with relatively little impact on demand (Frerk and MacLean, 2017). Where consumers do reduce their gas usage, this may be at the expense of their comfort and wellbeing.

Taxing household energy use therefore faces challenges of political feasibility. Options to prevent regressive impacts could be to reduce other energy taxes or recycle the revenue, which could be spent on improving the energy efficiency of low-income households' homes (Bowen, 2011), to reduce energy demand and therefore bills.

It is important to remember that while a carbon price can increase bills, the majority of expenses in a household bill reflect costs unrelated to climate policy. Analysis by the CCC shows that bill impacts associated with the shift to renewable energy have been more than offset by energy efficiency measures. Gas and electricity use have fallen by 23 per cent and 17 per cent respectively since 2008 through improved appliance, lighting and boiler efficiency, driven through minimum standards (CCC, 2016). This has saved the average household £290 a year and suggests that key barriers to increasing the price of electricity are political, rather than a material risk of increased fuel poverty. Looking towards a net-zero economy, the CCC's analysis suggests the bills will still be lower in 2030, even though the amount bill payers pay towards the rollout of low-carbon power will rise from £7 billion a year to £12 billion a year between now and 2030 (CCC, 2019a). Moreover, while there are instances of carbon pricing increasing bills, Grubb (2018) finds that in fact countries that have had higher average overall prices for energy since the 1970s have spent a lesser proportion of their income on energy, while those that maintained lower prices have spent more.

One alternative to a carbon price, put forward by Frerk and Mclean (2017), is a subsidy on low-carbon heat, which could be recovered through alternative tariff structures such as a protected block tariff where the costs of subsidies are only recovered on bills where consumption is above a certain level. A carbon price with a carbon dividend or rebate scheme would achieve a similar outcome.

All low-carbon heat solutions also require some changes to customers' heating systems in their home. The physical disruption involved in building underground heat networks, replacing household gas boilers or upgrading low voltage electricity networks should not be underestimated.

Complementary policies for the buildings sector

Carbon pricing should be part of a broader set of policy interventions for the buildings sector – a sector in which technologies to deliver net-zero do exist, but where as-yet this potential is unmatched by political will.

The Government's recent announcement to end fossil fuel heating in new-build homes from 2025 makes it even more pressing to build a compelling business and consumer proposition around low-carbon heating and the need for a higher carbon price to encourage the uptake of heat pumps. Complementary policies need to include more stringent regulation and enforcement of building efficiency standards and a national upskilling programme within the supply chain that will install many of these measures.

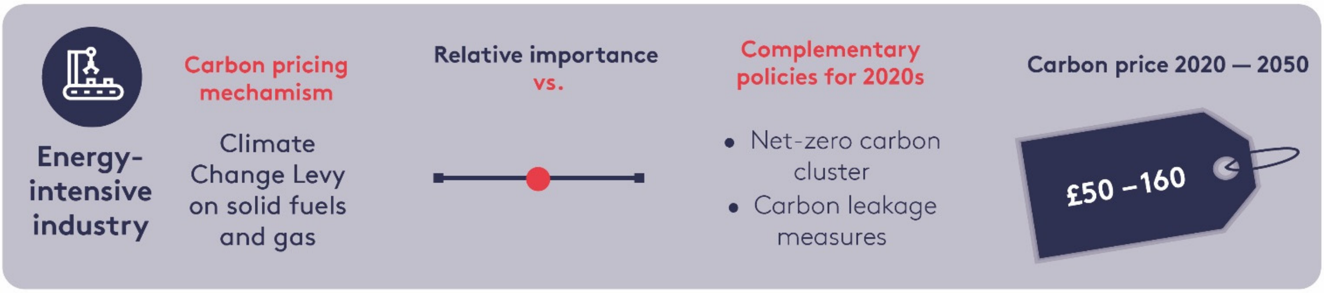
Significant funding will be required for the system costs associated with repurposing the gas grid for hydrogen, and for helping to reduce the upfront costs of heat pumps. Additionally, consumer preferences need to be better understood: awareness campaigns will be needed to generate public acceptability and secure buy-in regarding the need to transition away from conventional gas boilers to new technology. Long-term certainty over the future regulatory and governance framework for low-carbon heat is crucial. This includes technologies currently omitted from existing support frameworks such as hydrogen.

For decarbonising non-domestic buildings, further measures are required in addition to a carbon price. This involves strengthening the existing Energy Savings Opportunity Scheme and increasing access to capital through schemes such as the Salix Energy Efficiency Loan Scheme; both incentivise reduced energy demand, complemented by buildings regulation and electricity demand reduction efforts. In contrast, due to its focus on a limited number of technologies, the Renewable Heat Incentive is unlikely to be an effective instrument to effect the system-wide changes required to fully decarbonise the buildings sector, particularly if a hybrid pathway is adopted. This is supported by research by Rooney et al. (2018).

7. Industry

Key points and recommendations

- The carbon price faced by industry must become broader and more uniform. This carbon price could be levied by reforming the existing Climate Change Levy, raising its level and charging it according to the carbon content of fuels.
- For energy-intensive sectors a carbon price is still warranted to make the biggest polluters pay. A price starting at £50/tCO_2 by 2020, rising to £160/tCO_2 by 2050, would ensure equivalence between positive and negative emissions, on which the sector will depend. (Non-energy intensive industry is dealt with in Section 6 above, in the discussion on non-residential buildings.)
- Exemptions through Climate Change Agreements should be phased out or made consistent with a net-zero target.
- There should be no further levy on electricity or transport fuels, which are subject to their own carbon price.
- In energy-intensive sectors such as steel and cement, regulatory measures and technology support may be more effective for completing their decarbonisation than the very high carbon price that would be required.
- For selected trade-exposed sectors support measures may have to be strengthened to protect their international competitiveness. However, competitiveness concerns will abate as more and more countries move to a net-zero trajectory.



