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BECCS deployment

The risks of policies forging ahead of the evidence

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Summary

- Under current emissions trajectories, the chance of limiting global warming to 1.5°C is less than 1 per cent. The slow pace of global decarbonization has created an inevitable need to remove CO_2 from the atmosphere to prevent runaway climate change.
- Around 61 per cent of the largest emitting countries have committed to net zero targets, which are inherently reliant on carbon removal options, such as bioenergy with carbon capture and storage (BECCS).
- A worst-case scenario of over reliance on BECCS policies and their poor implementation could delay or deter emissions reductions, and result in 'imagined offsets'. One analysis indicates that this could cause an additional temperature rise of up to 1.4°C.
- While scientists treat models as 'experimental sandpits', policymakers tend to see them as 'truth machines'. As a result, there is a clear risk of policy and market support mechanisms developing ahead of resolving crucial scientific and engineering uncertainties. The UK is leading efforts to develop policies and market frameworks to support BECCS, and must do so cognisant of the risks of under-performance and supply chain impacts, especially if BECCS is scaled internationally.
- This is particularly pertinent given that the 'middle-of-the-road' 2050 IPCC global pathway towards 1.5°C compliant scenarios envisages around 1.5 $GtCO_2$/yr of BECCS removals. If this were supplied solely by wood pellets it would require a scaling of supply by more than 12,000 per cent, relative to what Drax, the UK's largest bioenergy producer, currently combusts at its Selby power plant.
- Due to the potential scaling pressures on wood pellet supply chains, the risk of carbon debt[1] remains of concern. As one recent study pointed out, 'in the US coastal southeast there were fewer live and growing-stock trees and less carbon in soils with every year of milling operation than in the rest of the eastern US'. As such, a diversity of feedstocks should be pursued.

1 Carbon debt: the amount of carbon stored within a tree that must be replaced by the next generation of growth before the emissions captured and stored by BECCS can be considered negative.

- Biomass supply chains embody non-marginal emissions. Setting aside the risk of carbon debt, and assuming robust reporting of supply chain emissions, a future BECCS-to-power plant that combusts wood pellets is likely to exhibit a carbon efficiency[2] of around 76 per cent. Significantly less than the 90 per cent capture rate targeted at the plant level and planned for in models.
- In the UK, wheat straw may be the feedstock with the optimal carbon efficiency: 74–72 per cent of CO_2 is geologically stored, and 26–28 per cent emitted to the atmosphere. As such, for a finite land area, wheat straw based BECCS would remove more CO_2 from the atmosphere, compared to other feedstocks.
- Based on the UK's Committee on Climate Change (CCC) 2050 further ambition scenario for BECCS-to-power, if 100 per cent of the feedstock were provided by domestically grown wheat straw, 27–31 per cent of the UK's current agricultural land area would be required, a substantial proportion that could have implications for food prices.
- There is a clear trade-off between the energy generation efficiency and capture rate. There are indications that first generation BECCS-to-power facilities will exhibit lower power generation efficiencies than that envisaged by the CCC. Inefficient BECCS power plants would likely require a greater carbon removal subsidy to maintain operation as power revenues would be relatively low compared to efficient equivalents.
- If BECCS is to play the crucial role that models, policymakers and net zero targets imply, then carbon efficiencies and the energy output–capture rate trade-off needs to be at the heart of policy development, otherwise there is a risk that already tight carbon budgets become unresolvable, leading to runaway climate change. As such, policymakers should:
  - Enforce tighter bioenergy supply chain emission regulations that are well monitored and verified; likely to be more attainable if feedstocks are domestically grown.
  - Prioritize reductions over removals, ensuring that proven low-carbon technologies are deployed with earnest, options for demand reduction are given political priority, and green hydrogen is swiftly developed.
  - Legislators should consider separating net zero targets into reductions and removals, with an appropriate split that represents the current uncertainty in the overall BECCS system performance, inclusive of supply chain emissions. Overtime, a regular review cycle could expand the role of removals as BECCS performance moves from being masked behind commercial confidentiality to meeting key performance indicators.

2 Carbon efficiency can be thought of as the proportion of carbon input to the whole BECCS system that is geologically stored.

01 Introduction

The slow pace of decarbonization has resulted in high reliance on atmospheric CO_2 removal, which is mainly represented by BECCS in climate models, to prevent runaway climate change. However, removal offsets present significant risks.

Climate scientists fear that runaway climate change could occur if world temperatures increase by more than 2°C. Current global warming sits at around 1°C above pre-industrial levels,[3] CO_2 emissions continue to remain stubbornly high, and the COVID-19 pandemic and associated lockdowns have had little impact on long-term emission reductions.

As the world wrestles with the reality that we are failing to decarbonize the global economy with sufficient speed and an overshoot of carbon budgets looks increasingly likely, policymakers are turning to solutions that could remove CO_2 from the atmosphere, collectively known as greenhouse gas removals (GGRs), and deal with residual emissions.[4] Within many global climate change mitigation scenarios, including those assessed by the IPCC, bioenergy with carbon capture and storage (BECCS) is often the most relied upon of the various GGR options.

The shift away from straightforward reduction targets and towards combined reductions and removals targets has galvanized more countries to pledge and legislate for more ambitious climate action. While this should be applauded, society also needs to step back and scrutinize methods of reaching net zero, specifically, the implications and risks of negative emission technologies (NETs) like BECCS. Failure to consider the trade-offs and system impacts of BECCS will undoubtedly have consequences.

3 National Centers for Environmental Information (2020), 'Global Climate Report – Annual 2020 State of the Climate', https://www.ncdc.noaa.gov/sotc/global/202013.
4 Residual emissions: emissions that remain after all technically and economically feasible opportunities are implemented.

In 2018, a report from the European Academies Science Advisory Council, which advises the EU and is comprised of the national science academies of the 27 member states, highlighted that relying on NETs, including BECCS, rather than pursuing greater emissions reductions, could catastrophically fail, resulting in 'serious implications for future generations'.[5]

There are various forms of BECCS, each with a different energy output, principally BECCS-to-power, hydrogen, and biofuels (see Box 1 for more information). This paper examines some of the major trade-offs and risks associated with BECCS-to-power. Chapter 1 sets out the role of BECCS within carbon budgets, the growing global scale of reliance, how influential models have forged the role of BECCS, as well as describing the UK's leading role in developing BECCS and the risks of removals offsets. Chapter 2 looks at the need to ensure that the boundary of the system is correctly defined, and the necessary land requirements. Chapter 3 investigates the efficiency of BECCS power plants and how inefficient facilities could provide greater removals. Chapter 4 characterizes the risks of carbon debt as BECCS is scaled up, and the carbon efficiency of various feedstocks. Chapter 5 looks at the optimal feedstock option for BECCS, under the UK's Committee on Climate Change (CCC) further ambition scenario, and the implications for land and costs. Finally, Chapter 6 recommends steps to minimize reliance on BECCS and reduce the risks.

Box 1. What is BECCS?

GGRs can broadly be broken down into nature-based solutions (NBS), such as afforestation, and NETs, which are principally comprised of BECCS and direct air carbon capture and storage (DACCS). BECCS refers to any technology that utilizes bioenergy to produce energy, while also capturing and storing the majority of the CO_2 emissions. Bioenergy could take the form of woody biomass (whole trees and forest wastes, such as thinnings) or dedicated bio-crops such as switchgrass, and agricultural wastes and residues. The produced energy can take the form of electricity, hydrogen or biofuels.

All crops and trees absorb atmospheric CO_2 as they photosynthesize. If CO_2 emissions from the combusted biomass (in the case of BECCS-to-power) can be captured and stored, and the combusted biomass replaced by new growth, then in aggregate CO_2 could be removed from the atmosphere. This is contingent on emissions along the supply chain being sufficiently low as to not counteract the CO_2 stored.

Carbon capture and storage (CCS) is therefore key to transforming a bioenergy power plant into a BECCS facility. The 'capture rate' is the proportion of CO_2 that the CCS equipment captures, relative to that released to the atmosphere, and is generally cited as being 90 per cent or more. Post-combustion capture generally utilizes a solvent that the stack emissions are passed over. The molecules of the solvent attach themselves to CO_2 molecules, which are then released from the solvent by applying heat. This heat can be supplied from the combustion of the initial biomass. However, this is the same heat that is being utilized within the turbine to generate electricity. As such, there is an 'energy penalty' attached to the CCS process that lowers the efficiency

5 EASAC (2018), *Negative emission technologies: What role in meeting Paris Agreement targets?,* Halle (Saal): European Academies Science Advisory Council, https://easac.eu/publications/details/easac_net.

of the BECCS power plant relative to an equivalent bioenergy power plant. Or in other words, BECCS-to-power facilities will experience greater declines in power production efficiency to achieve higher capture rates.

The permanence of stored CO_2 is critical, as is the ability of the system to safely and efficiently transport the captured CO_2 to underground geological formations. Furthermore, if the geologically stored CO_2 is used for enhanced oil recovery (EOR), which has been the case with some CCS projects (such as Petra Nova in Texas), oil-based emissions could increase, as injecting captured CO_2 into otherwise disused oil wells raises the pressure and allows more oil to be extracted.

1.1 Carbon budgets, net zero targets and the role of BECCS

Climate scientists and policymakers often talk in terms of carbon budgets. The IPCC defines these carbon budgets in relation to staying below 2°C of global warming, or as the Paris Agreement sets out, 'well below 2°C'. Beyond this level, runaway climate change could be triggered as climatic and Earth system feedback mechanisms release increasing volumes of greenhouse gases (GHGs). For instance, as temperatures rise, the permafrost in Russia increasingly melts. This results in the release of methane that is 30 times more potent a GHG than CO_2 over 100 years, hence global temperatures could accelerate. The IPCC climate models show a cluster of abrupt shifts or tipping points that are likely to be initiated between 1.5°C and 2°C.[6] The initiation of these tipping points could hugely accelerate climate change and generate catastrophic impacts for people and societies the world over. Carbon budgets tend, therefore, to be defined in relation to staying below 2°C in 2100.

The IPCC climate models show a cluster of abrupt shifts or tipping points that are likely to be initiated between 1.5°C and 2°C. The initiation of these tipping points could hugely accelerate climate change and generate catastrophic impacts for people and societies the world over.

