The role of bioenergy with carbon capture and storage in the UK's net-zero pathway

May 2021

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Research Report

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SUSTAINABLE RESOURCES

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Final Report
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The UCL Institute of Sustainable Resources generates knowledge that promotes the sustainable use of natural resources globally. Our multidisciplinary team produces innovative research across the topics of resource efficiency, circular economy, eco-innovation, and low carbon societies.

The research presented in this report was funded by the European Climate Foundation (ECF). We would like to thank Keith Allott, Joss Garman and Amy Mount at ECF for their comments on a draft; and civil servants at BEIS and Defra for their assistance with data and feedback on some of our early analysis. The analysis, conclusions and recommendations in the report are solely our responsibility.

Executive Summary

This report explores the potential role for bioenergy with carbon capture and storage (BECCS) in the UK's pathway to net-zero by 2050, and the implications for sustainability and policy. It analyses five scenarios of the future that include different assumptions about biomass availability, the rate of progress with greenhouse gas removals via BECCS and direct air capture, and demand for energy and other resources. The sustainability of the use of biomass in these scenarios is assessed, alongside the extent to which BECCS can deliver removals. The report also considers the implications of our analysis for government policies and regulations.

Our policy proposals build on three important principles:

1. Government policies must prioritise actions to reduce emissions. The deployment of GGRs is not an alternative to emissions reduction.
2. Our analysis has shown that action to reduce emissions should include a major emphasis on reducing demand for energy and other products. This will increase flexibility in how the net-zero target can be met, and reduce the risks of relying on GGR measures that might not deliver what they promise.
3. Any GGR measures that are required are used to balance remaining emissions across the economy as a whole. They should not be used to achieve 'carbon neutrality' for sectors such as power or surface transport that can reduce emissions to zero.

Across the five scenarios, BECCS removes between 38 and 80 million tonnes of CO_2 equivalent ($mtCO_2e$). The role for BECCS is smaller than the range in the CCC's sixth carbon budget scenarios (43.5 to 96.5$mtCO_2e$). In some scenarios, direct air capture plays a larger role than in the CCC scenarios. Not surprisingly, the largest contribution from BECCS is in an Engineered Removals scenario which assumes accelerated innovation and deployment of BECCS and direct air capture, and larger biomass resources. The smallest contribution is in a Low Demand scenario, which requires the lowest amount of removals.

The share of BECCS capacity in different sectors varies by scenario. In all scenarios, BECCS is used for power generation and/or hydrogen production. The distribution between these two sectors is very sensitive to assumptions about carbon capture rates. If a lower capture rate is assumed, BECCS tends to be deployed in the power sector.

Not all of the scenarios meet net-zero by 2050. The Reduced Removals scenario that has the highest residual emissions achieves a 95% reduction by 2050. This is largely because of delays with carbon capture technologies, including BECCS. This does not mean the net-zero target is unachievable. In principle, additional emissions reductions or removals could be deployed to close the gap.

Our analysis confirms that BECCS could play a significant role in meeting net-zero in the UK. However, it also highlights important risks associated with a net-zero strategy that relies on BECCS to deliver significant greenhouse gas removals. Two risks are particularly important:

- **Risks to timely scale up and deployment**. Past experience with carbon capture and storage (CCS) suggests that technical, economic, financial and policy uncertainties could delay the deployment of carbon capture technologies and associated pipeline and storage infrastructure. Furthermore, the significant reliance on engineered removals will increase the capacity of pipeline and storage infrastructure required.

- **Sustainability risks**. Life cycle emissions from BECCS supply chains could reduce or completely cancel its effectiveness as a method for removing CO_2 from the atmosphere. This includes the impacts of 'carbon debt': the time it takes to recover the carbon stocks lost due to bioenergy expansion. In addition, the use of BECCS at a significant scale could lead to negative impacts on biodiversity, ecosystems and the use of land. Our scenarios include converting 0.74 to 1.45 million hectares of land for bioenergy in the UK alone. This represents up to a 40% increase in agricultural land. Further biomass resources may need to be imported, which will make monitoring of sustainability more challenging.

If these risks are not mitigated successfully, there may be insufficient time to shift to other strategies to close the gap in emissions. This analysis suggests five actions to mitigate them.

- First, **reducing demand for energy and other resources** through efficiency and a more circular economy will, in turn, reduce the amount of removals required. This includes action to reduce emissions from those sectors where residual emissions are expected in 2050 (e.g. agriculture and air travel).
- Second, policy incentives are required to support a **diverse range of removal options**. This could involve the reform of carbon pricing so that its scope is extended to removals, alongside strict sustainability criteria. This will help to ensure that cheaper, less risky removal options, such as some forms of afforestation, are prioritised.
- Third, **specific policies** will be required to scale up engineered removal technologies including BECCS. Generic policies like carbon pricing are insufficient because these technologies are too capital intensive and risky. This could be achieved through contracts for BECCS deployment, which should be implemented incrementally and cautiously. Large facilities on the scale of Drax should not be supported straight away.
- Fourth, **policy support for BECCS should be conditional**, and subject to rigorous evaluation and performance review. This will allow costs, technical performance, life cycle emissions and sustainability to be assessed before scaling up further. If BECCS is not delivering removals effectively, the government should increase efforts to reduce residual emissions and shift support for greenhouse gas removals to other options.
- Fifth, **regulations for biomass sustainability need to be reformed** and extended to cover the full supply chain: from biomass supply to energy production, and the capture of CO_2 for use or storage. It is misleading to assume carbon neutrality at the point of combustion. This includes the alignment of regulations across borders to ensure a level playing field between UK and imported biomass, and the inclusion of changes to land use in carbon accounting rules.

1. Introduction

The UK is one of the first countries to legislate for a net-zero emissions reduction target. Emissions of all greenhouse gases need to be reduced to net-zero by 2050. Furthermore, the UK has one of the most ambitious medium-term targets. The government recently accepted the Climate Change Committee's advice on the sixth carbon budget, which includes a legally binding target to reduce emissions by 78% from 1990 levels by 2035.

Many countries are very likely to require significant use of greenhouse gas removal (GGR) methods to meet their climate change targets. This is to offset remaining emissions from sectors that are hard to abate completely – particularly agriculture, aviation and some industrial sectors. A range of GGR methods are available or in development including nature based solutions such as afforestation and changes in agricultural practices; and engineered removals through bioenergy with carbon capture and storage (BECCS) or direct air capture (see Box).

This report explores the potential role of BECCS in the UK's pathway to net-zero, including the implications for the energy system, sustainability, policy and regulation. The prospect of BECCS deployment on a large scale has already led to significant debate and controversy. For example, assessments by UCL and Chatham House have examined the inclusion of BECCS in global Integrated Assessment Models (Brack and King, 2020; Butnar et al, 2019). These assessments raise questions about sustainability, land use and the extent to which claimed climate change benefits will be delivered.

Box: BECCS and Direct Air Capture

Bioenergy with carbon capture and storage involves the combustion of biomass (e.g. from dedicated energy crops or residues from forestry management) to generate electricity, or another energy carrier such as hydrogen or heat. The emissions of carbon dioxide (CO_2) are captured during this process. The CO_2 is then piped to a long term geological storage reservoir such as a depleted oil or gas field. In principle this overall process removes CO_2 from the atmosphere because atmospheric CO_2 has been absorbed by biomass resources as they grow.

By contrast, direct air capture involves taking CO_2 directly out of the air, which is at much lower concentrations than in the flue gas of a power or industrial plant. Direct air capture plants require significant quantities of energy for the chemical process that extracts CO_2 from the air. Therefore costs are currently high. The CO_2 is then transferred to a long term storage reservoir.

At present, there is very little deployment of BECCS in the UK or elsewhere in the world. The main components of BECCS have been demonstrated or deployed: full-scale power plants with carbon capture and storage (CCS) are in operation in the USA and Canada; and large power plants such as Drax in the UK have been burning biomass fuel for several years. However, these two elements of BECCS have only been combined at scale for corn bioethanol production at one plant in the USA. A small-scale BECCS experiment was initiated at the Drax power plant in 2018.

The UK government is currently developing a strategy for the transition to net-zero. Whilst the Energy White Paper and Ten Point Plan published in late 2020 indicated some important priorities, further detail is required about how emissions will be reduced sufficiently quickly. This includes more details on how the development, deployment and regulation of GGRs will be carried out.