Emissions performance of industry

The industrial sector in the UK is diverse and includes sub-sectors such as steel, cement and chemicals refining. Emissions from the sector have decreased by almost 52 per cent since 1990, with reductions averaging 3 per cent annually from 2009–2016. However, in 2017 emissions actually rose by 1 per cent and the sector now accounts for 21 per cent of the UK's total greenhouse gas emissions (CCC, 2019b).

The CCC's fifth carbon budget assessment report (November 2015b) suggests that industrial emissions can be reduced from their 2014 level of 109 MtCO_2e to 88 (81–94) MtCO_2e in 2030, and to 65 (47–74) MtCO_2e in 2050. This requires an initial emissions abatement of 2 MtCO_2e per year over the period 2020–2030, and 1–2 MtCO_2e per year from 2031 to 2050.

The CCC's report to Parliament on net-zero (CCC, 2019a) updated this estimate: the CCC now suggests that under its Core scenario emissions could be reduced to 56.6 MtCO_2e in 2050, and under its Further Ambition scenario to as little as 9.8 MtCO_2e by 2050. The difference between the two scenarios reflects the new technological pathway to a net-zero industrial sector.

The path to a net-zero industrial sector

It is important to note that the path to net-zero includes and utilises many existing technologies. The technologies that the CCC presents under its Core scenario to meet the 80 per cent emission reduction target consist of: energy efficiency, which accounts for 5 $MtCO_2e$ of annual abatement in 2050; greater resource efficiency, representing 5 $MtCO_2e$ of abatement in 2050, carbon capture and storage (CCS) for the ammonia and cement sectors, delivering 6 $MtCO_2e$ of abatement in 2050; electrification of low temperature heating processes, contributing 1 $MtCO_2e$ of abatement; and reduced methane leakage and further use of biomethane, delivering 4 and 1 $MtCO_2e$ respectively (CCC, 2019a). The path to net-zero involves raising expectations of these existing measures, particularly for the use of CCS, while achieving even deeper abatement relies on the anticipated availability of hydrogen as a fuel-switching option.

To deliver net-zero, the CCC expects abatement from CCS to increase almost fourfold from the Core scenario to 22 $MtCO_2e$. Using hydrogen and electrification for decarbonising industrial heat and off-road machinery has the potential to abate a further 23 $MtCO_2e$. Greater resource efficiency, further CCS used for fuel combustion, and reduced carbon leakage deliver another 9, 5 and 4 $MtCO_2e$ respectively. A net-zero pathway that deploys these technologies reduces industrial emissions from 56.6 $MtCO_2e$ under the original 80 per cent emissions reduction target to 9.8 $MtCO_2e$. It is expected to cost £8 billion per year, with an average sector abatement cost of £120/tCO_2e. This can be broken down as follows: £100/tCO_2e for decarbonising iron and streel, £95/tCO_2e for cement and £120/tCO_2e for stationary combustion (CCC, 2019a). The overall cost of achieving a net-zero pathway for industry is anticipated to be £7.7 billion per year, considerably more than the £0.3 billion per year under an 80 per cent reduction pathway.

It is anticipated that these measures are achievable by 2050 but this is contingent on certain technologies achieving ambitious milestones on the way. For example, CCS needs to be deployed by 2025. For those processes where CCS is not applied, it is assumed that hydrogen fuel switching and electrification of process heat will also begin in 2025.

Despite the deployment of these technologies it is expected that there will still be residual emissions from industry. It is unlikely that the industrial sector will ever reach gross-zero emissions, so any residual emissions may need to be addressed through procuring negative emissions from other sectors.

Demand-side measures for industry

Demand-side energy reduction measures offer high abatement potential, and often at a lower cost than supply-side measures. These types of measures should be encouraged. Examples include reduced demand for industrial products and primary resources as a result of an increasingly circular economy (involving reuse, recycling and replacement of products), which reduces CO_2 emissions by reducing the production of virgin materials (McKinsey and Co., 2018). Also, light-weighting (i.e. replacing heavy with lighter weight materials such as carbon fibre in the transport sector to improve fuel efficiency [Ricardo-AEA, 2013]) can reduce the demand for steel, while cement can be replaced by materials such as wood.

The role of carbon pricing in reducing emissions from industry

The industrial sector requires a combination of energy efficiency, demand-side measures, and major breakthrough technologies that come with relatively high capital costs and are thus difficult to commercialise. The EU emissions trading system has the potential to be an effective policy instrument to drive emissions reductions and low-carbon innovation. For example, although cap-and-trade programmes have tended to encourage polluters to adopt existing abatement technologies – with little effect on innovation – new evidence suggests that the EU Emissions Trading System (EU ETS) may have bucked this trend and encouraged innovation rather than adoption (Calel, 2018).

However, EU ETS prices are not sufficiently and consistently high or stable to support the development of breakthrough decarbonisation technologies. Even with substantial price rises, free allocation of permits under the ETS has so far acted as a derogation from internalising the full cost of emitting.

This view is echoed by industry, which asserts that the price signal in itself is not enough to develop new low-carbon process technologies, while increased prices can be detrimental to companies in the short term (Hildingsson et al., 2018). As raising prices can result in prices becoming too asymmetrical across jurisdictions, there is a question over whether industry will relocate to countries where carbon prices are lower, causing carbon leakage (see also 'Political economy issues' below).

Additionally, sectors such as steel and cement suffer from both technological lock-in in carbon-intensive processes, and from low price elasticity. This could mean that even carbon prices that are much higher than at present will have little effect on these sectors' emissions. The result of price asymmetry and low elasticity may result in organisations losing market share to domestic competitors with a lower carbon intensity and to international competitors that are subject to weaker regulatory environments.

The low price elasticity derives from there being limited substitution options from less carbon-intensive materials. For example, the only material that matches the strength of steel for manufacturing uses is aluminium, which is currently highly power-intensive (furthermore, recent global increases in aluminium production have been powered by coal generation in China). Wood can substitute for steel in construction, but this raises questions both of wood availability and of reconfiguring construction systems to include much more wood.