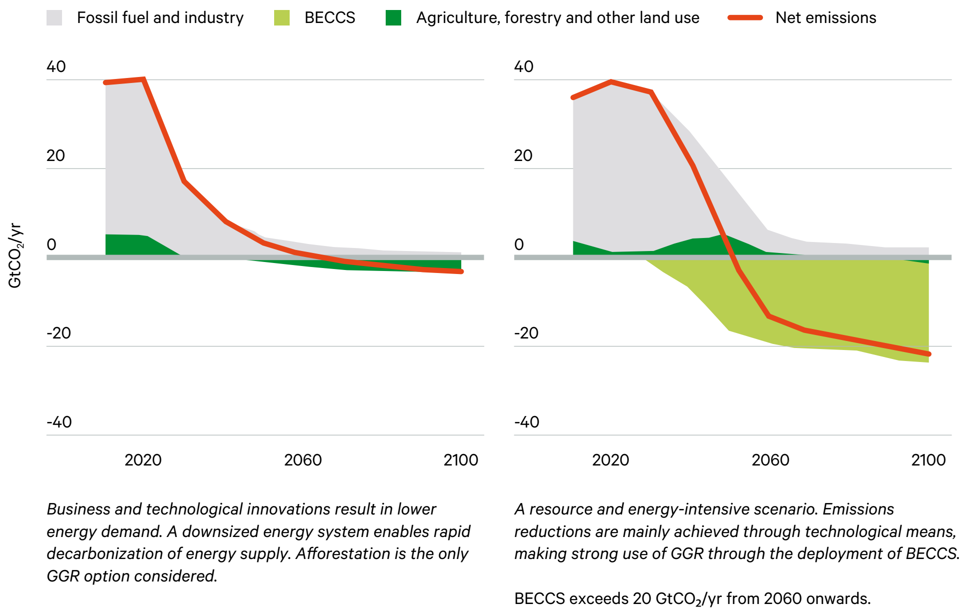
For a 50 per cent chance of limiting warming to 1.5°C, the world has a carbon budget of 770 gigatonnes of carbon dioxide ($GtCO_2$).[7] The global carbon budget rapidly

6 Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G. and Swingedouw, D. (2015), 'Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models', *Proceedings of the National Academy of Sciences of the United States of America*, 112(43), doi:10.1073/pnas.1511451112.
7 IPCC (2018), *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,* Geneva: Intergovernmental Panel on Climate Change, https://www.ipcc.ch/sr15.

shrinks for a greater probability of averting worse impacts of climate change. For a 67 per cent chance, the carbon budget drops to 570 $GtCO_2$. Both these budgets are already substantially smaller today than when they were defined by the IPCC in 2018. The slow speed of global decarbonization and growing demand for energy has created an inevitable need to remove CO_2 from the atmosphere. Under current emissions trajectories, the chance of limiting global warming to 1.5°C is less than 1 per cent.[8]

The high emitting countries of the G20 have failed to deploy low-cost, low-carbon technologies – such as solar PV, wind turbines, electric vehicles, heat pumps and electric arc furnaces – with sufficient speed. This lack of action, combined with the political disdain for constraining demand for high-carbon products and energy services, has led to the reliance on removing CO_2 from the atmosphere – namely via GGRs, including BECCS. Regardless of the historic failure to reduce carbon emissions, some sectors of the economy remain challenging to decarbonize, such as high temperature industrial processes, shipping, aviation and agriculture. These emissions are collectively known as residual emissions and, on top of the shortfall of carbon budgets, create the need for GGRs like BECCS.

Figure 1. IPCC illustrative pathways towards balanced carbon budgets, and the role of BECCS



Source: IPCC (2018), *Global Warming of 1.5°C*, p. 14.

While 2050 net zero targets often do not explicitly define the level of GGRs,[9] they implicitly rely upon BECCS and other engineered GGR options. The alternative would be closer to an absolute-zero target, where reliance on GGRs is significantly minimized. An example of this can be seen in Figure 1, where emissions are rapidly

8 CCC (2018), *UK-China Cooperation on Climate Change Risk Assessment: Developing Indicators of Climate Risk*, London: Climate Change Committee, https://www.theccc.org.uk/publication/indicators-of-climate-risk-china-uk.
9 Rogelj, J., Geden, O., Cowie, A. and Reisinger, A. (2021), 'Net-zero emissions targets are vague: three ways to fix', *Nature*, 591(7850), doi:10.1038/d41586-021-00662-3.

decreased as 'business and technological innovations result in lower energy demand', and GGR is provided by natural systems, such as afforestation. Six countries have now legislated for net zero (including the UK), a further six have proposed net zero legislation (including the EU),[10] Chinese President Xi has pledged carbon neutrality by 2060,[11] and President Biden has pledged to implement net zero legislation.[12]

1.2 The scale of BECCS being relied upon

One of the seminal papers to advocate the advantages of BECCS anticipated removals of 12 $GtCO_2$/yr in 2100.[13] Most of the integrated assessment models (IAMs) utilized by the IPCC to assess future emissions and carbon budgets heavily rely on NETs. In the 2018 IPCC special report on *Global Warming of 1.5°C* (SR1.5),[14] 81 of the 90 scenarios relied on NETs.[15] The pathways consistent with limiting global warming to 1.5°C required 0 to 8 $GtCO_2$/yr of BECCS removals by 2050. As can be seen in Figure 1, BECCS exceeds 20 $GtCO_2$/yr of removals from 2060 onwards in the extreme IPCC illustrative scenario, equivalent to almost two-thirds of current annual energy sector emissions. However, a more cautious assessment in a systematic review of the literature concluded that the most likely scope for BECCS, accounting for other sustainability aims, was 0.5–5 $GtCO_2$/year.[16] The 'middle-of-the-road' IPCC pathway illustrates around 1.5 $GtCO_2$/yr of BECCS removals globally by 2050. In this pathway, technological development follows historical patterns. Under an International Energy Agency (IEA) 'beyond 2°C' scenario, BECCS deployment reaches 4.9 $GtCO_2$/yr by 2060,[17] however, under the IEA's most recent net zero analysis reliance on BECCS has decreased, '1.9 Gt CO_2 are removed in 2050 via BECCS and DACCS'. [18]

1.3 BECCS in the integrated assessment models

The IAM models are critical in influencing climate policy, globally and nationally. They underpin the decarbonization pathways published by the IPCC, which national governments look to when setting their national targets and legislation.

IAMs are complex modelling frameworks that span diverse disciplines, such as energy systems, land use, climate and macroeconomic modelling. As with all models, the quality of the output is constrained by the quality of the underlying

10 Energy & Climate Intelligence Unit (2021), 'ECIU Net Zero Tracker', https://eciu.net/netzerotracker.
11 UN News (2020), '"Enhance solidarity" to fight COVID-19, Chinese President urges, also pledges carbon neutrality by 2060', https://news.un.org/en/story/2020/09/1073052.
12 *Guardian* (2021), 'The race to zero: can America reach net-zero emissions by 2050?', https://www.theguardian.com/us-news/2021/mar/15/race-to-zero-america-emissions-climate-crisis; S&P Global Market Intelligence (2021), 'Biden to use first 100 days to jump-start climate change agenda', https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/biden-to-use-first-100-days-to-jump-start-climate-change-agenda-62101500.
13 Smith, P. et al. (2016), Biophysical and economic limits to negative CO_2 emissions, *Nature Climate Change*, 6(1), doi:10.1038/nclimate2870.
14 IPCC (2018), *Global Warming of 1.5°C.*
15 Carbon Brief (2018), 'In-depth Q&A: The IPCC's special report on climate change at 1.5C', https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c.
16 Fuss, S. et al. (2018), 'Negative emissions – Part 2: Costs, potentials and side effects', *Environmental Research Letters*, 13(6), doi:10.1088/1748-9326/aabf9f.
17 IEA (2017), *Energy Technology Perspectives 2017*, Paris: International Energy Agency, https://www.iea.org/reports/energy-technology-perspectives-2017.
18 IEA (2021), 'Net Zero by 2050 – A Roadmap for the Global Energy Sector', https://www.iea.org/events/net-zero-by-2050-a-roadmap-for-the-global-energy-system.

assumptions. In the case of BECCS, these assumptions include the amount of energy produced for a given input of bioenergy feedstock, the capture rate, and supply chain emissions, to name a few.

Critical to understanding why many of the IAM scenarios indicate such heavy reliance on BECCS is their cost optimizing nature.[19] The models attempt to find the least-cost means of achieving a given temperature limit. As BECCS is anticipated to produce energy and remove atmospheric CO_2 simultaneously, and that both these societal goods have associated costs and benefits to them, it is arguable that there is an inbuilt bias in IAMs towards selecting BECCS. This is concerning as many of the cost assumptions pertaining to decarbonization options within the IAMs are out of date, such as solar PV and other renewables,[20] which have rapidly fallen in cost over the last decade.

A recent analysis of six IAMs by Butnar et al. (2020) provides an excellent resource with which to understand the quality of the BECCS parameters within the IAMs.[21] Many assumptions lack transparency, this is particularly true of the technological elements of BECCS, such as the transport and storage of CO_2,[22] as can be seen in Figure 2. Of particular importance is that all six IAMs Butnar et al. (2020) assessed assume the bioenergy burnt within a BECCS facility is carbon neutral. Or in other words, that the emissions associated with producing the bioenergy is sequestered over the life-time growth of the biomass. However, as is discussed in Chapter 4, supply chain emissions are non-marginal.

Another key observation from Butnar et al. (2020) is that the efficiency of BECCS in converting feedstock embodied energy to useful energy often depends on exogenous inputs to the IAM models.[23] Hence, these inputs are determined outside the model and are not therefore dynamically connected to other model parameters. The efficiency of BECCS is crucial. Taking the example of a BECCS-to-power facility: if the generating efficiency of the facility is low then the power produced for a given input of feedstock will be lower, meaning it is less likely to be selected by the cost optimizing IAMs (energy has an associated cost). However, as discussed in Box 1, the efficiency of BECCS in producing power is causally linked to the capture rate. The more CO_2 that is captured, the more heat (in post-combustion capture) that is required to separate the solvent from the captured CO_2. Hence, IAMs utilizing exogenous efficiencies and capture rates is concerning if these two exogenous inputs are not consistent with each other, given they are causally connected.

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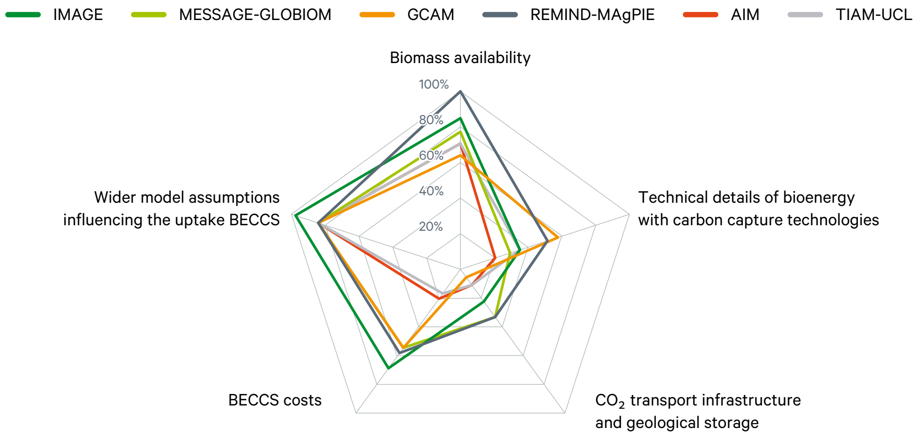
19 Gambhir, A., Butnar, I., Li, P-H., Smith, P. and Strachan, N. (2019), 'A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS', *Energies*, 12(9), doi:10.3390/en12091747.
20 Ibid.
21 Butnar, I., Li, P-H., Strachan, N., Pereira, J. P., Gambhir, A. and Smith, P. (2020), 'A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): A transparency exercise', *Environmental Research Letters*, 15(8), doi:10.1088/1748-9326/ab5c3e.
22 Ibid.
23 Ibid.