This report provides important new evidence for the government and other decision-makers about the role that BECCS could play, and how the associated risks can be taken into account. Following a brief description of the research methodology in section 3, the report discusses five distinctive scenarios for the UK energy system, including the role of BECCS and other GGRs in section 4. Section 5 and analyses the implications of these scenarios for sustainability - including for land use, biodiversity and life cycle greenhouse gas emissions. Section 6 concludes with a policy and regulatory framework for BECCS that aims to balance the need for real-world demonstration and testing with management of technical and environmental risks.

2. Exploring the role of BECCS

Each scenario includes a different combination of outcomes across these factors (see **Error! Reference source not found.**). They were developed initially as a narrative description of change between now and 2050. These narratives were then quantified using an energy systems model: UK TIMES. This enabled a more detailed analysis of each scenario. In some cases, the narrative description of change was amended to ensure consistency with the corresponding model run.

*Table 1 - **Five scenarios to explore the potential role of BECCS in the UK.** Scenario abbreviations: Net-Zero (NZ); Engineered Removals (ER); Low Biomass (LB); Reduced Removals (RR); Low Demand (LD)*

Amount of GGR required in 2050	Low (<80 $mtCO_2eq$) **LD**	Medium (80-110 $mtCO_2eq$) **NZ, LB, RR**	High (>110 $mtCO_2eq$) **ER**	
Overall GGR strategy	Majority via known nature-based solutions	Mix of nature based and engineered; minimum use of direct air capture **NZ, LD**	Mix of nature based and engineered; more ambitious direct air capture **LB, RR**	Majority via engineered removals, including direct air capture **ER**
Annual biomass resource availability	Low (<180 TWh) **LB**	Medium (180-250 TWh) **RR, LD**	High (250 TWh+) **ER, NZ**	
Use of imported resources to meet energy needs	Low: emphasis on self sufficiency **LB, LD**	Medium: UK engages in significant trade **NZ, RR**	High: increased imports of resources **ER**	
Strategy for the industrial sector	Similar size and composition to today **NZ, LB, RR**	Continued decline in energy intensive industries	Larger industrial sector, with some improvement in efficiency **ER**	More efficient industrial sector (shift to circular economy) **LD**
Sectoral use of BECCS	Primarily for power generation **ER, LD**	A mixed approach **RR**	Primarily in industrial sectors (e.g. hydrogen) **NZ, LB**	

Brief narrative descriptions of the five scenarios are as follows:

A. **Net-Zero (NZ).** This is a balanced scenario that meets the net-zero target in 2050 through action across the economy. Availability of biomass resources is moderate, with a cautious approach to imports. A mix of GGR measures are deployed to balance around 90 million tonnes of remaining greenhouse gas emissions in 2050. This includes a significant capacity of BECCS for hydrogen production, and a limited deployment of direct air capture to meet the net-zero target.

B. **Engineered Removals (ER).** The deployment of engineered GGR technologies including BECCS is more rapid than expected. This is partly as a response to delayed emissions reductions in some sectors, which becomes apparent in the 2030s. It results in a high requirement for removals by 2050 to balance over 140 million tonnes of remaining emissions. High biomass availability enables BECCS deployment at a large scale in the power sector, complemented by 50 million tonnes of removals from direct air capture.

C. **Low Biomass (LB).** Constraints on the availability of biomass affect some energy generation and negative emissions options. This is partly due to a lack of confidence in international standards for sustainability. There are around 95 million tonnes of remaining emissions in 2050. There is an emphasis on investment in afforestation, BECCS for hydrogen production and direct air capture to balance these emissions.

D. **Reduced Removals (RR).** Whilst there is good progress with decarbonisation of some sectors such as power and surface transport, There are slower emissions reductions from heating and industry. This is partly due to delays in the commercialisation of CCS technologies in the UK which affects the deployment of BECCS and direct air capture. Despite significant BECCS deployment in the 2040s, the contribution to removals is lower than expected due to biomass supply chain emissions. As a result, there are 40 million tonnes of net emissions in 2050.

E. **Low Demand (LD).** There is comprehensive and sustained action to maximise energy and resource efficiency across the UK economy. This includes a shift to a more circular economy, and lower demand for some goods and services. There is a greater emphasis on nature-based removal methods than in other scenarios, which is enabled by a larger shift away from meat and dairy. There is also a cautious approach to biomass imports. Nevertheless, there is significant investment in BECCS to meet the net-zero target, which is used for power and hydrogen production.

The model that has been used to quantify these scenarios, known as UK TIMES, is a single region energy systems model of the UK. It has been widely used for both academic research and for public policy development – including to support the 5th and 6th carbon budgets and the Energy White Paper published in 2020 (BEIS, 2020). It is technology rich, and includes the many different options that can provide the energy services required across the UK economy. It incorporates several GGR methods and technologies including afforestation, BECCS and direct air capture. This model is particularly well suited to scenario analyses that cover several decades (in this case, the period to 2050). It also balances the need to meet demand for energy services whilst taking into account constraints such as carbon budgets and targets. All of the five scenarios discussed in this report meet the legislated carbon budgets to 2037, and get as close as possible to the 2050 net-zero target.

The completed scenarios were analysed to understand the implications for the deployment of BECCS and other GGR options. This includes the implications for land use, emissions from biomass supply chains and other sustainability impacts (see sections 4 and 5). Sensitivity tests were also applied to the model runs to understand the potential impacts of changes in technical performance of BECCS systems and the extent of changes in diets. The results of the scenarios were used to develop a policy framework for BECCS (see section 6). The framework is designed to address important risks associated with BECCS deployment that are highlighted by the scenarios and the sustainability analysis. It focuses on policies for innovation, deployment, regulation of biomass supply chains and performance monitoring.

3. What role could BECCS play in the UK?

By committing to reaching net-zero GHG emissions by 2050 the UK government has subscribed to energy pathways that mark a significant departure from 'business as usual'. Reaching these targets will be challenging. The first **Net-Zero (NZ)** scenario takes a balanced approach to the energy and economic transition required. It implies a strong shift away from fossil fuel use, with an energy supply mix centred on renewables, with significant nuclear power investment, and an important contribution from bioenergy (Figure 2). Residual fossil use still represents 10.6% of primary energy, and corresponds to applications in hard to decarbonise sectors including oil products in aviation.

While these changes are partly underway, the depth, speed, and magnitude of system change required here is significant and is similar to that shown in recent scenarios from the Climate Change Committee (CCC, 2020). Figure 1, for example, shows that the UK power sector will deliver close to three times the amount of electricity it generates today, the majority of which will come from variable renewables. This is directly linked to phasing out fossil fuels from end use sectors, and their replacement with alternatives that are clean at point of use[1]. The partial electrification of transport and residential heat are popular examples of such replacements, with a recent report from the UK Energy Research Centre suggesting that refurbishing up to 19,000 homes per week is required between now and 2050 for the latter (Rosenow et al, 2020).

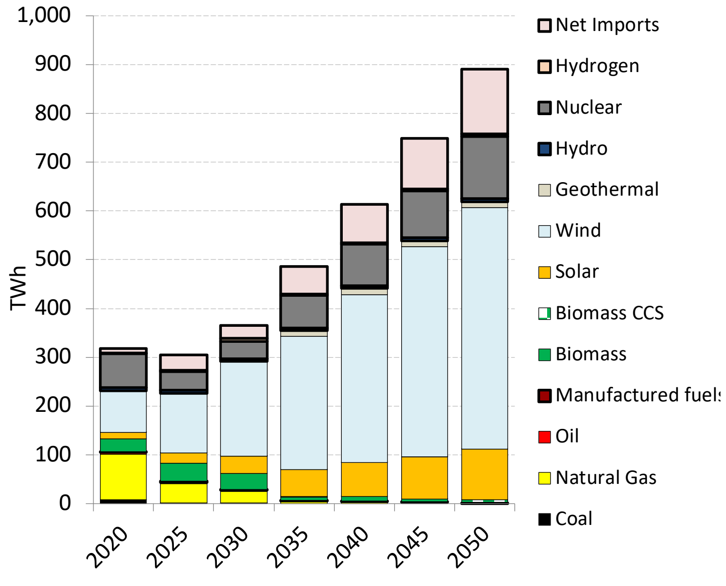

Figure 1- centralised electricity supply (NZ scenario)

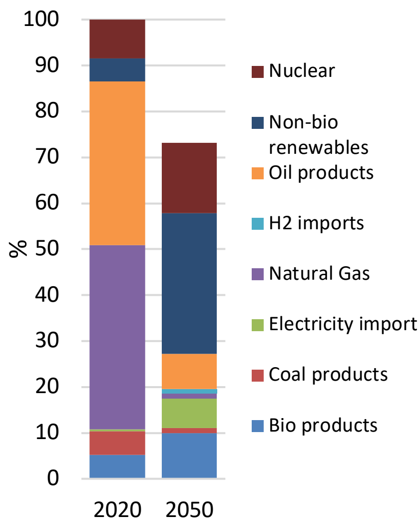

Figure 2 - NZ fuel share of primary energy, normalised to 2020

By allowing the electrification of end-use services to work alongside a wider range of decarbonisation options, the NZ scenario takes a relatively risk-averse approach to delivering clean energy services. However, the different speeds of scale up for these options, combined with biomass availability and the extent to which alternative fuels can reach complex end use sectors, means that difficult trade-offs remain. Figure 3 shows that,

[1] For which emissions of carbon dioxide are either non-existent or captured using CCS technology.

for the NZ scenario, these prioritise the use of biomass for hydrogen production (with CCS) over a smaller use in power BECCS. This hydrogen is used in a mixed industrial sector, where clean electricity and direct biomass combustion also play a role. The transport sector is only partially decarbonised, since fossil fuels continue to be used in the aviation sector. Ambitiously, shipping relies on a combination of ammonia, liquified natural gas and small amounts of liquid biofuels.