Consequently, producers can pass through carbon prices to end users with little impact on demand. As discussed above, the industrial sector is also highly competitive and faces leakage concerns. Therefore, there is a greater challenge in using carbon pricing to shift the dial in this sector compared with others, due to high levels of cost pass-through and competitiveness issues (Material Economics, 2018). Other regulation-based measures will be required to accelerate the path to decarbonisation – probably on an international basis and supported by R&D. Therefore until technologies exist to fully abate the industrial sector, the balance between a price on carbon and complementary policies is tilted towards the latter.

Nevertheless, a higher carbon price could be levied by reforming the existing Climate Change Levy, raising its level and charging it according to the carbon content of fuels, with exemptions through Climate Change Agreements being phased out.

A price aligned with the central shadow carbon price value would be sufficient for the industrial sector. This would start at £50/tCO_2 by 2020, rising to £160/tCO_2 by 2050 and would ensure equivalence between positive and negative emissions, on which the sector will depend. This price level is derived from the marginal abatement cost of technologies needed to reduce emissions to zero mentioned above, including CCS and stationary combustion. Although some abatement measures cost well in excess of £160, there is no need to impose these costs since deeper emissions cuts can be achieved via negative emissions at lower cost.

Political economy issues around decarbonising industry

Historically, industry has been a politically sensitive sector because, in many cases, it competes in global markets. This generates competitiveness and carbon leakage risks and so industrial sectors that are exposed to international competition will be more difficult to transition to net-zero than those that are not. Competitiveness issues remain a serious obstacle to implementing much higher carbon prices.

Sub-sectors such as glass, fertilisers and paper and pulp are more exposed to competitiveness risks than are fabricated metals, plastic products or ceramics, due to the high trade intensity and significant share of imports of manufactured products from countries facing relatively low electricity prices (Cambridge Econometrics, 2017). This exposure has a material impact on the extent to which countries will and can implement high carbon prices in order to develop low-carbon strategies and technologies within their industries.

Attempts to mitigate competitiveness concerns through free allocations of permits, as occurred under the EU ETS, can also have undesired distributional impacts. In most markets emitters will pass a proportion of carbon costs onto product prices and thus to consumers. As a result, emitters profit from the free allocation, while consumers bear the costs. According to De Bruyn et al. (2016), almost all sectors in the UK profited from over-allocation of emission allowances between 2008 and 2014; the cement sector saw the greatest absolute profits, while the glass and bricks sectors benefited the most relative to their size.

With this in mind, there is scope to increase the carbon price, as we describe above, while not impacting on competiveness. A carbon price is still warranted to make the worst polluters pay.

Complementary policies for the industrial sector

Although prevalence of technological heterogeneity within the industrial sector does support the argument for market-based regulatory mechanisms such as carbon pricing to encourage innovation and technology adoption (Sorrell et al., 2011), in some instances high carbon prices may not suffice, because many of the barriers to low-carbon investment are non-financial. The fact that negative-cost opportunities have yet to be acted upon also suggests that carbon prices alone will not be enough. Upfront investment costs for many zero-carbon technologies may also be too high for individual industry players to bear, especially in sectors and companies facing low profit margins. Public investment (for instance through loan guarantees or repayable advances) will therefore be important to incentivise low-carbon investment and overcome high capital cost barriers. One option could be to channel funds through the Industrial Transformation Fund.

Scaling up funding for R&D and commercialisation of abatement technologies will be of high importance. This could occur through fulfilling and enhancing funding to existing policies, such as the Government's proposed £170 million 'net-zero carbon cluster' for heavy industry (BEIS, 2018b), a £15 million call for CCS innovation funding for feasibility studies and research infrastructure, and a £20 million hydrogen supply programme (ibid.). Going forward, CCS and hydrogen are likely to require significantly more funding and policy support than they are currently receiving, both to improve the technologies themselves and to assist with their commercialisation.

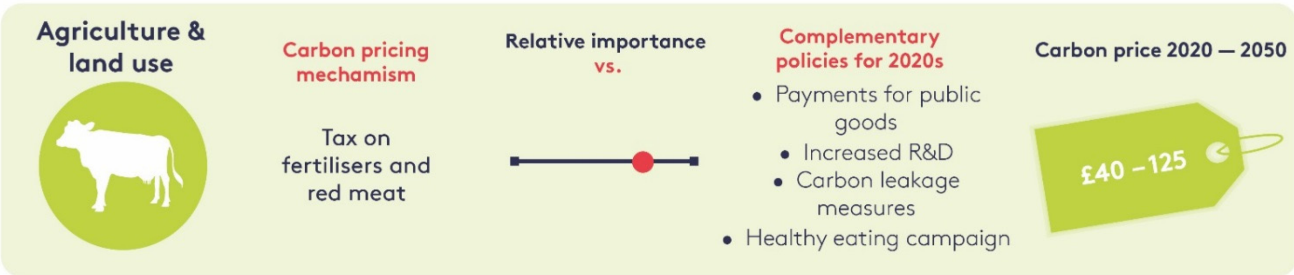
Given the technical and political economy barriers facing the industrial sector, a complementary approach that introduces low-carbon standards, encourages circularity and favourable cultural dispositions within firms will be required alongside measures to prevent carbon leakage and maintain international competitiveness.

Compensatory measures should be targeted to specific subsectors most at risk of carbon leakage, but gradually phased out over time as other countries also begin to move towards a net-zero carbon trajectory. A more stringent approach to free allocation of permits could be complemented by the introduction of border carbon tariffs as an additional measure to facilitate deep decarbonisation while mitigating against the risks of carbon leakage and loss of industrial competitiveness.

8. Agriculture and land use

Key points and recommendations

- Greenhouse gas emissions in agriculture and land use are currently under-regulated. However, the reform of the agricultural support system, which will be required after Brexit, will provide an opportunity to create a zero-carbon sector. Land use measures such as planting trees can also deliver some of the domestically-sourced negative emissions that a net-zero target will require.
- Policy interventions need to be holistic and deliver a wider set of environmental and societal objectives (e.g. related to nature conservation, health and food security) to create a sector that is more environmentally sustainable in other ways too. A new payment-for-ecosystem-services scheme will be better placed than a carbon price to deliver some of the key farming efficiency and land use improvement measures needed in a net-zero world.
- However, a carbon price on red meat products and fertilisers starting at £40/tCO_2e in 2020 and rising to £100/tCO_2e in 2050 would incentivise many mitigation actions. More expensive measures, such as grain legume rotations, may need complementary regulation or financial support.