Figure 2. Summary of IAM transparency ranking of BECCS modelling assumptions



Source: Butnar, Li, Strachan, Pereira, Gambhir and Smith (2020), 'A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): A transparency exercise'.
Note: Percentages represent transparency of each IAM as percentage of full transparency of modelling assumptions, i.e. 100 per cent equate to fully transparent assumptions.

1.4 The UK must be cognisant of offsetting risks

The UK is one of the countries leading the development of BECCS. The UK's CCC forecasts 51 million tonnes of carbon dioxide per year ($MtCO_2$/yr) of BECCS removals by 2050, under its further ambition scenario.[24] This would be equivalent to around 12 per cent of 2019 GHG emissions. The UK is developing policy and market frameworks to support BECCS, as is evident in the following ways:

- The UK government recently conducted a public consultation on GGRs;
- The CCC has published various net zero scenarios that heavily rely on BECCS;
- A decision on government subsidy support for BECCS is pending;
- The Department for Business Energy and Industrial Strategy (BEIS) published a white paper in December 2020 – *Powering our Net Zero Future* – which describes BECCS biomass as 'one of our most valuable tools for reaching net zero emissions';[25] and
- A biomass strategy is due in early 2022, which 'will establish the role which BECCS can play in reducing carbon emissions across the economy'.[26]

With around 61 per cent of the largest emitting countries and around 21 per cent of the world's 2,000 largest public companies now committing to net zero, the robustness of the UK's development of BECCS support policies is crucial in ensuring

24 CCC (2019), *Net Zero: The UK's contribution to stopping global warming,* London: Climate Change Committee, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming.
25 BEIS (2020), *Energy white paper: Powering our net zero future*, London: Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future.
26 Ibid.

BECCS does not undermine efforts to decarbonize, and simply result in a shift towards offsetting fossil fuel emissions, rather than reducing them. Recent reports have highlighted this risk, for instance, the ECIU's March 2021 report states, 'reliance on them [offsets including removal offsets] may present risks to effective mitigation… offsetting cannot be a substitute for significant emissions cuts'.[27]

Historically, offsetting has been constrained to afforestation, an NBS form of atmospheric CO_2 removal. When this type of carbon sink enhancement is traded in carbon markets, emissions continue elsewhere.[28] The development of NETs as a form of GGR has increased the scope of potential offsets that could be utilized by companies. Microsoft is considering using BECCS and DACCS, British Airways' parent company IAG is exploring DACCS, and of the 42 companies that had announced net zero targets in 2019–20, nearly two-thirds plan on using NETs.[29] Many of these companies simply plan on compensating for emissions with offsets, rather than committing to actual reductions.[30]

The UN's clean development mechanism (CDM) is the world's largest and oldest offsetting scheme. In 2016, the EU determined that only 2 per cent of CDM credits had a 'high likelihood' of delivering CO_2 reductions.[31] Assessment of the first 14 applications of offsetting programmes under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) 'hardly meet any of the requirements and may not even be considered carbon-offsetting', and 'most programs do not yet have procedures in place or planned for avoiding double counting'.[32] The risks of double counting and reducing decarbonization efforts are real, as was recently highlighted by Rogelj et al. (2021) – 'sometimes the targets [net zero] do not aim to reduce emissions, but compensate for them with offsets… cheap offsets can mean that a company makes limited effort to address its own emissions… targets must specify… whether the intent is to reduce, remove or offset the emissions'.[33]

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27 ECIU (2021), *Taking stock: A global assessment of net zero targets,* London: ECIU, https://eciu.net/analysis/reports/2021/taking-stock-assessment-net-zero-targets.
28 McLaren, D. (2019), 'The problem with net-zero emissions targets', Carbon Brief, 30 September 2019, https://www.carbonbrief.org/guest-post-the-problem-with-net-zero-emissions-targets.
29 Vivid Economics (2020), *An investor guide to negative emission technologies and the importance of land use,* London: Vivid Economics, https://www.vivideconomics.com/casestudy/an-investor-guide-to-negative-emission-technologies-and-the-importance-of-land-use.
30 Rogelj, Geden, Cowie and Reisinger (2021), 'Net-zero emissions targets are vague: three ways to fix'.
31 Cames, M., Harthan, R., Füssler, J., Lazarus, M., Lee, C., Erickson, P. and Spalding-Fecher, R. (2016), *How additional is the Clean Development Mechanism? Analysis of the application of current tools and proposed alternatives,* Freiburg: Öko-Institut eV, https://www.oeko.de/publikationen/p-details/how-additional-is-the-clean-development-mechanism.
32 Schneider, L., Michaelowa, A., Broekhoff, D., Espelage, A. and Siemons, A. (2019), *Lessons learned from the first round of applications by carbon-offsetting programs for eligibility under CORSIA,* Berlin, Zurich, Seattle: Öko-Institut eV, https://www.oeko.de/publikationen/p-details/lessons-learned-from-the-first-round-of-applications-by-carbon-offsetting-programs-for-eligibility-u.
33 Rogelj, Geden, Cowie and Reisinger (2021), 'Net-zero emissions targets are vague: three ways to fix'.

02 The system boundary is crucial

BECCS is often viewed from the perspective of facility level challenges, which risks masking the complexity of the entire system and the inherent trade-offs.

The common narrative surrounding BECCS tends to focus on the capture rate of BECCS facilities. Combined with the assumption that biomass is carbon neutral, this results in a somewhat simplistic conclusion that if the capture rate is high, then the BECCS facility will remove an equivalent amount of CO_2 from the atmosphere to that absorbed by the plants during their growth. As previously mentioned, capture rates are often cited as being 90 per cent or more by BECCS developers, within the IAMs, academic literature and within policy briefings.

BECCS is a complex system, as with all complex systems there are inherent trade-offs between different design criteria (cost vs capture, for example); the trade-offs and nuances need to be front and centre to avoid the downsides and maximize the chance of mitigating climate change. BECCS requires:

— An optimal choice of feedstock, of which there are many, requiring consideration of the supply chain emissions of differing feedstocks and the land required to grow them;

— A balancing of BECCS between energy production or CO_2 capture; and

— The permanent storage of captured CO_2 in underground geological formations.

Given that biomass feedstock supply chains are complex, with countries often importing biomass from other regions, and that the CO_2 needs to be transported to an underground geological formation, there is clearly a need to expand the boundary of the system when analysing the net negativity of BECCS.

The boundary of the system is crucial given the increasing global reliance on BECCS. The UK government would be short-sighted to develop policies without considering the implications of scaling BECCS, as is implicit in the move by so many countries to adopt net zero targets. While the supply chain emissions and land requirements of BECCS might be manageable from the perspective of the UK sourcing biomass to offset its residual emissions, the pressure on those supply chains and land as BECCS is scaled could lead to increasingly sub-optimal outcomes.

2.1 Capture rates are critical, but risk hiding the whole story

Both CCS and BECCS are still very much in development. CCS has been under development for many years, but despite political support, the global roll-out of CCS has not yet occurred. In 2007, the EU committed to deploying 12 demonstration power plants by 2015, and new fossil fuel power plants fitted with CCS by 2020. To date, these projects are yet to materialize.[34]

CCS capture rates require third-party verification to confirm that the technology performs as well as is claimed by those in the industry. This is of particular importance as more BECCS is incorporated into country policies.

CCS capture rates require third-party verification to confirm that the technology performs as well as is claimed by those in the industry. This is of particular importance as more BECCS is incorporated into country policies. The handful of CCS demonstration facilities that have been built, for which there is third-party verification, indicate the real-world, whole system capture net negativity may be substantially lower than the facility level capture rate (often cited as 90 per cent or greater). A third-party study in late 2019 of data from a coal with carbon capture and use (CCU) facility and a synthetic direct air carbon capture and use (SDACCU) facility shows capture rates of less than 11 per cent over 20 years, and 20–31 per cent over 100 years.[35] These significantly lower whole system carbon removal efficiencies are a result of the study factoring in supply chain emissions and emissions associated

34 Froggatt, A., Stevens, P. and Bradley, S. (2020), *Expert Perspectives on Norway's Energy Future*, London: Chatham House, https://www.chathamhouse.org/2020/06/expert-perspectives-norways-energy-future.
35 Jacobson, M. Z. (2019), 'The health and climate impacts of carbon capture and direct air capture', *Energy and Environmental Science*, 12(12), doi:10.1039/c9ee02709b.

with powering the CCS equipment. While this is only one study, and the results do not necessarily translate neatly to BECCS, it does demonstrate the need to look beyond the facility level capture rate and consider the wider system.

2.2 Biomass land requirements

The land required to grow biomass for BECCS is significant and dependant on the choice of biomass feedstock, with potential consequences for food production and biodiversity. Furthermore, biomass will be required for other components of the globally decarbonized energy system, such as biofuels for transport and biomass-based heating. Biomass-based energy is already the largest source of renewable energy worldwide. The majority is consumed as fuelwood, charcoal and agricultural residues in developing countries; an estimated one-third of the global population rely on this source of energy to some extent. Traditional uses of bioenergy accounted for an estimated 9.5 per cent of global primary energy supply in 2018.[36]

The IPCC 2019 report on climate change and land concluded that, 'although estimates of potential are uncertain, there is high confidence that the most important factors determining future biomass supply are land availability and land productivity. These factors are, in turn, determined by competing uses of land and a myriad of environmental and economic considerations.'[37] The IPCC SR1.5 report indicated that 1.5°C compliant pathways would require around 25–46 per cent of arable and permanent crop land in 2100.

36 IEA (2020), *Global primary energy, electricity generation, final consumption and CO_2 emissions by fuel, 2018*, https://www.iea.org/data-and-statistics/charts/global-primary-energy-electricity-generation-final-consumption-and-co2-emissions-by-fuel-2018.
37 IPCC (2019), *Special Report on Climate Change and Land*, Geneva: Intergovernmental Panel on Climate Change, https://www.ipcc.ch/srccl.