It is important to note that biomass with CCS provides a double advantage. It provides energy while also providing net removals of atmospheric CO_2 over its entire lifecycle. Because residual emissions in hard to decarbonise sectors remain in 2050 and need to be balanced by removals, options that remove CO_2 will be preferred by optimisation modelling frameworks over carbon neutral options such as green hydrogen. They may also be preferred over direct air capture since they produce, rather than consume, energy for each unit of carbon removed[2].

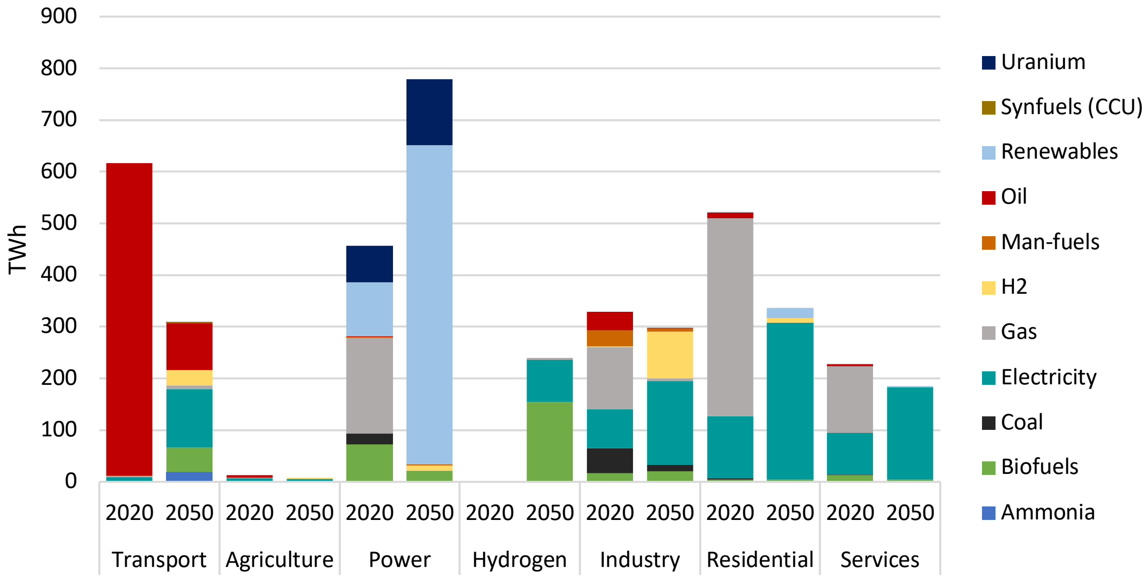

Figure 3 – Energy consumption per sector in the NZ scenario. Note that electricity and hydrogen produced in their respective upstream sector is also included under the end use sector where it is consumed.

The reduction in emissions is not enough and needs to be accompanied by the deployment of a range of GGR options. Figure 4 shows that these include 67mtCO_2e of engineered carbon removals through a significant investment in BECCS for hydrogen production, as well as 13.3mtCO_2e captured through direct air capture and storage. They also imply significant levels of natural removals[3], including relatively well understood approaches such as the replanting of endemic forest species or the re-wetting and sustainable management of drained peatlands. The scenario also relies on up to 8.6mtCO_2e of CCS applied to point-source emitters in the industrial sector – a practice which, like other engineered removals, has yet to be established at scale.

[2] Note that these advantages may be challenged if biomass supply chain emissions increase, lowering end product sustainability (see section 4); or if public opposition to widespread energy crop production begins to emerge.
[3] For the avoidance of doubt, “afforestation” is the establishment of managed mixed endemic forest on land not previously covered by forests; “reforestation” is the re-establishment of forestry on land previously covered by forest; and “energy crops” are densely planted, high yielding monoculture crop species used specifically for energy purposes.

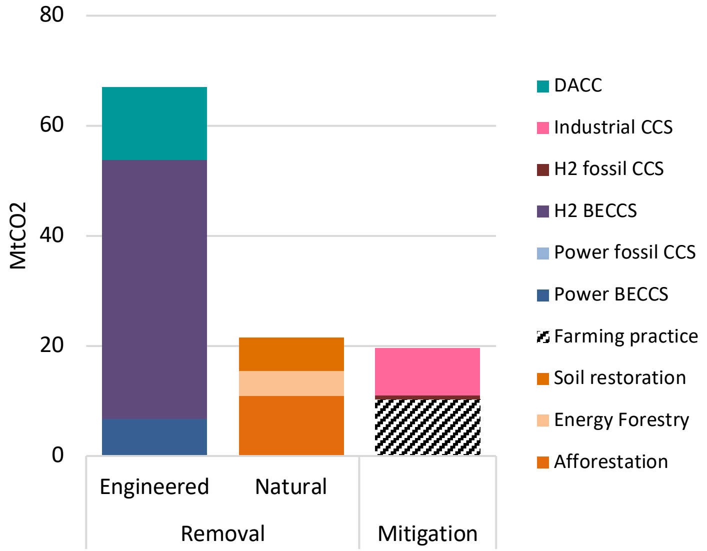

Figure 4 - Emissions removed or mitigated in the NZ scenario

The **Engineered Removals (ER)** scenario explores a future where there are delays in emissions reductions in some sectors. The response is a strong push for the deployment of engineered removals via BECCS and direct air capture, as well as mitigation through hydrogen production using natural gas with CCS. These technologies are developed earlier than in the NZ scenario, and are available by from the late 2020s. Deployment grows at pace and delivers carbon capture efficiency levels that exceed expectations, reaching close to 100% capture by 2050. The ER scenario is also optimistic about biomass availability, including imports from fast developing international markets. It assumes the highest levels of biomass availability of all five scenarios.

The result, shown in **Error! Reference source not found.**Figure 5, this is a scenario which is able to balance more than double the residual emissions in 2050 when compared to the NZ scenario. Shifting from natural gas is no longer required to the same extent, and fossil energy use is still very high in 2050 (at 47% of primary energy). Gas with CCS replaces biomass and electrolysis as the source of hydrogen production, which frees up 154TWh of pelletised biomass. This is combined with additional biomass imports (Figure 6) to generate electricity instead. Here it provides the double impact of decarbonising 71TWh of electricity while also removing 80MtCO_2 through BECCS. 50MtCO_2 of residual emissions are removed by direct air capture by 2050. This is twice the level of DACS suggested in 2018 by the Royal Society and Royal Academy of Engineering report on GGR options. This report also highlighted the high costs that would be involved[4] (Royal Society and RAEng, 2018).

[4] Demonstration projects have been so far known to sequester in the order of 50 kilotonnes per year.