Emissions performance of agriculture and land use

Agriculture contributed 10 per cent of the UK's greenhouse gas emissions in 2017 (45.6 MtCO_2e), with 56 per cent of these emissions being methane (primarily from livestock farming) and 31 per cent nitrous oxide (primarily from arable farming) (BEIS, 2019b). Emissions from agriculture have been on a general downward trend, falling by around 16 per cent since 1990. By contrast, the land use sub-sector acted as a net sink, reducing the UK's emissions by 9.9 MtCO_2e in 2017; in 1990 land use was a small net emitter, contributing 0.3 MtCO_2e. The switch from emitter to sink has been driven by reduced rates of conversion of land to cropland, increased uptake of carbon dioxide by trees as they reach maturity, and less intensive agricultural practices (ibid.).

The path to net-zero agriculture and land use

The agriculture and land use sector includes emissions from agricultural soils, stationary combustion sources and off-road machinery, in addition to emissions and sinks from forest land, cropland, grassland, rural settlements and harvested wood products. In its Core scenario, the CCC projects an aggregate 7.5 MtCO_2e could be abated from the sector – 4.9 MtCO_2e from agriculture and 2.6 MtCO_2e from land use. With policies sufficient to support a net-zero target this could increase to a combined reduction of 40.5 MtCO_2e, with 23.8 MtCO_2e remaining (17.2 MtCO_2e abated and 26.3 MtCO_2e of residual emissions in agriculture, and 23.3 MtCO_2e abated with a net sink of 2.5 MtCO_2e in land use).

There are four core categories of abatement measures for the agriculture and land use sector (CCC, 2019b), which we describe below.

Efficient farming techniques

More efficient farming techniques include: improved cattle and sheep health to reduce methane emissions using nitrate as a feed additive to reduce enteric emissions; improving nitrogen use efficiency for crops through measures such as loosening compacted soils; employing precision farming technologies to deliver nutrients and water more effectively (Moran et al., 2010; Balafoutis et al., 2017); breeding more nitrogen-efficient crops; and including grain legumes in rotation with other crops (for example, beans and peas require low levels of nitrogen [Eory et al., 2015]).

While all of these actions would be needed even to meet an 80 per cent emissions reduction target, the CCC's Further Ambition scenario sees even greater uptake of these measures to reach a net-zero target (CCC, 2019a).

Improved land-use management

Land can be better managed by increasing activities that reduce greenhouse gas emissions and sequester carbon dioxide, including by increasing the area given to hedgerows and forestry on farmland, afforestation, restoration of peatlands and planting of energy crops.

In addition to implementing these practices on currently available land, the CCC projects in its Further Ambition (net-zero) scenario that 25 per cent of land currently used for agricultural production could be released for abatement and sequestration opportunities, through a combination of improved agricultural productivity, redistributing some livestock from upland grazing areas to other grassland, encouraging a shift to healthier diets (see below), reducing avoidable food waste by 20 per cent (addressed in Section 9 below) and moving 10 per cent of horticultural crops into indoor production systems (CCC, 2019a).

Increased efficiency of farm vehicles and processes

Efficiency in this area can be achieved through measures including the electrification of on-farm vehicles and take-up of battery-powered robotics to displace diesel-fuelled vehicles for seed drilling and fertiliser application (which currently account for 93 per cent of the emissions from machinery in the agriculture sector); increasing energy efficiency in agricultural buildings; and increasing the use of renewable energy for energy-intensive processes such as drying and storage of arable crops (including through on-site energy generation). Analysis from the CCC (2019b) suggests these activities could reduce emissions from on-farm vehicles and processes by 90 per cent, abating 4 $MtCO_2e$ (2 $MtCO_2e$ more than in the CCC's Core scenario, predicated on higher uptake than that envisaged by the CCC).

Dietary change

Dietary change is not included in the CCC's Core scenario, but the potential of a diet based more heavily on plants than on animal products to reduce agricultural emissions and create sequestration opportunities is now widely acknowledged (see, for example, Poore and Nemecek, 2018; Scarborough, 2014; Wirsenius et al., 2011; Kehlbacher et al., 2016; CCC, 2018b). The challenge lies in the social and cultural change underpinning a widespread shift to such a diet.

A 20 per cent reduction in the consumption of red meat and dairy would both reduce the number of enteric emissions from livestock by causing an 8 per cent reduction in the number of cattle and sheep, and free up land for afforestation, restoration and other sequestration options (CCC, 2019b). The CCC recognises in its speculative abatement options that the potential emissions reductions could be even greater were there to be more significant dietary change towards, for example, the level of meat consumption recommended in the UK Government's EatWell Guide which stipulates a reduction in the consumption of beef, lamb and dairy, much higher than the CCC's recommended 20 per cent.

The role of carbon pricing in agriculture and land use

The applicability of carbon pricing to the agriculture and land use sector differs across the four core categories of abatement action required, as discussed below. However, overall we recommend a price starting at the lower range of the recommended shadow carbon price, at £40/tCO_2e in 2020 and rising to £125/t by 2050.

Carbon pricing and farm efficiency measures

While previous CCC analysis has suggested that costs of farm efficiency measures vary greatly across the different types, many come at a net benefit to farmers (CCC, 2018b): in its net-zero advice, the CCC finds average savings from improved agricultural productivity measures of £55/tCO_2e, while land use measures have an average cost of £85/tCO_2e (CCC, 2019a).

The negative cost of many of the key efficiency improvements for livestock and crop farming suggests that cost is not the primary barrier to their uptake, so a carbon price is unlikely to be the most effective measure to incentivise their use (Kesicki, 2011). Instead, regulation or provision of training opportunities to facilitate their use may be justified. The CCC also recommends targeted R&D funding to develop farming efficiency technologies further (CCC, 2019b).