03 Inefficient BECCS power plants – the optimal choice?

First generation BECCS power plants could have significantly lower power efficiencies than assumed. Inefficient BECCS would remove more CO_2 for an equivalent generating capacity, but would likely require a greater carbon removal subsidy.

3.1 Maximum power generation or CO_2 capture

An often-overlooked consideration is that to achieve the targeted 90 per cent, or higher, capture rates in BECCS-to-power plants, there is a significant energy requirement from the CCS equipment. Post-combustion capture requires heat to release the CO_2 molecules captured by the solvent, and additional energy is required to compress the captured CO_2 so that it can be piped to storage sites. This 'energy penalty' has the consequence of reducing the efficiency of the facility in converting the embodied energy of the biomass into electricity. As such, the capture rate and energy efficiency of the BECCS-to-power facility are intrinsically and inversely connected, creating a trade-off between power production and CO_2 capture. Or in other words, the more efficient at producing power a BECCS facility is, the less CO_2 that is captured.

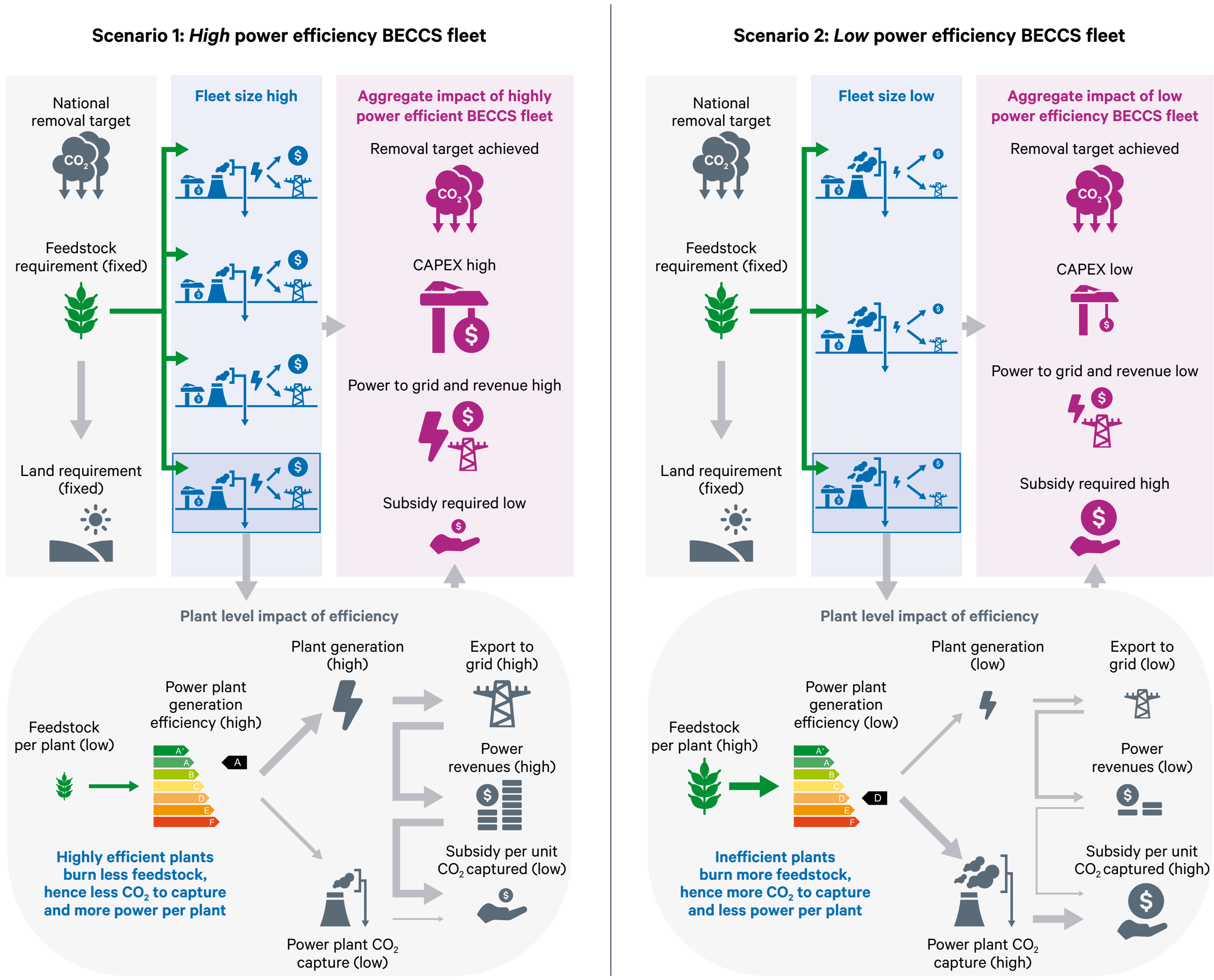
Another way of looking at this is to start with the nameplate generating capacity of a BECCS power plant, and ask – how would a reduction in power efficiency impact the CO_2 capture potential? Given that Drax is seeking to become one of the UK's first BECCS power plants, it is interesting to start with its current bioenergy power plant and play through the thought experiment in this context. Drax's Selby biomass facility has a capacity of 2.6 gigawatts (GW), producing around 14.1 terawatt hours per year (TWh/yr) of power from 7,374 kilotonnes (kt) of wood pellets, which equates to around 38.9 TWh of embodied energy and 13.3 $MtCO_2$ of embodied CO_2 within the wood pellets.[38] As such, the efficiency of the wood pellet power plant is around 36.2 per cent, and the load factor[39] is around 62 per cent, meaning power was generated for nearly two-thirds of the year. It is the embodied CO_2 of the wood pellets that could, in the future, be captured by the CCS equipment.

Assuming a 90 per cent capture rate, there are two ways in which the volume of captured CO_2 could potentially be increased. Firstly, the power plant could run for a greater proportion of the year – increasing the load factor. This would require the dispatch protocol of the power plant to change, which – if the government chose to give BECCS-to-power plants priority dispatch to the grid – would be perfectly feasible, in effect turning BECCS-to-power plants into baseload power generators, rather than load following on the grid.[40] This would, however, lower system flexibility and hence reduce the amount of variable renewables that could be integrated into the network. Secondly, the BECCS-to-power plant could decrease its power efficiency, in doing so it would combust more wood pellets to generate the same amount of power, hence the CO_2 available to potentially capture increases. In both instances, the limiting constraint is the generating capacity of the facility (currently 2.6 GW at Selby).

As a result of this trade-off it would be reasonable to suggest that a future UK BECCS removal target should define a fixed amount of biomass to be used within BECCS facilities, either domestically grown within the UK or imported. And as such, the efficiency of future BECCS power plants should simply be as high as possible to provide maximum power generation, as this would in turn increase revenues and hence decrease the subsidy that BECCS facilities would require to capture CO_2.[41] This is a valid argument, but there are still downsides, principally that the number of BECCS facilities (or to be more accurate turbines) would need to increase. This is because the nameplate generating capacity of BECCS facilities running at maximum load factor limits the amount of biomass a given turbine can process. Figure 3 illustrates this highly efficient BECCS fleet future (scenario 1), as compared to a fleet of inefficient BECCS power plants (scenario 2). As can be seen, the efficient facilities generate more power and hence revenues, lowering the CO_2 capture subsidy, at the expense of more turbines being required. As each BECCS turbine has an associated capital expenditure (CAPEX), the cost to build the infrastructure is relatively high. In scenario 2, the lower efficiency facilities each combust a greater volume of feedstock, capture more CO_2 per facility, but generate less power revenues. Meaning the aggregate CAPEX is lower, but the subsidy requirement would be relatively high.

38 Drax Group plc (2021), *Drax Group plc Annual report and accounts 2020*, https://www.drax.com/wp-content/uploads/2021/03/Drax_AR2020.pdf.
39 Load factor: average load divided by the peak load in a specified time period.
40 Load following: a power plant that responds to demand on the network, rather than either a variable renewable or a baseload facility like a nuclear power plant.
41 This 'subsidy' does not necessarily need to take the form of a direct payment from the government to the BECCS facility. It could be a market mechanism, for which consumers ultimately pay the cost.

Figure 3. The impacts of power efficiency of a future BECCS fleet on subsidies and aggregate CAPEX



Source: Compiled by the author.
Note: Applicable to BECCS-to-power and assumes each BECCS power plant runs at maximum load factor in baseload operation.

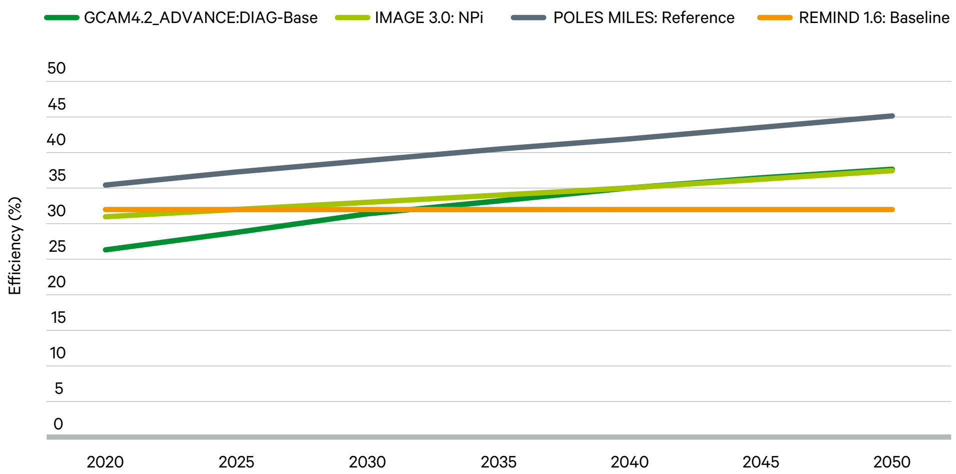
Another way of looking at Figure 3, would be to say that the biomass feedstock volume is not fixed, and that a fixed capacity of BECCS power plants can combust any amount of biomass feedstock. In this case, inefficient facilities would capture the greatest volume of CO_2, would have a relatively lower CAPEX, but would require a relatively high subsidy.

Given the Drax group is pioneering post-combustion BECCS technologies, it is informative to compare the efficiency of a Drax-like BECCS power plant to the efficiencies within the IAMs. Current R&D trials at Drax indicate an energy penalty of around 170 megawatts (MW) for each 630 MW turbine,[42] which if not improved upon would imply the overall efficiency of the BECCS-to-power facility could fall from 36.2 per cent to 20.9 per cent, relative to the same plant without CCS. As such, if the first of a kind (FOAK) BECCS power plant is to be a Drax-like

42 Baringa (2021), *Value of Biomass with Carbon Capture and Storage (BECCS) in Power: Summary Report*, Drax, https://www.drax.com/wp-content/uploads/2021/04/Drax-Baringa-Report-Summary-2021.pdf.