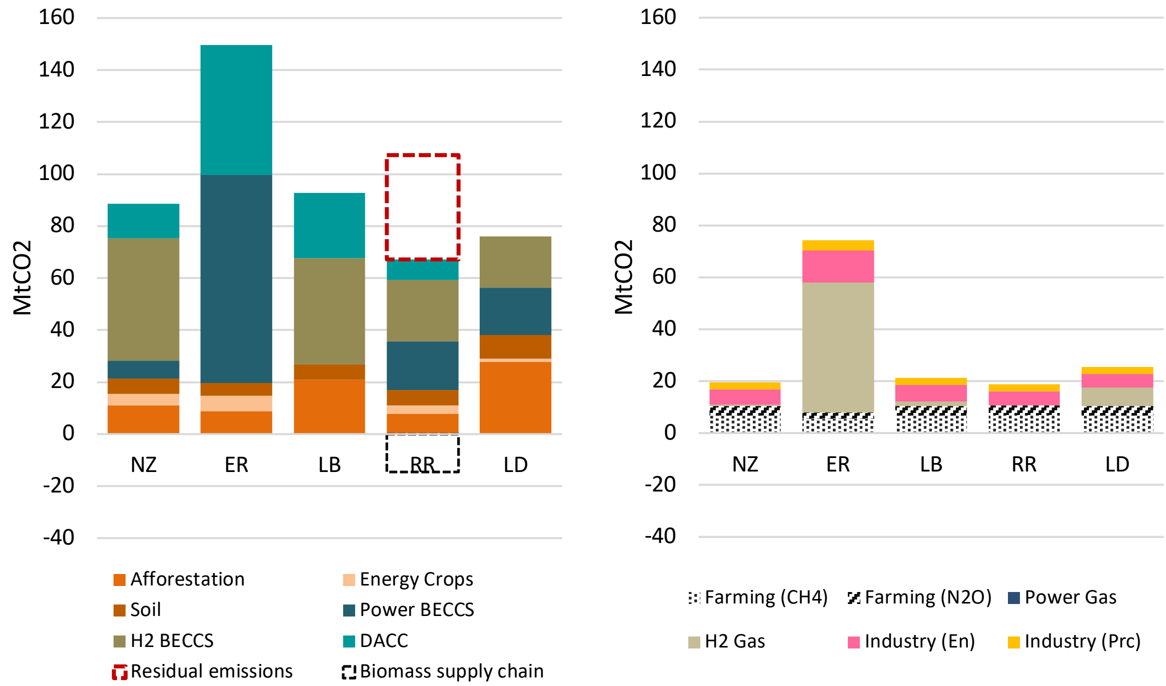

Figure 5 - Total CO_2 removal by different GGRs (left) vs total CO_2 captured by mitigation approaches which use land and CCS (right)[5]

The ER scenario makes strong assumptions about how key pieces of the net zero puzzle develop. The apparent ease with which this scenario achieves the net-zero target is partly underpinned by significantly higher levels of biomass use. Domestic biomass supply in this scenario reaches 215TWh, over half of which is provided by energy crops. Imports increase to represent 40% of the 358TWh consumed in 2050. This would mean that the UK accesses 1.1% of the 100EJ of total global biomass that is thought to be available on a sustainable basis (Creutzig et al., 2015). Whether this is possible and ethical, are questions which regulations and policies should consider (see section 5). This level of biomass consumption is still well within the range published by the CCC in their recent advice on the sixth carbon budget (214TWh to 402TWh) (CCC, 2020).

This apparent ease is also dependent on the timely development and fast scaling of engineered removals technologies. Direct air capture capacity reaches 19MtCO_2 by 2040, more than doubling again to 50MtCO_2 by 2050. The combined deployment of CCS and BECCS also increase rapidly from capturing 18MtCO_2 in 2035 to over 140MtCO_2 by 2050. This includes 80MtCO_2 from BECCS in the power sector, 50MtCO_2 from hydrogen production from gas and 16MtCO_2 via industrial CCS. Importantly, this also includes the development of sufficient CO_2 transport and offshore storage infrastructure in the same time frame. Achieving this will be very challenging. Previous analysis for the UK has suggested that potential scale up of CCS infrastructure in the first decade could, at best, reach between 2 and 8MtCO_2 per year.

[5] Sequestration through Energy Crops refer to increases in soil carbon stocks through applying SRF and SRC, and are strongly dependent on the land use change implied. Power gas or coal with CCS are considered in the modelling but are not used in any of our scenario runs, hence their omission from figure 5.

Both these assumptions come with the significant risk that any delay may leave the net-zero target out of reach. On the CCS technology side, a lack of early support and of long-term investment for complex technologies and infrastructures could lead to much slower progress with engineered removals. On the biomass supply side, the high levels of demand assume that international markets for sustainable biomass will be both available and underpinned by credible supply chain governance systems. These two risks are explored in more detail in the **Low Biomass (LB)** and **Reduced Removals (RR)** scenarios.

The LB scenario combines a cautious approach to both domestic and international biomass availability for energy markets with a medium ambition in terms of removals via direct air capture. Direct air capture is increased in this scenario to 25 $MtCO_2$. As a result, all 1.84Mha of land used for energy crops in the NZ scenario is allocated to domestic reforestation. This removes 21$MtCO_2$ but reduces the availability of biomass for the energy system by 42TWh. Similarly, concerns about sustainability of international biomass imports in the LB scenario lead to supply reductions of 60%, so it provides just 32TWh by 2050[6] (Figure 6). While the LB scenario does not leave residual emissions in 2050, this scenario remains on the margin of failing to meet our emissions targets (see sensitivities below). In principle, any such shift could be covered by increased deployment of direct air capture as allowed in the more optimistic Engineered Removals scenario.

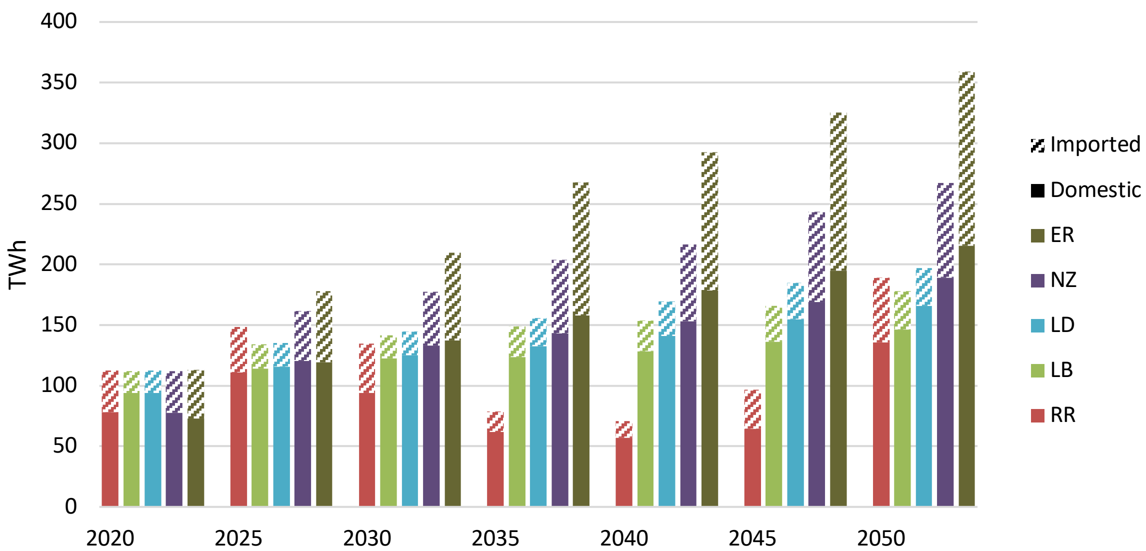

Figure 6 - Imported and domestic biomass consumption per scenario[7]

The RR scenario goes further in understanding both technology and biomass availability risks. It includes a lack of early emissions reduction, followed by slow technology progress. This delay in scale up significantly limits the deployment of direct air capture, leaving the system to rely on CCS technologies that do not reach the levels of efficiency seen in the ER scenario. In addition, it explores the impact of limitations to the sustainability of biomass. Supply chain emissions in the RR scenario represent up to half of the embodied carbon in the biomass used (see biomass supply chain box in Figure 9**Error! Reference source not**

[6] Imports of wood-pellets to the UK totalled 8.7Mt in 2019. Assuming an energy content of 18.7gigajoules per tonne, this translates to 45.2TWh.

[7] Note that values for 2020 are non-constrained model results rather than national statistics as the model is calibrated to a base year in 2020.

found.). As a result, there are 40MtCO_2 of residual emissions in 2050 from hard to decarbonise sectors.

The fifth **Low Demand (LD)** scenario explores the impact of reducing the demand for energy and other products. This scenario takes a relatively conservative view of what could be achieved through demand reduction. It combines technical solutions with changes in the choices made by citizens. Examples of the former include better roll-out of energy efficient technology in end-use sectors across the residential, industrial and service sectors. The latter includes changes in diets that reduce the pressure on land requirements and emissions from the agricultural sector, and reductions in car ownership and flying.