Applying a carbon price to incentivise efficiency practices would also be challenging for practical reasons, due to the difficulties in monitoring, reporting and verifying emissions from the land use sector. The challenge arises from a lack of certainty around the emissions associated with certain activities or change in activities, and their interactions with different climatic conditions (Nesbit et al., 2018). Quantifying emissions is based on an estimate taken from a sample of farm holdings across the UK as due to the large number of micro-, small- and medium-sized enterprises it is difficult to gather data from all farm holdings (ibid.). These challenges, combined with the fact that most agricultural emissions are in the form of methane or nitrous oxide, mean that it is difficult to arrive at a clear estimate of CO_2-equivalent emissions for each farm and to monitor the impact of different abatement measures. Carbon pricing is therefore unlikely to be an appropriate tool to incentivise the uptake of farm efficiency measures. However, a tax on fertiliser can provide a visible price signal to complement regulatory measures that encourage more efficient nitrogen use and will be more easily accounted for than a tax on individual farm emissions across all processes.

Carbon pricing and land management

Similar accounting challenges apply to switching land use away from farmland or other uses towards sequestration activities such as afforestation. In addition, it is difficult to apply a price to land on the basis of potential alternative uses of that land, as this would require an assessment of all of the possible alternative uses and a value-judgment on which would be the most appropriate use for each parcel of land, a complex, costly and imprecise exercise. A market for negative emissions (as discussed in Section 3 above) or a positive incentive scheme would allow farmers and landowners to make their own decisions over how best to use their land, based on a comparison of profitability of the land from agricultural use compared with potential sequestration opportunities. An incentive scheme could be a payment-for-ecosystem-services scheme, whereby farmers receive payments for providing public goods services such as protecting and enhancing biodiversity (Lightfoot et al., 2017).

The CCC (2019a) notes that preparation of a post-Common Agricultural Policy framework, which will be required after the UK leaves the EU, represents the most significant opportunity to target non-CO_2 emissions in agriculture. The CCC's proposals for this framework include: development of a new regulatory baseline reflecting the 'polluter pays' principle; and allocating public money for public goods through an Environmental Land Management Scheme.

Carbon pricing, efficiency and electrification

Carbon prices in the electricity, buildings and transport sectors will help to incentivise greater uptake of renewable electricity for on-farm vehicles and processes, and energy efficiency improvements. However, this will have carbon leakage implications, as the pig, poultry and dairy sub-sectors are energy-intensive and highly exposed to international trade. Pig farmers have been impacted by reduced trade competitiveness in the past, when the UK government implemented higher animal welfare standards for pigs (CCC, 2013). The fertiliser sector will also be impacted by higher energy prices, although fertiliser production is less energy-intensive in the UK than the EU27 average as its main energy source is natural gas as opposed to coal (Sato et al., 2014).

Carbon pricing and dietary change

The CCC recommends a series of ‘nudge’-type strategies to reduce meat consumption, such as increasing the availability of plant-based food options in schools and hospitals, and public awareness campaigns. While such measures are important, analysis by Chatham House suggests that “interventions to change the relative prices of foods are likely to be among the most effective in changing consumption patterns” (Wellesley et al., 2015). Several recent studies have shown that from both an environment and a health perspective, red meat is not priced according to its social cost and therefore we recommend a tax on red meat products that could deliver a triple benefit of reduced enteric greenhouse gas emissions, freeing up agricultural land to be used for sequestration opportunities, and improved health outcomes (Bowles et al., 2019; Springmann, Mason D’Croz et al., 2016; Springmann, Godfray et al., 2016; Springmann et al., 2018).

Beef is also a trade-exposed industry, but given that the purpose of the tax is to incentivise behaviour change, it could be imposed at the point of sale rather than point of origin, allowing UK beef to compete on an equal footing with imports.

Political economy issues around decarbonising agriculture and land use

Major structural changes are underway in how subsidies are delivered to farmers because of the UK’s forthcoming withdrawal from the Common Agricultural Policy (CAP) as a result of leaving the EU. Farmers currently receive large direct subsidies under the CAP through measures targeting income support, market volatility and rural development (European Commission, n.d.). The UK Agriculture Bill, which is currently before Parliament, seeks to reform this subsidy scheme by directing payments towards farmers for providing services such as “air and water quality, public access and productivity”, while phasing out direct subsidies (House of Commons Library, 2018b). This approach could deliver significant emissions abatement in the agricultural sector (CCC, 2019b).

However, CAP payments made up 55 per cent of UK farm incomes in 2014 (Institute for Government, 2019), so it will be important to ensure that the new policy is communicated clearly to farmers in advance of its enforcement and that information and training are provided into how to undertake activities that would be eligible for payment under the scheme. Land use change that reduces emissions through afforestation may be associated with biodiversity loss if care is not taken to ensure a mix of tree species: illustrated, for example, by a *Nature* study that found that cropland could support more varieties of birds and bees than single-species forests (Hua et al., 2016). Such considerations should be addressed by the post-CAP scheme.

A tax on meat could cause affordability problems, particularly for low-income households, who already spend a higher percentage of their incomes on food products than better-off households (Scarborough et al., 2014). Further, emissions mitigation action in the land use sector could increase competition for land, also impacting on food prices. For example, carbon sequestration, planting crops for bioenergy, afforestation and reforestation all restrict the amount of land available for agricultural expansion or other uses (Smith and Bustamante, 2014). The IPCC projects that stringent forest conservation and demand for biomass for energy and biofuels could increase food prices by between 52 and 82 per cent by 2100. Appropriate redistributive policies are therefore necessary to prevent food insecurity.

Any advice to reduce meat consumption should also occur in line with health guidelines, as reducing meat intake, while offering benefits such as reducing consumption of saturated fat and increasing consumption of fibre (Scarborough et al., 2014; Aleksandrowicz et al., 2016), can also lead to an increase in sugar consumption and reduced consumption of some essential micronutrients (Payne, 2016).