BECCS facility, we seem to be heading towards inefficient facilities relative to that assumed within the IAMs (Figure 4). For example, of the IAM models, by 2030, GCAM assumes an efficiency of 31.3 per cent, IMAGE 32.9 per cent, POLES MILES 38.8 per cent and REMIND 32 per cent.[43]

Figure 4. Efficiency of BECCS assumed within IAMs



Source: Krey et al. (2019), 'Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models'.

3.2 Inefficiency reduces societal good

Although inefficient BECCS power plants might have a greater potential to capture more CO_2, the global economy has become accustomed to cheap and readily available energy. Not only is the energy output important, but so too is the energy input to derive the output. Energy return on energy invested (EROEI) is the ratio between the amount of usable energy, relative to the amount of energy used to obtain that usable energy. For BECCS-to-power, example energy inputs include: the drying of the biomass, and the other pelleting processes, energy used for transportation and the energy penalty. An EROEI of one would indicate the useable energy of a given technology is equal to the amount put in, and indeed EROEI declines exponentially as it approaches one. It has been known for many years that the EROEI of bioenergy is significantly lower than other renewables. A report commissioned by the UK government in 2013 highlighted that while oil and gas had a global EROEI of around 35 in 1999, wind power 18 and solar PV 6 to 12, biodiesel in the US was as low as 1.3.[44] There is, however, a large variety in the methodologies

43 Krey, V. et al. (2019), 'Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models', *Energy*, 172: pp. 1254–1267, doi:10.1016/j.energy.2018.12.131.
44 Department for International Development (2013), *EROI of Global Energy Resources: Status, Trends and Social Implications*, https://www.gov.uk/research-for-development-outputs/eroi-of-global-energy-resources-status-trends-and-social-implications.

used to calculate EROEIs,[45] principally relating to the boundary of the system within which energy inputs and outputs are defined. For instance, solar PV EROEIs range between 1.6 and 12 and biofuels 0.8 to 10.[46]

In relation to BECCS, a 2018 paper highlighted that, 'Implicit in these scenarios [IAMs] is the assumption that BECCS is a net producer of energy… the net electricity balance of a UK-based BECCS facility can be either positive or negative'.[47] The paper calculated the EROEI for various feedstocks, with power plant efficiencies of 26 per cent, finding that domestic wheat straw produced 0.16 megajoules (MJ) of electricity for every 1 MJ of bioenergy input to the system, when energy inputs along the supply chain were accounted for. Wheat straw performed marginally better than switchgrass and miscanthus, with SRC willow nearing an EROEI of 1.

The careful planning and consideration of BECCS supply chains could increase the EROEI, and hence the useful energy to society. However, if poorly managed, and the energy output of BECCS relied upon to displace energy and emissions from fossil fuels, low BECCS EROEI's could actually lead to an increase in fossil fuels, due to their utilization as inputs along the supply chain, and hence threaten energy security.[48]

45 Fajardy, M. and Mac Dowell, N. (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?', *Energy & Environmental Science*, 11(6), doi:10.1039/C7EE03610H.
46 Murphy, D. J., Hall, C. A. S., Dale, M. and Cleveland, C. (2011), 'Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels', *Sustainability*, 3(10): pp. 1888–1907, doi:10.3390/su3101888.
47 Fajardy and Mac Dowell (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?'.
48 Ibid.

04 Feedstock choice: Carbon efficiency and carbon debt

The risks of carbon debt remain a concern due to potential scaling pressures on wood pellet supply chains. In the UK, wheat straw may provide the optimal carbon efficiency as a feedstock.

There has been much debate over supply chain emissions of wood pellets, both in the context of BECCS and traditional biomass power plants.[49] The Drax power plant in the UK is the largest importer of wood pellets in Europe. Drax has put significant efforts into trying to ensure its supply chain is decarbonized and attempting to ensure that the sourcing of its wood pellets is sustainable. The subsidies it receives from the UK government are dependent on adherence to sustainability criteria, which include requirements for legal and sustainable sourcing (including provisions for minimizing harm to ecosystems as well as for maintaining the productivity of the forest and ecosystem biodiversity health and vitality) and targets for GHG savings per unit of electricity (though this only covers emissions from the supply chain of the feedstock – harvesting, processing and transport; emissions from combustion are excluded on the assumption these are recaptured by forest growth).

Under GHG reporting requirements, biomass is considered carbon neutral at the point of combustion. However, the reality of supply chain emissions and potential carbon debt could result in wood-pellet-based BECCS failing to deliver the negative

49 Brack, D., Hewitt, J. and Marchand, T. M. (2018), *Woody Biomass for Power and Heat: Demand and Supply in Selected EU Member States*, London: Chatham House, https://www.chathamhouse.org/2018/06/woody-biomass-power-and-heat.

emissions that are technically possible. Carbon debt is the amount of carbon stored within a tree, plus the emissions from the supply chain of the feedstock, that must be replaced by the next generation of growth before the emissions captured and stored by BECCS can be considered negative. The following sections discuss carbon debt in the context of current sourcing of wood pellets from forests in the southeast of the US – where Drax sources more than 60 per cent of its wood pellets – and how the pressures on supply chains as BECCS scales up in the future could cause carbon debt to become a significant issue.

4.1 Carbon efficiency of a UK Drax-like wood pellet supply chain

Before turning to the carbon debt of wood pellets, it is worth examining the potential carbon efficiency of a future UK BECCS power plant on the basis of Drax's supply chain emissions, as Drax itself reported in 2021.[50] Figure 5 shows the supply chain emissions, converted into carbon efficiency, factoring in a 90 per cent capture rate and losses due to the energy needed to pipe the CO_2 to the storage site. Carbon efficiency can be thought of as the proportion of carbon input to the whole BECCS system that is geologically stored. Or alternatively, as the proportion of carbon input (i.e. CO_2 sequestered by biomass during growth) to the whole BECCS system that leads to net removal when accounting for life cycle emissions of the biomass feedstock. Carbon efficiency is synonymous with carbon negativity: a carbon efficiency of 0 per cent would result in BECCS being carbon neutral, rather than net negative.[51]

As can be seen from Figure 5, the supply chain emissions that Drax reports,[52] combined with assumptions as to downstream CO_2 losses from the uncaptured emissions, as well as those from transport and storage would see around 24 per cent of the aggregate embodied CO_2 emitted to the atmosphere, and around 76 per cent geologically stored. This of course assumes trees are planted to replace those combusted in the BECCS facility, and ignores the time needed for the growing trees to recapture the carbon emitted on combustion (see the discussion on carbon payback periods below).

In most policy discussions, the capture rate is often referred to as the principal loss of CO_2, and the wood pellets are assumed to be carbon neutral. But as can be seen from Figure 5, emissions from the pelleting, transportation, and piping of the CO_2 to storage sites are not insignificant. Furthermore, it should be noted that Figure 5 does not touch upon or include any arguments surrounding carbon debt and assumes that an equivalent mass of trees is grown to replace that comprising the wood pellets. As such, Figure 5 is free of those debates and is therefore a representation of the carbon efficiency at any given moment of BECCS operation.

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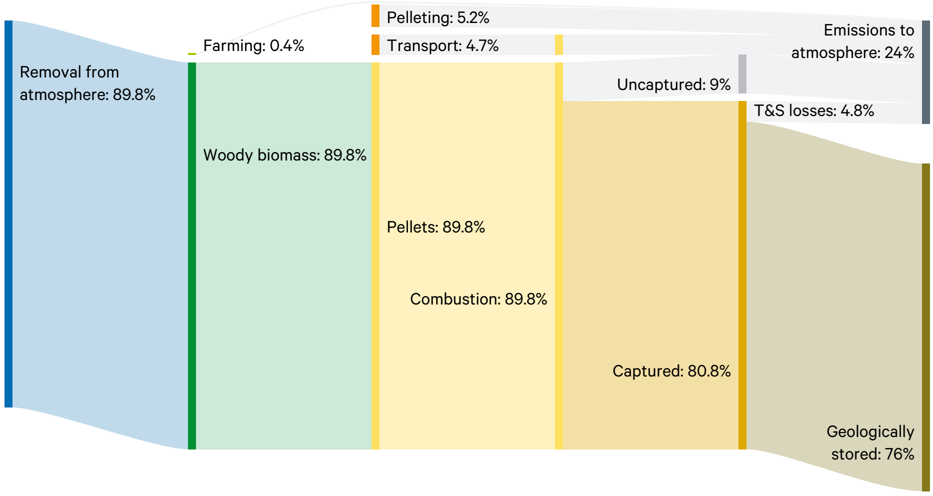
50 Drax (2021), *Drax Group plc Annual report and accounts 2020*.
51 Fajardy, M. and Mac Dowell, N. (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?', *Energy and Environmental Science*, 10(6), doi:10.1039/c7ee00465f.
52 Drax (2021), *Drax Group plc Annual report and accounts 2020*.

Figure 5. Carbon efficiency of a future wood pellet BECCS-to-power plant, based on Drax's current supply chain, assuming a 90 per cent capture rate and 5 per cent transport and storage losses (T&S)



Source: Adapted from Drax (2021), *Drax Group plc Annual report and accounts 2020*.
Note: Values from Drax's annual report converted on the basis of the embodied CO_2 of the wood pellets (1.8 kg CO_2/kg dry matter (DM), also calculated from Drax's annual report).

4.2 The risks of wood pellet carbon debt as BECCS is scaled

As the number of net zero pledges by countries indicates, along with the forecasts of the IEA and IAM pathways of the IPCC SR1.5 report,[53] the future scale up of BECCS could be enormous. As Table 1 indicates, to scale BECCS-to-power solely combusting wood pellets to meet the UK CCC 2050 target of 51 $MtCO_2$/yr would require the combustion of more than four times that currently burnt at Drax, and 126 times greater to meet the 'middle-of-the-road' IPCC 1.5°C pathway, also by 2050. Such a significant global scaling of wood pellet demand risks putting significant pressures on the global supply chains. Clearly alternative feedstock choices are available, other than woody biomass. However, given that the leading BECCS developer uses 97 per cent woody biomass (3 per cent agricultural residues[54]) and the global supply of pellets comprised of other feedstocks remains marginal, the scaling comparison of Table 1 is an indicator of the upper limit to wood pellet scaling over the next 30 years. It is also interesting to note that the UK CCC BECCS removal target of 51 $MtCO_2$/yr would require 119 per cent of the 26 Mt of wood pellets consumed across the EU27 + UK, which in turn represents 50 per cent of global consumption.[55]

53 IPCC (2018), *Global Warming of 1.5°C*.
54 Drax (2021), 'Sourcing Sustainable Biomass', https://www.drax.com/sustainability/sustainable-bioenergy/sourcing-sustainable-biomass.
55 Bioenergy Europe (2019), *Report Pellet*, Statistical Report 2019, https://epc.bioenergyeurope.org/wp-content/uploads/2020/02/SR19_Pellet_final-web-1.pdf.