Taken together, these changes lead to savings of 14MtCO2_e in 2050. This is achieved through halving consumption of meat and dairy, a 35% shift away from personal car transport, an 11% increase in rail (compared to 2018 levels), and a 15% reduction in aviation passenger numbers. This scenario also includes an increase in efficiency measures that reduce heat requirements by 15% in the service sector and a reduction in industrial energy use by an additional 4.7% compared to the NZ scenario. Taken together, these measures illustrate what more ambitious efforts to reduce demand can achieve without lowering quality or life or energy service levels. It is possible to go further, and to achieve lower energy demand than in the LD scenario[8].

Figure 5**Error! Reference source not found.** shows that this scenario relies on a mixed role of BECCS in both power and hydrogen applications. The first provides 17TWh electricity in 2050, but delivers 24% of the net removals required in this scenario (18 mtCO_2). The second sequesters 19 mtCO_2 while producing 25.6TWh hydrogen via BECCS. This scenario has one similarity to the ER scenario, which is a continued role for gas. A large majority of the gas used in the LD scenario (61%) is used for producing hydrogen. By contrast to the ER scenario, the use of unabated gas in the residential and industrial sectors are very strongly reduced in the LD scenario.

Although the LD scenario lowers the pressure on the energy system and provides more 'emissions space', it still relies on BECCS to meet the net-zero target. It does not require direct air capture, and relies strongly on nature-based solutions since more land is available for afforestation. While BECCS delivers additional energy output while sequestering carbon, our scenarios illustrate some of the risks involved. Arguably direct air capture could substitute for BECCS, but this would increase costs and energy consumption.

The increased focus on reducing emissions to net-zero in the UK and other countries has led to a greater focus on the potential of nature-based solutions to deliver greenhouse gas removals. These solutions intrinsically rely on specific and complex uses of land, a resource that is often in limited supply. Afforestation and energy crops both assume significant levels of land conversion and the establishment of either standing, managed forests, or cultivated plantations of fast-growing species. Results presented here consider the use of up to six

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[8] "Energy service" refers to a service that is derived from energy, for example, the use of electricity in heat pumps provides heat as a useful energy service. Forthcoming analysis by the UK Centre for Research into Energy Demand Solutions (CREDS) explores higher levels of ambition in energy demand reduction in more detail. This is still in progress at the time of writing, and therefore was not available for use in this report's Low Demand scenario

different species of energy crop[9], including non-native options, and one mixed native species approach to afforestation and reforestation. Summarised in Table 2, land conversion across all five scenarios range from 1.8 million hectares (Mha) in the NZ and LB scenarios to 2.7Mha in the LD scenario. The latter exceeds all others due to additional reforestation on land freed up by diet and other changes.

Taken together, these land use changes are linked to planting rate assumptions in 2050 of between 24 and 70 thousand hectares (kha) per year for afforestation, and 11 and 63kha per year for energy crops. This places this work both well within the ranges In recent advice by the CCC[10]; and, also, well above recent demonstrated planting capacity in the UK which has stagnated between 10 and 15kha per year since the early 2000s (CCC, 2020).

Table 2 – Reliance on land-based measures across scenarios

2050	Unit	NZ	ER	LB	RR	LD
Afforestation	[Mha]	0.94	0.75	1.84	1.41	2.39
Energy Crops	[Mha]	0.90	1.45	0.00	0.74	0.27
Soil Restoration	[$MtCO2_e$]	5.95	5.14	5.95	5.95	9.23
Farming practice	[$MtC02_e$]	10.61	8.48	10.61	10.61	10.61

These five scenarios rely on a wide range of assumptions that define how energy demand can be met whilst meeting carbon budgets and targets. Many of these assumptions are very uncertain. Therefore, it is also important to understand how the outcome could be affected if these assumptions change.

Some changes in assumptions have been built in to the design of this report's scenarios. For example, the ER scenario relies on heavy availability of both significant amounts of sustainable biomass and advanced carbon capture and storage technologies from an early stage. The impact that both these assumptions could have on achieving the net-zero target if they were to fail are tested through the LB and RR scenarios. The results from these scenarios illustrate the risks of relying heavily on engineered removals, particularly from BECCS, to meet the net-zero target.

Two further assumptions that are relevant to BECCS merit further attention since they are embedded in all five scenarios. They are: 1) assumptions about the efficiency of carbon capture systems; and 2) assumptions about a shift in diets. Changes in these assumptions have been tested through further 'sensitivity tests' to understand how this affects the modelling results.

The first sensitivity test is techno-economic in nature, and challenges the assumption that the efficiency of carbon capture systems will improve to very high levels by 2050. This sensitivity is applied across all engineered removal options and implies that efficiencies of capture remain constant over time. This translates into an efficiency loss of between 3 and 5 percentage points compared to the original scenarios. Presented in Figure 7 below through the sectoral use of biomass, this small change has the potential to significantly shift the

[9] These include eucalyptus, paulownia, sitka spruce, native species, willow and miscanthus.

[10] For reference, CCC CB6 advice planting rages for 2050 vary from 30 to 70kha/a for afforestation, and from 10 to 60kha/a for energy crops; total land-take for these options totalling up to 1.968 and 1.415Mha by 2050 respectively.

development of the energy system by affecting the deployment of BECCS for power and hydrogen production. While clearly delivering similar levels of abatement, this change can lead to stark physical infrastructure changes between sectors. This is especially the case in the LB and RR scenarios.

These results highlight that the use of BECCS in the system is driven both by the level of net removal that one option can offer compared to another, as well as by its ability to deliver a specific end use commodity. The energy system uses the full amount of biomass available from domestic and imported sources in both the original 'reference' scenarios and the sensitivity scenarios.

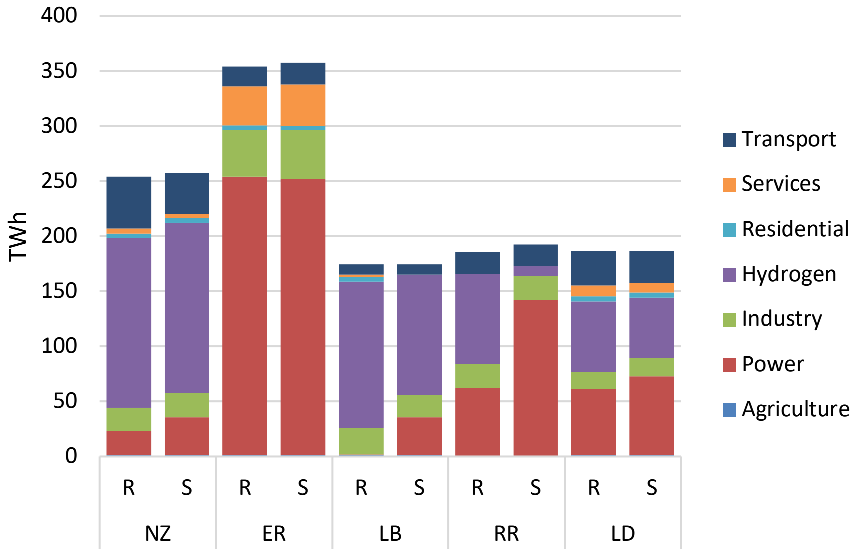

Figure 7 - Sensitivity to lower assumed CCS efficiency. 2050 biomass consumption per sector (R reference modelling run, S sensitivity modelling run)

The second sensitivity test investigates the impact that failing to shift our diets could have on each scenario. Quantitatively, this change has the direct impact of adding emissions to the carbon balance in 2050. These amount to 6.67MtCO_2 in annual emissions for all scenarios except the LD scenario, which includes a larger increase of 13.85MtCO_2 due to a more ambitious dietary shift. The results highlight which scenarios are robust to this direct increase in emissions – all other things being equal. Scenarios that are already struggling to stay within carbon budgets will see higher residual emissions as a result. Figure 8 shows that this affects the LB and RR scenarios, where residual emissions in 2050 increase by 2.9MtCO_2 and 6.7MtCO_2 respectively.