The CCC found that dietary change would have no additional cost to households. Given the desire to shift consumer behaviour towards reduced red meat consumption and the significant combined health and environmental benefits to individuals of reduced red meat consumption, a relatively high carbon price is justified so long as it is accompanied by redistributive mechanisms to prevent food insecurity. We recommend a carbon price of £40 per tCO_2e in 2020 (£0.66/kg beef and £1.16/kg lamb), rising to £125 by 2050 (£2.05/kg beef and £4.13/kg lamb) in 2050[8]. An even higher price may be justified if taking into account the health co-benefits of meat reduction (Springmann, Godfray et al., 2016), however that is beyond the scope of this report.

Complementary policies for the agriculture and land use sector

As outlined above, a carbon price can play a key role in improving vehicle electrification and efficiency measures (through the impact of prices in the power, transport and buildings sectors), and in dietary change through a meat tax. However, significant changes to farming practices and land use will require alternative policies, including those described below.

A payment-for-public-goods (which includes ecosystem services) scheme could be introduced. The CCC identifies an opportunity in a post-Brexit world for the UK to replace the current CAP subsidy system "with a system of support that delivers a better quality of environment, sustaining food production, and other economic, social and environmental benefits" (CCC, 2018b). Direct subsidies could be replaced with a payment-for-ecosystem-services model.

Compensation or anti-carbon leakage measures could be targeted specifically at the pig, poultry, dairy and fertiliser sub-sectors (Sato et al., 2014). Compensation policies can also be strategic – for example, rather than implementing a lower carbon price for trade-exposed sectors (which would undermine any mitigation incentives in these sub-sectors), policies could assist these sub-sectors to implement greater efficiency measures to reduce their costs while also reducing emissions. On this principle, UK government policies have enabled pig and poultry farmers to receive a 90 per cent discount on their energy bills if they meet certain energy efficiency targets (CCC, 2013).

Expanding the scope of R&D and other policies targeting farming efficiency measures would reduce emissions from enteric digestion and nitrogen use, complemented by greater regulation on fertiliser use to incentivise uptake of key measures such as precision farming technologies (Defra, 2018b).

Greater promotion of healthy eating could be made, for example, through the Government's 'EatWell' guidance (CCC, 2018b), complemented by redistributive schemes to protect food security.

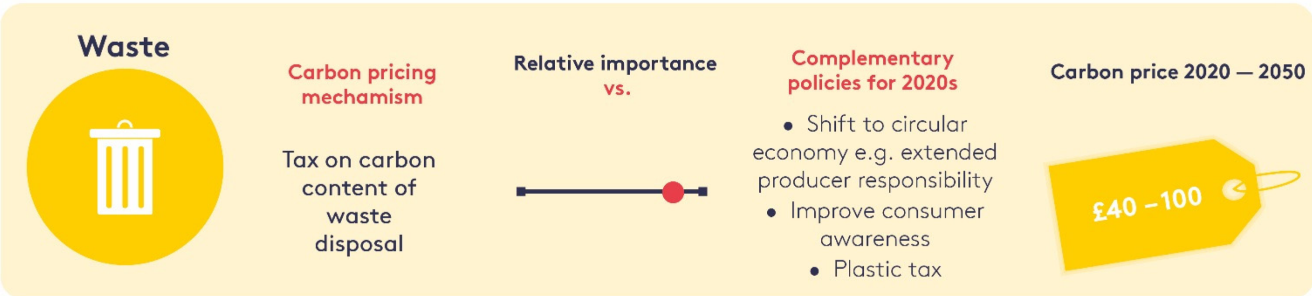
Plans and funding for afforestation could be expanded, with an aim to achieve 50,000 hectares of new woodland per year (CCC, 2019b). More sequestration options could be made available to the land-use sector, which, could be incentivised through a market for negative emissions, as set out in Section 3 (Figure 5) above.

8 2016 emissions intensity of meat figures sourced from UN Food and Agriculture Organization (2016).

9. Waste

Key points and recommendations

- Carbon pricing in the waste sector needs to be embedded in a wider waste strategy that also discourages waste and promotes a circular economy. There needs to be awareness of potential environmental trade-offs, for example in waste-to-energy solutions that can have local air quality implications.
- The existing landfill tax has been successful in discouraging landfilling and associated greenhouse gas emissions. The waste sector now needs a broader-based carbon price, starting at around £40/tCO_2 by 2020 and rising to £100 in 2050, structured to specifically discourage greenhouse gas emissions, rather than to decrease the weight or volume of waste.
- A strategic move towards carbon-based targets and producer responsibility for waste may offer an effective framework through which to measure and reduce greenhouse gas emissions through carbon pricing.



Emissions performance of the waste sector

The waste sector includes landfill sites, waste incineration and waste water, and contributed around 4 per cent of the UK's greenhouse gas emissions in 2017. Emissions from the waste sector fell by 69 per cent between 1990 and 2017, due to factors including a reduction in the amount of biodegradable waste going to landfill (due largely to improved collection and use of food waste), and an increase in the amount of landfill gas used for energy (BEIS, 2019b). The majority – 92 per cent – of greenhouse gas emissions from the waste sector are methane, with some nitrous dioxide arising from waste water and biological treatment emissions, and some carbon dioxide from waste incineration (BEIS, 2019b). Of this, landfill emissions – which are almost entirely methane – account for around 70 per cent of the waste sector's total emissions.

Significant efforts are already underway to manage the waste sector to address environmental externalities, of which greenhouse gas emissions are only one component. Other externalities targeted by waste management strategies include pollution of air, soil and water; noise; odour and reduced visual amenity, all of which have implications for the health and comfort of communities and for biodiversity (Eshet, 2006; HM Government, 2018a).

The path to net-zero in the waste sector

The CCC recognises four key categories of abatement options for the waste sector (CCC, 2019b):

- **Waste prevention,** through reducing plastic packaging, improving product design to expand product lifespan and recyclability, and promoting behavioural shifts away from fast fashion and unnecessary food purchases. By improving packaging and product design at the start of a product's lifecycle, there can be easier collection, sorting and high quality recycling of waste (Energy Transition Commission, 2018).