Table 1. Scaling up BECCS-to-power solely combusting wood pellets to the UK CCC target and global IPCC IAM indications

	EU27 + UK (2018)	Drax (2020)	UK CCC Target* (2050)	Global IPCC** 1.5°C (2050)
Wood pellets burnt/required (Mt)	26	7	31	926
Embodied CO_2 ($MtCO_2$)[56]	47	13	57	1667
CO_2 capture potential (90% capture rate) ($MtCO_2$)	42	12		
CO_2 capture target (90% capture rate) ($MtCO_2$)			51	1500

*Net zero, further ambition scenario;[57] **'*middle-of-the-road*' IPCC 1.5°C compliant pathway.[58]
Source: Compiled by the author.

The initial combustion of biomass, along with the associated life cycle emissions of the biomass feedstock, create what is termed a 'carbon debt'. Over time, regrowth of the harvested forest removes this carbon from the atmosphere, reducing the carbon debt. The period until carbon parity is achieved is usually termed the 'carbon payback period'.

Calculating carbon payback periods is complex, because they depend not only on the type of feedstock used, but on the counterfactual – what would have happened to the feedstock if it had not been used for energy. The shortest carbon payback periods derive from the use of residues and wastes from forest industries that imply no additional harvesting and would otherwise be burnt as waste or left to decay, releasing carbon to the atmosphere in any case. The longest carbon payback periods derive from increasing harvest volumes in managed forests, harvesting natural forests or converting them into plantations, or displacing wood from other uses. Where whole trees are harvested and used for energy, not only is the stored carbon in the tree released into the atmosphere immediately, but the future carbon sequestration capacity of the tree is lost, and it takes time for the residual trees or new trees to compensate. Plantation forests have higher growth rates than natural forests and are typically harvested at a relatively young age, while naturally regenerated forests tend to be older and have larger trees when harvested; therefore, more stored carbon is lost when natural forests are harvested.

On the other hand, in the absence of forest management, the rate of net carbon absorption by most forests falls as the incidence of dead and diseased trees increases, and over time the forest may also become more vulnerable to wildfire or other disturbances. There can, therefore, be benefits over the long term from some

56 These figures represent the emissions released on combustion. A more comprehensive analysis, including emissions from energy use in the supply chain and forgone removals of carbon dioxide from the atmosphere due to the harvesting of live trees and emissions from the decay of roots and unused logging residues left in the forest after harvest, is discussed in Birdsey, R., Brack, D. and Walker, W. (forthcoming 2021), *Greenhouse gas emissions from burning US-sourced woody biomass in the EU and UK,* Research Paper, London: Royal Institute of International Affairs.
57 CCC (2019), *Net Zero: The UK's contribution to stopping global warming.*
58 IPCC (2018), *Global Warming of 1.5°C.*

level of management, and in the absence of demand for wood for energy or other products, many forests may not be managed in a manner that can increase forest carbon stocks.[59] However, this assumes that forest management for conservation is not subsidized in the way that biomass for energy currently is.

It is often claimed that using thinnings of trees from forest management practices – which account for about 30 per cent of Drax's feedstock – results in shorter carbon payback periods because they promote tree growth and allow higher stocking of trees.[60] It should, however, be noted that the evidence on thinning practices indicates forest carbon stocks are either redistributed (to the remaining trees),[61] or decline.[62]

While using wastes and residues as feedstock minimizes the carbon payback period, the volumes available are limited. Thus, as BECCS is developed at scale, there is a risk of using feedstocks with longer and longer carbon payback periods. Particular attention needs to be paid to the carbon payback period if roundwood from mature trees[63] enters the supply chain. This is principally because mature trees take many years to grow, and support greater soil carbon, meaning any next generation tree replacement (plantation saplings) would be subject to a significant carbon payback period. The carbon payback period of a mature tree is likely to be at the upper end of the range of 44–104 years (calculated for a clearcut forest),[64] but could be longer,[65] meaning geologically stored CO_2 from mature trees should not be considered carbon negative until the next generation of trees has grown for this period of time.

Figure 6 illustrates the risks of carbon debt, as wood pellet supply is scaled to service the future global demand from BECCS. It should be noted that the diagram is not applicable to a supply chain of wood pellets derived from plantations grown on marginal or degraded land. As can be seen, the energy requirement to dry high-moisture-content woody biomass, and conversion of mature forests to plantations represent the major potential supply chain emissions. The sustainability criteria in place currently in the UK and EU do not place limits on feedstocks by category, though in July 2021 the European Commission published proposals for modifications to the EU's sustainability criteria, which would end incentives for using saw or veneer logs, stumps and

59 Dale, V. H. et al. (2017), 'Status and prospects for renewable energy using wood pellets from the southeastern United States', *GCB Bioenergy*, 9(8), doi:10.1111/gcbb.12445.
60 Garcia-Gonzalo, J., Peltola, H., Briceño-elizondo, E. and Kellomäki, S. (2007), 'Changed thinning regimes may increase carbon stock under climate change: A case study from a Finnish boreal forest', *Climatic Change,* 81(3): pp. 421–454, doi:10.1007/S10584-006-9149-8.
61 Schaedel, M. S., Larson, A. J., Belote, T., Goodburn, J. M., Page-Dumroese, D. S. and Affleck, D. L. R. (2017), 'Early forest thinning changes aboveground carbon distribution among pools, but not total amount', *Forest Ecology and Management*, 389: pp. 187–198, doi:10.1016/j.foreco.2016.12.018; Zhang, X., Guan, D., Li, W., Sun, D., Jin, C., Yuan, F., Wang, A. and Wu, J. (2018), 'The effects of forest thinning on soil carbon stocks and dynamics: A meta-analysis', *Forest Ecology and Management*, 429: pp. 36–43, doi:10.1016/J.FORECO.2018.06.027.
62 Lin, J-C., Chiu, C-H., Lin, Y-J. and Liu, W-Y. (2018), 'Thinning Effects on Biomass and Carbon Stock for Young Taiwania Plantations', *Scientific Reports,* 8(1), doi:10.1038/s41598-018-21510-x; Bravo-Oviedo, A., Ruiz-Peinado, R., Modrego, P., Montero, G. and Ponce, A. R. (2015), 'Forest thinning impact on carbon stock and soil condition in Southern European populations of P. sylvestris L.', *Forest Ecology and Management*, 357: pp. 259–267, doi:10.1016/J.FORECO.2015.08.005.
63 Mature tree: CO_2 absorbed through photosynthesis near equals the CO_2 output via respiration, hence additional sequestration is significantly lower than that of a fast-growing immature tree.
64 Rolls, W. and Forster, P. M. (2020), 'Quantifying forest growth uncertainty on carbon payback times in a simple biomass carbon model', *Environmental Research Communications*, 2(4), doi:10.1088/2515-7620/ab7ff3; Sterman, J. D., Siegel, L. and Rooney-Varga, J. N. (2018), 'Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy', *Environmental Research Letters*, 13(1), doi:10.1088/1748-9326/aaa512.
65 Holtsmark, B. (2010), *Use of wood fuels from boreal forests will create a biofuel carbon debt with long payback time,* Discussion Papers No. 637, Oslo: Statistics Norway, https://www.ssb.no/a/publikasjoner/pdf/DP/dp637.pdf.

roots, and also prohibit sourcing from primary forests. Transparent monitoring and enforcement of sustainability criteria is often challenging. This is illustrated by investigating the sourcing of wood pellets from the US southeast.

As noted above, Drax complies with the UK's sustainability criteria for solid biomass. The company's 2020 annual report indicates that 36 per cent of its wood pellets are derived from low-grade roundwood. While this may be parts of trees not utilized for wood products, there is a risk that it can contain whole trees, even mature trees. Of the total supply, 63 per cent is sourced from the US southeast, of which 38 per cent is low-grade roundwood. Although Drax diligently reports the categories of feedstock sources used within its own mills, only 20 per cent is currently sourced from pellet mills it directly owns.[66] To ensure wood pellets sourced from suppliers are compliant with regulations, supply chain emissions are minimized and forests sustainably managed, Drax requires suppliers to be certified under the Sustainable Biomass Program (SBP).[67] However, concerns surround potential flaws in SBP standards,[68] with critics concerned SBP certification leaves open loopholes that could undermine the sustainability of wood pellets.