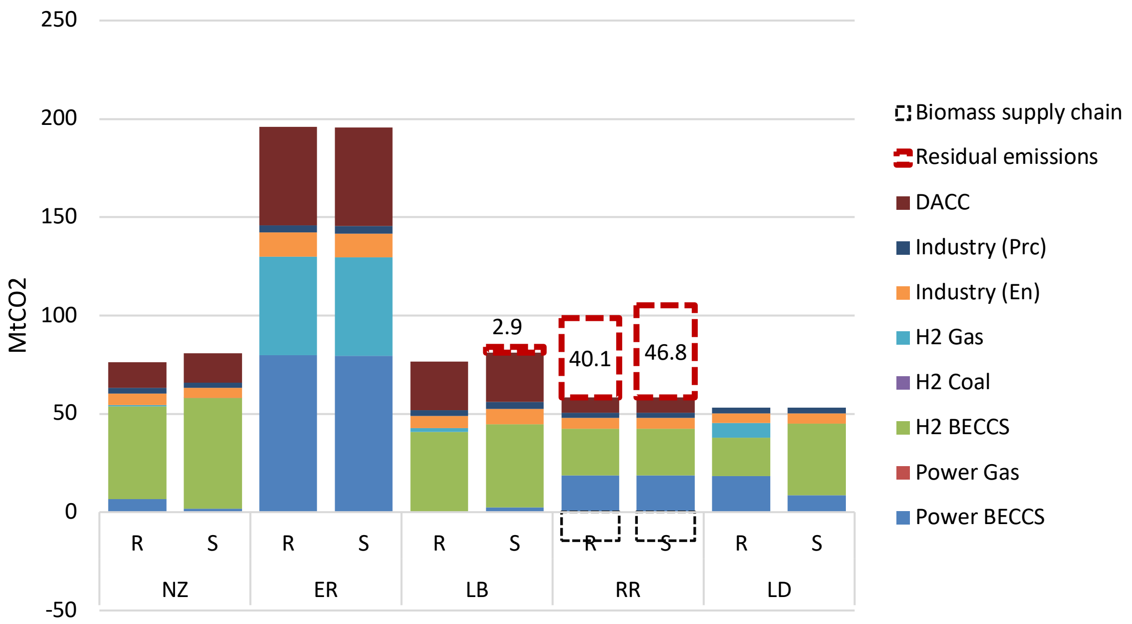

Figure 8 - 2050 emissions change in response to the no diet change sensitivity: engineered abatement and capture

The fact that residual emissions in the LB scenario are lower than the additional emissions due to the lack of changes to diets shows that it has some remaining flexibility to reduce emissions – but not quite enough. By contrast, the NZ, ER and the LD scenarios are robust to this sensitivity. They have the "emissions space" to compensate for a lower level of dietary change.

4. Is BECCS sustainable?

BECCS sustainability concerns usually focus on biomass resources, which typically come from large scale energy crops plantations or forestry residues. Our scenarios confirm that this is likely to remain a key concern about future BECCS supply chains. As our scenario results in Figure 5 show, BECCS could remove between 38 and 80mtCO_2e per year by 2050. At this scale, the amount of biomass feedstock needed to feed BECCS should grow significantly from todays' level of 317 petajoules per year to up to 850 petajoules per year (REA, 2019).

As highlighted in Table 2, cumulative land requirements to 2050 for meeting this increased demand for biomass in our scenarios varies. Energy crops require between 0.27 million hectares (Mha) for the LD scenario and 1.45 Mha for the ER scenario. Additionally, between 0.75 Mha and 2.39 Mha of land would need to be converted from current uses (or no use) to managed forestry across the five scenarios. Putting this into context, our results suggest increasing current forest area by over 70% compared to its current 3.2 Mha. It also means increasing the amount of cultivated land (currently 3.4 Mha) by up to 42%. Both will require strong policies and regulations to ensure that the transition is done in a sustainable way. They will need to consider biodiversity, social, economic and governance concerns alongside CO_2 removal targets. Furthermore, demand side actions will also be required to free up agricultural land, e.g. by reducing meat and dairy consumption.

Regarding the expansion of energy crops, the current focus is on cultivating fast growing perennial crops. Whilst farmed systems are maximising production of biomass and net primary production, they may lack biodiversity, which affects ecosystem resilience (Dasgupta Review, 2021). Farmed systems might also increase the release of non-CO_2 emissions, and air and water pollution from land management (Creutzig et al 2015, Albanito et al 2019, DeCicco and Schlesinger 2018, Fajardy and MacDowell 2017, Welfle et al 2017). Furthermore, the expansion of energy crops could cause competition for land with food and other uses, e.g. fibre, conservation, afforestation and reforestation (CCC 2018, IPCC 2018a, Hepburn et al 2019), or have implications for food security (Robledo-Abad et al 2017).

The expansion of forests with native and diverse species, as opposed to fast-growing mono-cultures, is regarded as preferential option by recent analyses (e.g. Camia et al., 2020, Dasgupta review, 2021). If these new forests are to be managed, there is an increased scientific agreement that a low intensity management is preferred, as the conversion of natural forest to managed forest or increased forest management induces a loss of local biodiversity (Holtsmark 2012, Slade et al 2018, Favero et al 2020). Increased forest management also leads to lower carbon sequestration in the forest, which is a form of carbon debt. This topic is increasingly mentioned in relation to the use of forestry residues for energy production.

Carbon debt occurs at a reference point in time when the land carbon balance is disrupted. This disruption refers either to land use change GHG emissions released by expanding energy crops, or to losses in carbon stocks caused by the harvest of biomass for energy. The time required to rebalance the initial carbon stocks (referred to as “payback” period, or “carbon breakeven” time) depends on the type of disturbance, the type of biomass harvested, the geographic scope of the analysis, and the type and frequency of harvest (Lamers and Juninger 2012, Holtsmark 2012). Current studies suggest that payback periods vary widely, ranging from up to twenty years for energy crop cultivation on marginal lands, to several hundred years when burning wood from natural forests, or reducing the harvest cycles of harvested forests (EASAC 2019, UK POSTNOTE 618, 2020).

Given the urgency of both global and domestic climate targets, prioritising low risk feedstocks is key. While some suggest that short payback times make most sense (Norton et al 2019, EASAC 2019, Camia et al 2020), others highlight that significant net emissions (Booth, 2018) and total ecosystem carbon losses from harvesting forestry residues (DeCicco and Schlesinger 2018, Booth 2020) should prioritise protection and increase uptake of carbon in biosphere over bioenergy (DeCicco and Schlesinger 2018).

Considering the wider environmental impact of these options adds another dimension to the problem. Focusing on comparing categories of supply options for the growing EU bioenergy market, Camia et al. (2020) found limited "win-win" interventions that provide carbon emission mitigation and improve local biodiversity and ecosystems. They include harvesting fine wood debris from coniferous forests (typically twigs and low-diameter branches) and afforestation on former agricultural land with low intensity harvest. Even here though, carbon payback periods can extend to fifty years. Careful monitoring of any biomass removal is required to ensure sufficient residues remain onsite to improve soil carbon and nutrient cycles (DeCicco and Schlesinger 2018, Camia et al 2020).

In addition to the sustainability challenges related to biomass feedstocks, we argue that further attention needs to be paid to the full supply chain of BECCS (see Figure 9 below).

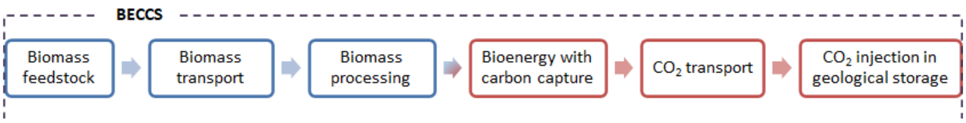

Figure 9. BECCS supply chain, from growing biomass though to bioenergy production with carbon capture, to CO_2 transport and final geological storage.

BECCS has perhaps one of the most complex supply chains of all the GGR options. As represented here, there are two key parts to BECCS supply chains. The first one is biomass to energy production, including the production of biomass feedstocks, biomass transport, and conversion of biomass to energy. This part of the supply chain is relatively well developed and coordinated, including at large scale, e.g. for operations at the Drax power plant. The second key part of the supply chain is the carbon capture and storage, starting with carbon capture (currently demonstrated for Drax), CO_2 compression, transport and geological storage. This part is not currently deployed widely and needs further innovation and support to be established at scale. The CCS side of BECCS presents a further challenge, as it may share infrastructure with other mitigation and removal technologies, e.g. direct air capture or fossil CCS. Therefore the scale of required infrastructure is likely to be larger than that required for BECCS. Indeed, our scenarios suggest that a higher level of removals by BECCS is also accompanied by high fossil CCS, adding to the stress on CCS deployment.

A first key insight from looking at BECCS as a complex supply chain, is that rewarding CO_2 removal by BECCS only at the point of carbon capture or geological storage might significantly underestimate other supply chain GHG emissions (Gough et al 2018, UK POSTNOTE 618, 2020). They include methane emissions caused by biomass or biomass pellet storage before processing into bioenergy (Roder et al 2015, Sahoo et al 2018). They also include GHG emissions from energy required for processing, including drying (Fajardy and MacDowell 2017, Roder et al 2015). Our Reduced Removals (RR) scenario shows the potential impact of supply chain emissions, which could result in a need for significantly higher levels of CO_2 removal needed for bringing the whole system to net zero.