- **Waste diversion,** through greater reuse and recycling, which in turn reduces emissions from the extraction of resources from the natural environment, reduces energy needs compared with producing products from raw materials, and reduces the amount of embedded carbon released into the atmosphere (HM Government, 2018a). Reducing demand for plastics used in packaging could see plastic use fall by 35 per cent each in cars and buildings value chains, 20 per cent in packaging, and 5 per cent in remaining product groups (Energy Transitions Commission, 2018). Ensuring high recycling rates also requires adequate sorting technologies. Examples include magnetic separation for ferrous metals, and new artificial intelligence-based technologies.
- **Waste management,** through methane capture technologies and improved landfill covering to reduce emissions at landfill sites, in addition to utilising more efficient waste treatment measures such as anaerobic digestion and advanced mechanical biological treatment (which combine sorting technology with biological treatment measures such as composting or anaerobic digestion).
- **Improved waste water handling,** including operational measures such as covering sludge thickening tanks and ensuring microorganisms have enough time to consume nitrous oxide emissions and greenhouse gas capture and treatment measures, including biological processes to oxidise methane into carbon dioxide.

These key actions the CCC proposes to reduce waste sector emissions rely primarily on preventing and diverting waste. Under its Core scenario (aligned with an 80 per cent emissions reduction target), the CCC envisages waste sector emissions could fall by 12.2 $MtCO_2e$ from 20.3 $MtCO_2e$ in 2017 to 8.1 $MtCO_2e$ by 2050. Key assumptions in this scenario are that biodegradable waste streams (such as kitchen and garden waste) would be eliminated in England, Wales and Northern Ireland by 2030 and in Scotland by 2021, and recycling rates would increase by 65 per cent in England by 2035 and by 70 per cent in Scotland and Wales by 2025 (with no change in Northern Ireland) (CCC, 2019b).

Under its Further Ambition (net-zero) scenario, the CCC envisages an additional 1.2 $MtCO_2e$ could be abated by increasing ambition, including by making separate collection of biodegradable domestic waste mandatory by 2023, reducing all food waste by 20 per cent, eliminating key biodegradable waste streams and increasing overall recycling rates to 70 per cent everywhere by 2025. In addition, waste-water treatment would be improved to reduce methane and nitrous oxide emissions from waste water handling by 20 per cent by 2050 (CCC, 2019b).

While not addressed in detail in the CCC's net-zero advice or technical report (CCC 2019a; 2019b), a key concern for the waste sector is the growing use of plastics, with global plastic use expected to increase from 320 Mt in 2015 to 1,300 Mt by 2100 (Energy Transition Commission, 2018). This could potentially use up one third of the entire available carbon budget compatible with a scenario where global warming is limited to 2°C above pre-industrial levels (ibid.), jeopardising the chance a achieving a 1.5°C scenario. Currently, producing a tonne of plastics emits around 2.5 tCO_2, while an additional 2.3–2.7 tCO_2 is embedded in a tonne of plastic product, which will eventually be released into the atmosphere when the product is discarded as waste. To reduce these emissions there is a need for better end-of-life management for plastics (ibid.).

The total cost of abatement in the waste sector is expected to be £110 million per year by 2050 under a net-zero scenario, compared with no additional cost under an 80 per cent emissions reduction target (CCC, 2019b). The CCC projects that alternative waste treatment approaches to landfilling (e.g. recycling) will have an abatement cost of £30–100/tCO_2e by 2050, with an overall average abatement cost of £10/tCO_2e.

The role of carbon pricing in reducing emissions from the waste sector

The landfill tax[9] has been successful to date, a carbon price has relatively low equity implications in the waste sector (see below). Therefore we recommend both a carbon-based landfill tax and a

[9] The landfill tax applies to all waste disposed of at a licensed landfill site unless the waste is specifically exempt, and is charged by weight, with two rates, currently £91.35/tonne at standard rate and £2.90/tonne for the lower rate (for inert or inactive waste).

plastic tax. As the abatement cost of recycling and alternative disposal technologies in 2050 is projected to be as high as £100 for marginal technologies, the sector should face the full shadow carbon price, beginning with £40 in 2020 and rising to £100 in 2050.

Landfill and household waste

While the UK's existing landfill tax is widely considered to have successfully reduced externalities arising from landfill, pricing emissions from waste is complex. Energy Systems Catapult explains that this is because: "waste management is not a simple two-option process which compares an emitting option (e.g. landfill) with a non-emitting option. Rather, recycling, energy recovery and other measures respond in different ways to price signals, and it is challenging to optimise a single price for the whole hierarchy" (quoted in Blyth, 2018). Even within a single option such as landfill, accounting for greenhouse gas emissions is difficult because the greenhouse gas content of landfill materials has been dropping over time as other waste management techniques have been introduced (ibid.; Defra, 2011). This also changes the economics of converting landfill gas into power (Blyth, 2018).

Nor is there any standard way in which the landfill tax is passed on to households. Local authorities may choose to increase council tax, or reduce services in other areas to account for the increased costs of waste collection. Regardless, each household receives the same additional charge or reduction in services, no matter how much or little they reduce their household waste, so there is little incentive for households to reduce the amount they send to landfill (ECOTEC, n.d).

Additionally, as the landfill tax is levied based on weight rather than greenhouse gas content, emissions reductions to date have been incidental rather than targeted. Under the tax, the weight of waste going to landfill fell from around 50 million tonnes in 2001–02 to around 12 million tonnes in 2015–16 (Elliott, 2016).

The Government's recently published waste and resources strategy for England (HM Government, 2018) may provide an emerging framework through which to levy charges on the waste sector based on the carbon content of materials. One of the strategy's objectives is to more effectively estimate the carbon content of mixed waste through compositional analyses. This will help to understand and better estimate the carbon footprint of a shopping basket of consumer products. The objective is reflective of a larger movement away from weight-based targets towards impact-based targets and reporting, focusing initially on carbon and natural capital accounting.