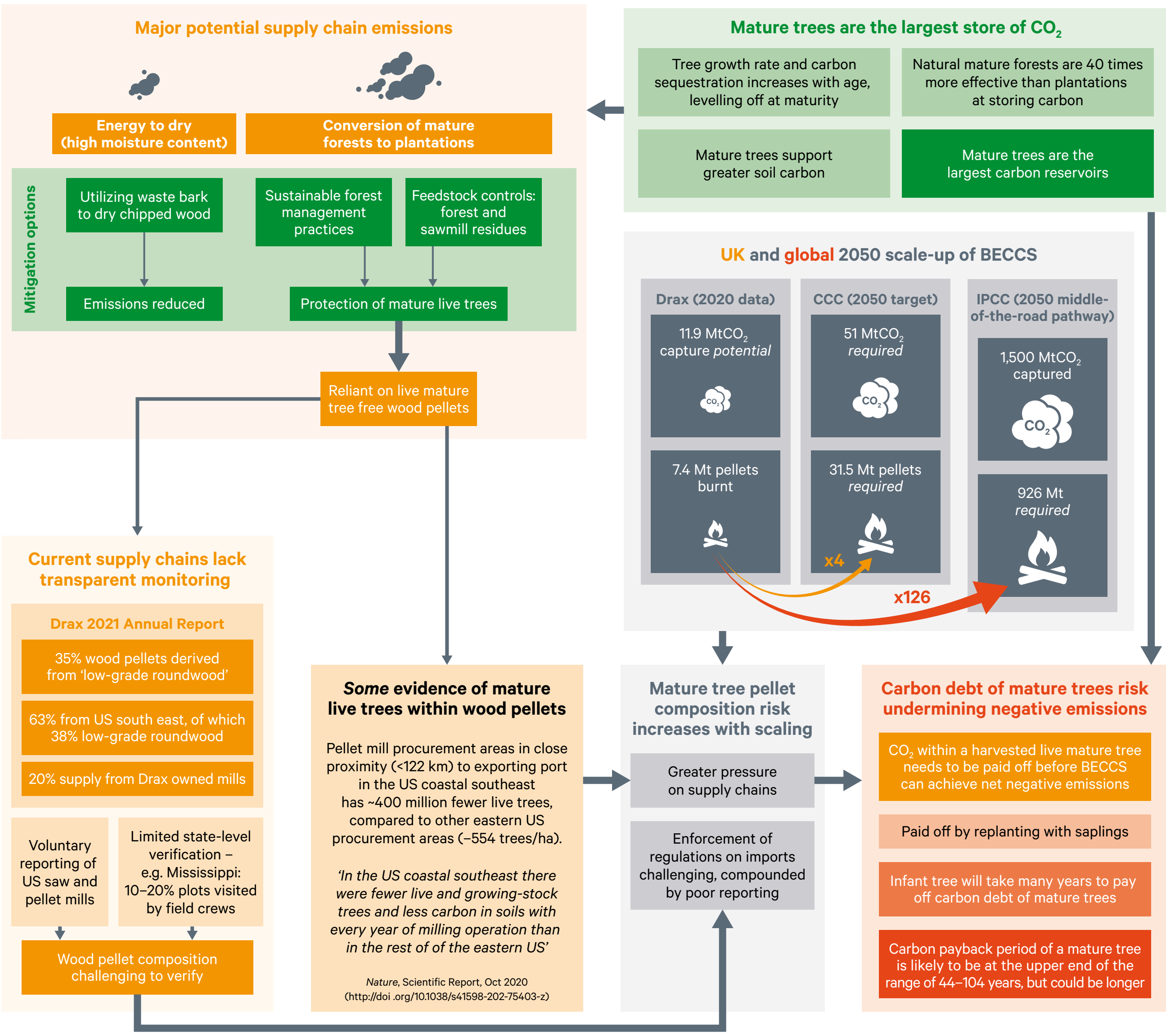
Reporting by saw and pellet mills in the US as to their forest extraction practices is not mandatory. The US Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis (FIA) programme utilizes sampling techniques to estimate the timber product output (TPO). The TPO data provides a means to estimate the feedstock sources used in the mills, as well as the health of forest and carbon stocks.[69] At the forest level, rather than the mill level, the vast areas of the forests and large number of plots necessitates the sampling approach adopted by the FIA. In the state of Mississippi, in 2019, there were nearly 4,000 plots that were forested, with around 10–20 per cent of those plots visited and measured by field crews each year.[70]

Utilizing the FIA data, a 2020 study investigated the impacts of recent wood pellet production expansion in the US. While the study found 'largely positive trends in timberland conditions… potentially negative trends suggests that continued monitoring of localized impacts of wood pellet mill operations is important'.[71] When looking at the specifics of pellet mill procurement areas in close proximity (within 122 km) to exporting ports in the US coastal southeast, the study found around 400 million fewer live trees compared to other eastern US procurement areas, equivalent to 554 fewer live trees per hectare. And importantly the study states that, 'in the US coastal southeast there were fewer live and growing-stock trees and less carbon in soils with every year of milling operation than in the rest of the eastern US'. It should be noted that this is only one study. However, very few studies have recently investigated the specifics of wood pellet demand

66 Drax (2021), *Drax Group plc Annual report and accounts 2020*.
67 Drax (2021), 'Sourcing Sustainable Biomass'.
68 NRDC (2017), *The Sustainable Biomass Program: smokescreen for forest destruction and corporate non-accountability,* https://www.nrdc.org/resources/sustainable-biomass-program-smokescreen-forest-destruction-and-corporate-non.
69 Young, J. B. and Edgar, C. B. (2019), *Advancing Estimation of Timber Products Output in the Lake States Region of the Northern United States,* Minnesota: University of Minnesota, https://conservancy.umn.edu/handle/11299/215045.
70 USDA (2020), 'Forests of Mississippi, 2019', https://public.tableau.com/views/FIA_OneClick_V1_2/Factsheet?%3AshowVizHome=no.
71 Aguilar, F. X., Mirzaee, A., McGarvey, R. G., Shifley, S. R. and Burtraw, D. (2020), 'Expansion of US wood pellet industry points to positive trends but the need for continued monitoring', *Scientific Reports*, 10(1), doi:10.1038/s41598-020-75403-z.

pressures on forest management and sourcing practices in this region. Given wood pellet sourcing in the US southeast has rapidly expanded in recent years, and the potential drawbacks of mill reporting and SBP certification, this study is an early indicator of the risks that increased demand pressure can place on supply chains. If these trends continue the risks of carbon debt associated with wood pellets could correspondingly increase. Considering the 44–104-year carbon payback periods, and that carbon budgets to limit global warming to 2°C run till the end of the century, pressure on wood pellet supply chains should be minimized to mitigate carbon debt risks.

Figure 6. The risks of carbon debt as wood pellet supply chains scale with increased global BECCS demand



Source: Compiled by the author.
Note: Applicable to mature forests, not for instance SRC willow. Not applicable to converting marginal or degraded land.

For an importing country, such as the UK, this future risk could be mitigated by sourcing woody biomass domestically as tight regulations are more easily enforced within a domestic supply chain, rather than import compliance being reliant on voluntary reporting, sampling or inadequate certification schemes.

To mitigate the risks of carbon debt undermining the carbon negativity of BECCS as wood pellet supply chains are scaled up, BECCS feedstocks should be diversified to ease future demand pressures. Furthermore, it is impossible for biomass pellets derived from other bioenergy feedstocks, such as grasses (miscanthus and switchgrass), to be whole trees in disguise. Or in other words, the issues of transparent reporting to ensure the minimization of carbon payback periods from the use of forest biomass all but vanish. That said, other feedstocks can exhibit a carbon debt if significant land-use change (LUC) is required to cultivate the first generation of that feedstock. For instance, if forests were clear felled to grow miscanthus, or indeed grassland or cropland converted. Or indeed if indirect LUC (ILUC) occurs due to displacing the original agriculture. The avoidance of carbon debt and associate payback periods is, therefore, contingent on ensuring that the conversion of land for the growth of bioenergy feedstocks is constrained to marginal and degraded land.

4.3 Carbon efficiency of the remaining feedstock choices

As was highlighted in section 4.1, paying due attention to feedstock supply chain emissions is integral in determining the carbon efficiency of BECCS. Figure 7 illustrates the carbon efficiency of four biomass feedstocks domestically grown in the UK (for a comparison see Figure A1 in annex for US imported values). The range of values in each Sankey diagram represents the upper to lower range of carbon efficiencies for different BECCS value chain configurations in the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework.[72] The upper end of the range represents a future scenario of decarbonized supply chains, with feedstocks grown on marginal and degraded land (hence near-zero LUC and ILUC emissions), while the lower end is based on current energy system carbon intensities, with high LUC and ILUC emissions factored in based on converting grassland, both modelled under the MONET framework. It should be noted that wheat straw is always assumed to have no associated indirect or direct land-use change emissions, as it is an agricultural residue. Furthermore, MONET does not consider other agricultural residues, waste wood, forestry wood, and municipal solid wastes. MONET also makes conservative assumptions regarding supply chain emissions, biomass losses along the value chain, as well as the emissions associated with piping the CO_2 to the geological storage site. As such, real world carbon efficiencies

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72 Fajardy and Mac Dowell (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?'; Fajardy and Mac Dowell (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?'; Farjardy, M. and Mac Dowell, N. (2020), 'Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal', *One Earth*, 3(2): pp. 214–225, doi:10.1016/j.oneear.2020.07.014; Fajardy, M., Chiquier, S. and Mac Dowell, N. (2018), 'Investigating the BECCS resource nexus: Delivering sustainable negative emissions', *Energy and Environmental Science*, 11(12), doi:10.1039/c8ee01676c; Fajardy, M. (2020), *Developing a framework for the optimal deployment of negative emissions technologies*, London: Imperial College London, https://spiral.imperial.ac.uk/handle/10044/1/80691.

may demonstrate higher values than those provided in Figure 7. However, the range of MONET values are important indicators, given the academic literature is extremely limited in assessing the potential carbon efficiency of BECCS, based on a range of feedstocks and differences between feedstock growth regions.

As can be seen from Figure 7c, wheat straw may provide a significantly superior carbon efficiency: 74–72 per cent of the CO_2 is geologically stored, and 26–28 per cent emitted to the atmosphere. Miscanthus is the second-best performing feedstock, with 74–33 per cent geologically stored. Switchgrass and SRC willow are significantly lower at 71 per cent to 8 per cent and 72 per cent to 3 per cent, respectively. It should be noted that for both these feedstocks, current supply chain emissions (i.e. carbon intensity of energy systems) and conversion of grassland (high LUC and ILUC emissions) result in only marginal net negativity.