How large are these supply chain emissions? Our literature review summarised in Figure 10 below suggests that they could be as high as 40 to 80% of the captured CO_2. Adding land use change emissions and/or considering carbon debt potentially caused by the harvest of biomass for energy could altogether negate any CO_2 removal by BECCS (UK POSTNOTE 618, 2020). It is important to note that these figures are subject to large uncertainties. Therefore, the impact of these factors on life cycle emissions should be further investigated and tested – including through monitoring of any BECCS demonstration projects in the UK and abroad.

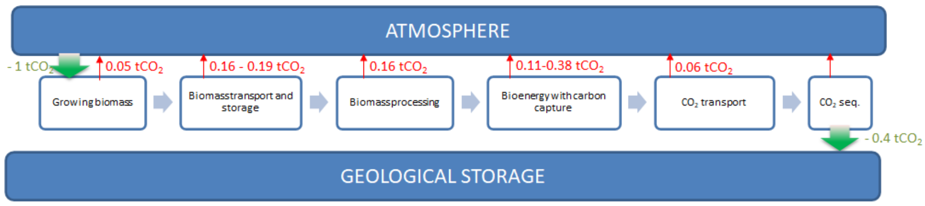

Figure 10. Potential BECCS supply chain emissions. *This assumes 5% CO_2e released due to farming/biomass harvest (based on Smith and Thorne 2013, Fajardi et al 2019), between 16 and 19% losses due to bailing/chipping, biomass transport and storage (Smith and Thorne, 2013, Roder et al 2015, Sahoo et al 2018, Fajardi et al 2019), further 16% due to biomass processing (Fajardi et al 2019), 11-38% due to bioenergy conversion and capture efficiency (Smith and Thorne, 2013, Fajardi et al 2019, National Academies of Sciences Engineering and Medicine 2019), 6% losses due to compression and transport of CO_2 (National Academies of Sciences Engineering and Medicine 2019).*

A second key insight is that the type of biomass resource is important to the overall GHG emissions over the full supply chain. As we have seen above, issues related to land use change, including high GHG emissions and carbon debt, loss of biodiversity, increased water consumption and pollution, need to be considered carefully when sourcing biomass from large scale energy crop plantations, or forestry residues, from the UK or abroad. We therefore argue that more emphasis should be placed on identifying waste-to-energy BECCS options, which until now have been overlooked (Slade et al., 2018). This would also allow linking the development of BECCS supply chains to strategies to develop a more circular economy.

A third very important observation is that a focus on carbon removal might bring unintended consequences for eco- and human- systems. These should be considered carefully when designing BECCS systems, and not mitigated after they happen. For instance, local water stress should be considered both when deciding where to cultivate biomass and where to place bioenergy production with CO_2 capture (Smith et al 2016a, National Academies of Sciences Engineering and Medicine 2019). Bioenergy cropland expansion plans in the UK and abroad needs to address and avoid risks related to land tenure, livelihoods, and Indigenous rights (Creutzig et al 2021). All these risks should be carefully considered when developing new BECCS regulations and carbon accounting, to ensure that all impacts in the UK and abroad are accounted for. As with all new energy infrastructures, local communities in the UK should be consulted before development as expansion could lead to unfair conditions for vulnerable communities, or could lead to “not in my backyard” attitude, which could bring important delays in BECCS deployment (RSA and RAE 2018). Transportation of CO_2 through pipelines or with ships involves a small risk of leakage or accidents, rules for efficient and safe transport and storage of CO_2 are needed, including allocation of liability or insurance arrangements (EASAC 2019).

5. A policy framework for BECCS

In the light of this analysis of the potential role of BECCS and the implications, what should the policy framework for BECCS look like? In this section of the report, we set out some of the features of this framework, with a focus on innovation policies, incentives for the deployment of GGR options including BECCS, and regulation of biomass supply chains.

These proposals build on three important principles:

1. Government policies must prioritise actions to reduce emissions first. Emissions across the UK economy should be reduced as much as possible in the short-, medium- and longer-term. The deployment of GGRs is not an alternative to emissions reduction.
2. Our analysis has shown that action to reduce emissions should include a major emphasis on reducing demand for energy and other products. This will increase flexibility in how the net-zero target can be met, and reduce the risks of relying on GGR measures that might not deliver what they promise.
3. Any GGR measures that are required are used to balance emissions that can't be reduced across the economy as a whole. They should not be used to help specific sectors achieve apparent 'carbon neutrality'. This is especially the case for sectors such as power, surface transport or heating where it is technically and economically feasible to reduce emissions to zero. The power or industry sectors might act as hosts for GGR removal technologies, rather than needing them for their own mitigation goals.

The current policy framework that is reflected in the Ten Point Plan and Energy White Paper of 2020 include several proposals that are relevant to BECCS (HM Government, 2020; BEIS, 2020). These include £1bn of funding for up to four CCS clusters; plans for hydrogen deployment that are likely to include 'blue' hydrogen from natural gas with CCS; and R&D funding for GGR technologies including direct air capture. There have also been more recent calls for evidence on GGRs and biomass to inform future policy.

If GGRs in general, and BECCS more specifically, are going to play a role in the UK's net-zero pathway, more detailed policies will need to be developed and implemented. Some of this policy detail applies to all technologies that involve carbon capture and storage (CCS). CCS has been the subject of specific policies and strategies by successive UK governments for 15 years. Whilst a significant R&D, detailed feasibility studies and small scale pilots have been carried out, this policy has failed in its objective to demonstrate and deploy CCS systems at scale. The current proposals in the Energy White Paper 2020 are the fourth attempt to support large-scale CCS in the UK. It is therefore essential that lessons are learned from the failure of the previous attempts. Among other factors, these failures were due to the high costs of CCS, a lack of public funding and the inability or unwillingness of private developers to take on a sufficient share of the costs and risks of early deployment.

Public funding for innovation

It is often argued that the main components of CCS systems have already been deployed at scale. This is the case for fossil fuel use with CCS, where there were 26 large scale projects in operation around the world in 2020 (Global CCS Institute, 2020). For BECCS, the situation is different. The components of some BECCS applications are also in operation at scale. For example, all of the key elements of the 'Drax model' of large scale biomass combustion with post-combustion carbon capture and storage have been implemented in practice, albeit separately.

However, the use of BECCS for hydrogen production, which is the main use of BECCS in some of this report's scenarios, has not been implemented fully. This is because hydrogen production would require biomass gasification at scale, followed by the separation of the synthetic gas into CO_2 (for transport and storage) and hydrogen. Biomass gasification has been trialled at smaller scales, including for hydrogen production, but has not yet been implemented at a large scale (IEA Bioenergy, 2018). Therefore, there may be a case for the UK government to support one or more BECCS demonstration projects for hydrogen production at an early stage. This will provide vital evidence about real-world performance, and will help to inform decisions about where BECCS could be most useful for reaching the net-zero target.

Alongside targeted support for demonstrating and scaling up BECCS, it is also important that there is continued research into the feasibility and sustainability of the full range of GGR options. This is an area where the UK has increased its investment in recent years to around £110m (BEIS, 2020b). This includes an academic research programme on GGRs which is now coming to a close; a new research hub and five associated GGR demonstrators, £31.5m; and a £70m BEIS programme to support innovation in direct air capture and other GGRs. The scope of the BEIS programme includes BECCS, but it is unlikely to have the resources to support large-scale implementation.

Deployment incentives for GGRs
In theory, a more comprehensive system of carbon pricing could be used to provide stronger incentives for decarbonisation across the economy – including the deployment of GGRs. Bodies such as the Zero Carbon Commission have called for extensive reforms to current arrangements in the UK, which would both increase the level and scope of carbon pricing (Zero Carbon Commission, 2020). The Commission acknowledges that even if these reforms were implemented, more sector specific arrangements would be required to drive decarbonisation at the scale and speed required. This is because of important differences in context between sectors – including differences in the status of low carbon technologies, the decision-makers involved, and costs and risks. The experience of renewables deployment in many countries, including the UK, demonstrates how important such sector specific policies have been for accelerating deployment and bringing down costs. Whilst the Commission's report doesn't cover GGRs in detail, they argue that specific arrangements will also be required for the deployment of GGRs – particularly those GGRs that involve changes to the use of land and to farming practices.