Given the challenge associated with accounting for greenhouse gas emissions from waste, it would be impractical to attempt to levy a tax on individual households on the basis of the greenhouse gas content of their waste. Responsibility for paying the landfill tax is likely to remain with local authorities and large organisations that dispose of waste directly. However, if the price is levied based on the greenhouse gas content of the waste it could incentivise local authorities to provide the necessary services (e.g. separate food and recycling disposal) and educational materials to enable households to take a more active approach in preventing and diverting waste, based on carbon content.

As the waste sector currently falls outside the EU ETS, the strategic move towards carbon-based targets may offer an effective framework for reducing greenhouse gas emissions through a carbon price. This could be in addition to implementing a carbon price on waste incinerators, which the Energy Transition Commission (2018) suggests should be "at least as high as landfilling taxes", an idea that has some political backing. The Government's waste and resources strategy states that it will consider the introduction of a tax on the incineration of waste if its ambition to maximise the amount of waste sent to recycling, diverting it from incineration, is not met.

Promoting a circular economy

A landfill tax only addresses one component of the waste-management cycle. The pathway to emissions reduction in the waste sector is situated within the increasingly recognised concept of the 'circular economy'. The circular economy involves a shift from the current 'take–make–waste' approach to resources, whereby resources are extracted from the natural environment, made into consumable products and then disposed of once finished with, to a system where resources are kept in use for as long as possible, with the aim to extract maximum value, then to recover and regenerate products and materials at the end of their useful life (WRAP, n.d.).

Under current patterns of materials use, demand for emissions-intensive materials such as steel, plastics, aluminium and cement could increase two- to four-fold by 2050 (Material Economics, 2018). A circular economy for these materials could reduce industry emissions alone by 56 per cent. Reaching net-zero entails building on principles and policies relating to the circular economy to ensure they are optimised for greenhouse gas reduction.

The Government's waste and resources strategy for England depicts the transition to a circular economy through following the waste management hierarchy of: prevention, preparing for reuse, recycling, other recovery and disposal (HM Government, 2018). Research from the Energy Transitions Commission (2018) suggests that around 50 per cent of total abatement potential associated with the shift to a circular economy globally could be undertaken at no or very low cost.

A carbon price further up the supply chain could address some of these steps. For example, the Energy Transitions Commission (2018) finds that a global carbon price of US$60/t$CO_2$e for plastics, if imposed on producers and covering both production and embedded emissions, "would increase the price of primary plastics production by around 20 per cent on average and significantly increase incentives for recycling".

However, broader behavioural change and improvements to product design might best be addressed through public awareness campaigns and regulation (see below).

Political economy issues around reducing emissions in the waste sector

Amending the landfill tax so that it is levied on carbon content rather than weight will have limited impact on households, but may impact certain local authority areas more than others, depending on the nature of the local industry and the type of waste produced within an area. This could have implications for the local authority's capacity to provide services to its community. However, ensuring adequate services exist for separating recycling and food waste could help to minimise these impacts.

There is little research on the impacts of a plastic tax on consumers. While such a tax may increase the price of goods that are usually cheaper, it will primarily be aimed at non-essential items and would ideally encourage re-use, including potentially increasing the market for second-hand goods.

Complementary policies for the waste sector

Both the landfill tax and any prospective plastic tax are limited in scope: the landfill tax due to its indirect impact on households and a plastic tax as it focuses on only one material. Both of these taxes should be situated within a broader portfolio of policies to encourage the behaviour change needed to develop a circular economy.

The Government's new strategy *Our Waste, Our Resources: A Strategy for England* pursues the concept of a circular economy through several key principles, aimed at fulfilling the waste management hierarchy as outlined above including:

- Extending the responsibility of producers for waste, including by ensuring they pay the costs of disposing of packaging of products they put on the market.
- Taxing plastic packaging made with less than 30 per cent recycled plastic (this could be integrated into a broader plastic tax).
- Setting minimum requirements to encourage resource-efficient product design.
- Establishing a Chemicals Strategy to manage chemicals more sustainably.
- Developing 'resource efficiency clusters' to work with businesses to develop a model for resource efficiency savings. (HM Government 2018)

The strategy uses a combination of pricing and regulatory approaches to deliver a circular economy. The Government proposes an extended producer responsibility scheme, which will be operational by 2023 and which will encourage producers to make more sustainable design, production and purchasing decisions, such as through lower fees for products that are easy to reuse, repair or recycle, and penalties for those that are not. Carbon intensity standards for packaging, appliances and other manufactured products will also be important for reducing waste sector emissions.

The steps outlined in the Government's strategy would go a long way towards reducing greenhouse gas emissions in the waste sector if fully implemented, by diverting waste away from landfill and reducing process emissions through increased recycling and reduced plastic production. The strategy therefore represents best practice policy and the Government should focus on implementing the strategy's targets and increasing them over time to ensure alignment with the CCC's net-zero advice.

Public awareness campaigns and clear communication strategies from both the public and private sector can also play a key role in instigating the widespread consumer behaviour changes needed to shift away from practices such as 'fast fashion' to a more circular economy (Daae et al., 2019).

Conclusions

In its advice to the UK government on net-zero, the Committee on Climate Change has outlined one of the most ambitious emissions reduction targets in the world to date. It should be legislated as soon as possible. To be credible the new target must be accompanied by an equally rigorous and stringent policy framework.

This report has argued that a strong carbon price should be at the core of this framework. Imposing a carbon price at the proposed levels will generate revenues of approximately £20 billion per year for at least the next decade. This creates enough fiscal headroom to enhance the public acceptability of carbon pricing through appropriate redistribution of the revenues, and will help fund research into and the development of negative emissions technologies or other low-carbon projects.

Although the core technologies are known, much about the UK's pathway to net-zero remains uncertain. The numbers presented in this report present a static representation of cost and must be revised over time, allowing for behaviour change and technological and process innovation.

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