With respect to incentives for GGRs in particular, a recent report for BEIS by Vivid Economics has discuss some of the options in detail (Vivid Economics, 2019). The Vivid Economics report also recognises the contextual differences between sectors where GGRs might be deployed (e.g. the power, industrial and agricultural sectors), and the need to integrate GGR deployment policies with other policies applied to those sectors. Its proposals also highlight an important tension for policy makers – between broad market-based incentives for GGRs that are designed to minimise overall costs and more specific incentives that are tailored for specific GGRs.

In the short- to medium-term, a broad market-based approach is unlikely to deploy BECCS at scale. This is because the up-front costs and risks of BECCS are likely to be too high, especially in the absence of CO_2 transport and storage infrastructure. Reforms to carbon pricing are needed, which should include support for lower cost GGRs such as afforestation. But there is also a need for specific incentives for the initial deployment of BECCS.

Building on the experience of renewable electricity technologies, long-term contracts would be one way to help finance the first tranche of BECCS capacity. These contracts should be awarded via a competitive process to put downward pressure on costs. They should not focus only electricity generation, however. As our scenarios show, there is significant uncertainty about where BECCS should be most usefully deployed. In some scenarios, there is little or no BECCS in the power sector – and investment focuses on hydrogen production instead. In this respect, our analysis differs from the recent Baringa report for Drax which concludes that BECCS on Drax is a 'no regrets' option (Baringa, 2021).

It will be essential to implement such contracts incrementally and cautiously, rather than supporting full-scale facilities. This will enable a modular approach to scaling up BECCS that allows sufficient time for the evaluation of costs, technical performance and supply chain emissions at each stage. This will build in flexibility, and allow the government to prioritise other decarbonisation or removal options if the economic and environmental performance of BECCS systems are not good enough. It will also help to ensure that the UK doesn't lock itself in to BECCS supply chains that do not offer the most effective and sustainable contributions to energy production and removals.

If BECCS is successfully scaled up, the design of contracts will also need to take into account the potential for conflicting objectives. This is particularly the case for the power sector. As the Baringa report notes, BECCS power plants could help to balance the electricity system alongside other measures such as demand side response, storage and interconnection. However, using BECCS plants to play such a balancing role would mean that they do not maximise their capacity factor – and hence, the amount of carbon removal achieved. Maximising removal implies running a BECCS plant as much as possible, rather than flexible operation.

If they are to deliver BECCS investment, such contracts would also depend on the development of pipeline and storage infrastructure. This infrastructure is likely to require a separate funding mechanism since it will make little sense for it to be dedicated to an individual BECCS project. The government and industry have already spent a lot of time developing plans for industrial clusters which could include carbon transport and storage infrastructure to facilitate industrial decarbonisation and hydrogen production. In our view, the cross-party Oxburgh review of 2016 made a good case for a regulated approach to investment in CO_2 pipeline and storage networks (Parliamentary Advisory Group on CCS, 2016). This would allow investors to earn a rate of return on this investment, along similar lines to developers and operators of other energy networks.

This more specific approach to supporting BECCS would need to be designed and implemented carefully, with regular evaluations of carbon removals achieved across the biomass supply chain (see below). Monitoring and evaluation will also need to examine emerging experience with costs and technical performance to ensure that the UK doesn't lock itself in to BECCS supply chains that do not offer the most cost effective, sustainable contributions to energy production and removals. As our scenarios illustrate, there may be finely balanced judgements to make about the sectoral focus of BECCS investment. Switching that focus, for example from power to hydrogen, will get increasingly difficult as infrastructures are built and sunk costs increase over time.

Regulations for BECCS sustainability

UK bioenergy production has doubled in the last decade, mostly driven by policy initiatives focused in three key sectors: transport, heat, and electricity generation (ESO FES 2020). The Renewable Transport Fuel Obligation (RTFO) incentivises the inclusion of bioethanol, biodiesel, and bio-methane in fuel blends. The Renewable Heat Incentive (RHI) incentivises the use of biomass in home boilers and increased biomethane into the natural gas network. The Renewable Obligation (RO) incentivises the use of solid biomass for power generation.

In 2019, a total of 323 petajoules (PJ) of biomass was used in the UK: about 49% for heat generation, 38% for electricity, and 13% for transport biofuels (REA 2019). It is interesting to note that each sector was powered by different biomass feedstocks. Heat generation was fuelled by agricultural and forestry residues, and by energy crops cultivated in the UK. By contrast, large scale electricity generation was supported by imported wood pellets. Transport biofuels came from imported liquid fuels and methane from waste fractions.

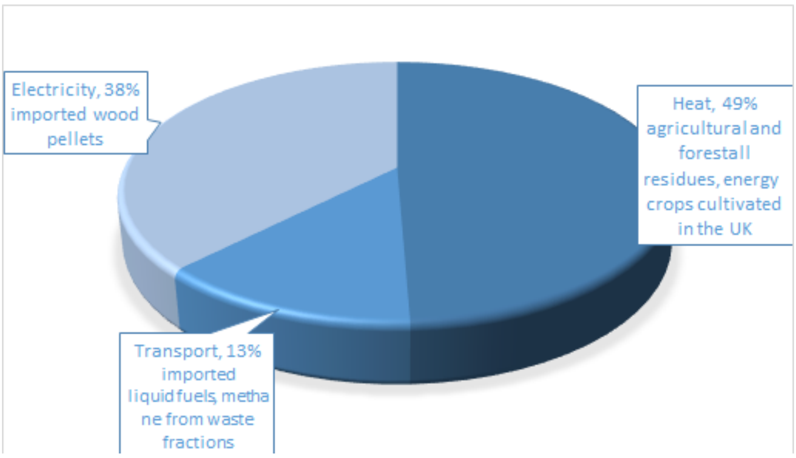

Figure 13. Biomass consumption in the UK, 2019, share by sector. Based on data published by REA (2019).

As shown in section 4, the demand for wood pellets increases significantly across the five scenarios. This includes both imported and domestically produced wood pellets from energy crops and forestry residues. Current bioenergy regulations in the UK cover some key sustainability issues related to sourcing biomass. The RTFO specifies indirect land use change rules, definitions of dedicated energy crops, and maximum shares of crop-derived biofuels in the national mix, to avoid competition for land with other uses. The updated RHI (2020) criteria include comprehensive sustainability indicators including forest monitoring, reporting and verification to demonstrate that forest productivity is maintained, local ecosystems are not harmed, biodiversity is maintained. Social indicators, such as labour and welfare, health and safety, are also specified, but only required to meet local and national legal requirements. These regulations have been evolving over time to include relevant sustainability concerns signalled by the scientific community. As the bioeconomy is projected to grow significantly in the next few decades (e.g. REA 2019; CCC, 2020), careful monitoring and updating of sustainability criteria should continue – and be based on developments in the scientific evidence.

Since BECCS could potentially become a key CO_2 removal strategy in the UK, these sustainability regulations should be expanded further to cover full supply chains: from biomass supply to energy production, and the capture of CO_2 for use or storage. Our key recommendations include:

- Sustainable international biomass supply chains require alignment of regulations across borders. The alignment would ensure that imported biomass meets all the sustainability criteria set for UK biomass, including potentially more stringent social requirements. This would also help to ensure a level playing field between UK and imported biomass.
- The link between biomass demand and its supply needs to be much more transparent, so responsibilities and accountability across the full supply chain becomes clearer. In particular, carbon accounting rules need changing to (1) recognise links between terrestrial carbon management and bioenergy production; and (2) revise the assumption of carbon neutrality at the point of combustion. The focus of terrestrial carbon management should be on increasing the rate of land CO_2 sequestration and avoiding carbon debt, which could potentially negate removal by BECCS for decades to come. Solely reducing the use of fossil fuel in the sectors using land (agriculture, forestry) will only contribute marginally to the overall BECCS supply chain emissions.
- Trade-offs and synergies between carbon sequestration provided by GGR options, including BECCS, and other ecosystem services, e.g. biodiversity, water quality, need to be evidenced. Protecting and increasing carbon stocks in the biosphere can also contribute to increasing local resilience to climate change effects, e.g. flooding, droughts.
- BECCS supply chains should be developed considering social priorities. These include health, safety, labour conditions of people involved in growing biomass feedstocks, especially in vulnerable communities, but also consultation of the larger public when planning large scale CO_2 transport infrastructure.
- Clear governance and policy structures need to be put in place to ensure BECCS is delivering CO_2 removal when accounted for over its full supply chain. This could include, but not limited to accounting, monitoring and verification frameworks applicable globally, provision of guidelines for reporting and verification of safe CO_2 storage, including for traded CO_2.

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