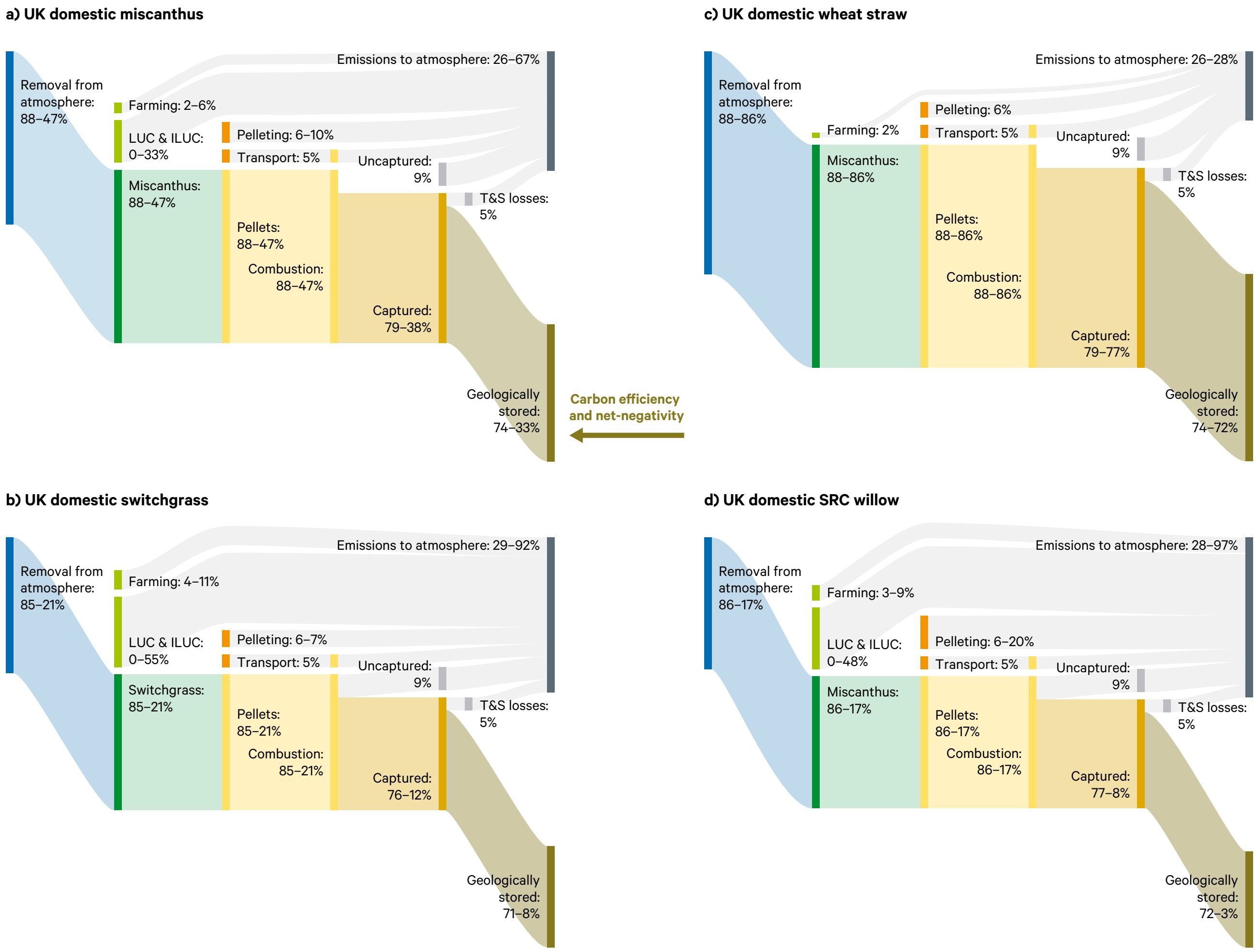
Wheat straw demonstrates a superior carbon efficiency due to marginal LUC and ILUC emissions, and a lowered drying requirement during the pelleting process. For the upper range scenario – where all feedstocks are assumed to be grown on marginal and degraded land and supply chain emissions are heavily decarbonized – the carbon efficiency gap between wheat straw and the other feedstocks significantly narrows. Under this optimistic scenario wheat straw outperforms miscanthus by 0.6 per cent in terms of carbon efficiency, 3 per cent compared to switchgrass and by 2 per cent compared to SRC willow. It should be noted that other agricultural residues could be used, and that these alternatives have not been assessed.

The upper range scenario carbon efficiencies of miscanthus, switchgrass and wheat straw decline when shifting to importing the feedstock pellets from the US (Figure A1 in annex), all by around 11 per cent, and SRC willow by around 12 per cent.

Given the principal objective of BECCS is to remove CO_2 from the atmosphere and permanently store it in geological formations, feedstock choice should ensure the greatest carbon efficiency and hence net negativity.

Given the principal objective of BECCS is to remove CO_2 from the atmosphere and permanently store it in geological formations, feedstock choice should ensure the greatest carbon efficiency and hence net negativity. While all the feedstocks illustrated in Figure 7 (and Figure A1) remove CO_2 from the atmosphere, the greater the carbon efficiency (proportion of CO_2 geologically stored) the less feedstock required to achieve a given removal target. If less feedstock is required, less land is needed, which in turn minimizes the risk of land tensions with food production. Another way to view this is that for a finite amount of land, more CO_2 would be geologically stored compared to atmospheric emissions if the feedstock with the greatest carbon efficiency and net negativity were chosen. On this basis wheat straw may offer the optimal choice. Furthermore, minimal LUC is associated with wheat straw given it is a waste product to wheat production, which is already ubiquitous across many countries' agricultural sectors. Although the upper range of carbon efficiencies in Figure 7 are representative of growing feedstocks on marginal and degraded land, ensuring conversion of land does not result in LUC and ILUC emissions is not a risk if wheat straw pellets were utilized.

Figure 7. Carbon efficiency of UK BECCS based on (a) miscanthus, (b) switchgrass, (c) wheat straw and (d) short rotation crop (SRC) willow, grown domestically in the UK



Source: Based on data from Fajardy and Mac Dowell (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?'; and data from the MONET model.[73]
Note: The range of values is representative of decarbonized future supply chains and minimal LUC/ILUC (low carbon) and current supply chains (current energy systems) with high LUC/ILUC assuming grassland conversion to bioenergy (high carbon). For US imported equivalent diagrams see Figure A1 in the annex.

73 Fajardy and Mac Dowell (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?'; Fajardy and Mac Dowell (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?'; Farjardy and Mac Dowell (2020), 'Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal'; Fajardy, M., Chiquier, S. and Mac Dowell, N. (2018), 'Investigating the BECCS resource nexus: Delivering sustainable negative emissions'; Fajardy (2020), *Developing a framework for the optimal deployment of negative emissions technologies*.

05 The perfect (wheat straw) system?

For a finite land area, wheat straw based BECCS would remove more CO_2 from the atmosphere. Risks need to be mitigated by, in part, prioritizing emission reductions.

The CCC plays an integral role in shaping UK government climate policy. While the UK government itself is yet to set a definitive target for BECCS or GGRs, the net zero scenarios published by the CCC offer the clearest indication of the scale of BECCS that the UK government is likely to pursue. It is important to note that the CCC scenarios provide no detail as to the type of feedstock, land requirement, efficiency of the BECCS power plants, or CAPEX required.[74] Without a clear understanding of these crucial parameters it remains challenging to conduct a robust assessment of the cost and benefits of pursuing, and indeed relying upon, BECCS. This chapter defines these missing key characteristics, based on wheat straw being the optimal feedstock choice due to its carbon efficiency presented in section 4.3.

In compiling the scenarios, the CCC drew on the IPCC IAM pathways,[75] and the UK Energy Research Centre (UKERC) conducted an evidence review in order to inform the CCC's BECCS projections.[76]

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74 CCC (2019), *Net Zero: The UK's contribution to stopping global warming*.
75 Ibid.
76 Ahut Daggash, H. and Fajardy, M. (2019), *Bioenergy with carbon capture and storage, and direct air carbon capture and storage*, London: The UK Energy Research Centre, https://ukerc.ac.uk/publications/bioenergy-with-ccs-and-direct-air-ccs.

The CCC's 'Further Ambition' scenario has BECCS providing around 51 $MtCO_2$/yr of removals in 2050, of which the largest share – 35.4 $MtCO_2$/yr – is provided by BECCS-to-power, rather than BECCS to hydrogen or biofuels.[77] This target is the starting point illustrated in Figure 8, which populates the system dynamics diagram of Figure 3 with CCC values, as well as those calculated here. The values in blue within Figure 8 are taken directly from the CCC report, namely: 112 TWh of resource would be required to deliver the target, from a fleet size of 5 GW generating 41 TWh of electricity, at a cost of £158/tCO_2.

5.1 Implications of a highly efficient BECCS fleet

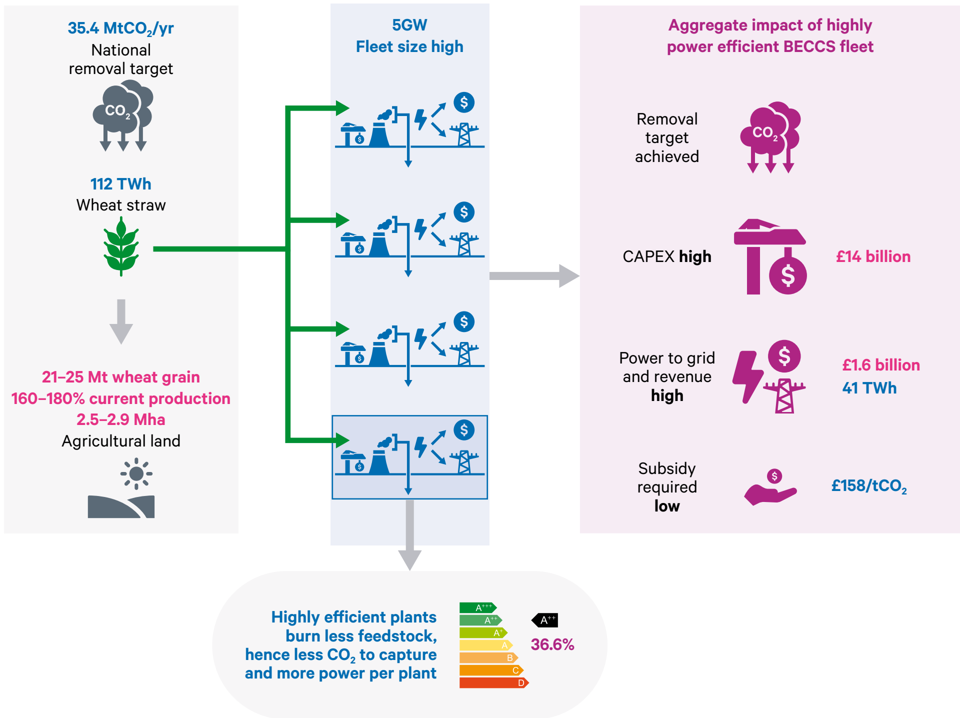
As discussed in Chapter 3, the efficiency of BECCS power plants has a significant impact on the required CO_2 capture and storage subsidy, the fleet CAPEX and land requirement. The fleet average efficiency is simple to infer: dividing the power production (41 TWh) by the embodied energy of the feedstock (112 TWh). As can be seen in Figure 8, the implied efficiency is therefore 36.6 per cent. As discussed in section 3.1, the Drax wood pellet plant has an efficiency of around 36.2 per cent, which if converted to a BECCS power plant would likely fall to around 20.9 per cent due to the energy penalty of the CCS equipment. This implied efficiency indicates a future BECCS fleet that is significantly more advanced than a Drax-like BECCS power plant – requiring an energy efficiency increase of 15.7 percentage points. This should be compared to the historical efficiency improvement of thermal power plants in Europe, which increased by 6.9 per cent over the 20 years between 1990 and 2010.[78] Furthermore, examining the UKERC evidence review, the range of BECCS efficiency provided to the CCC was between 20 per cent to 38 per cent,[79] based on the range within the literature, again indicating the CCC is implicitly planning for a highly advanced future BECCS fleet by 2050, which historical efficiency improvements indicate may be challenging to achieve.

The relatively high efficiency of 36.6 per cent has wider system implications. As discussed in section 3.1, higher efficiencies result in less feedstock being combusted in each BECCS power plant (assuming baseload operation). As such, the fleet size (5 GW) required to achieve the 35.4 $MtCO_2$/yr target would be larger than if the facilities were less efficient but generate more power (41 TWh), and hence derive greater power revenues. This has two subsequent consequences. Firstly, the CAPEX to build the BECCS fleet would be greater. Based on a BEIS 2020 publication that defines an nth of a kind[80] BECCS power plant costing £2,793/kW,[81] which implies a CAPEX of £14 billion for the fleet. Secondly, assuming a wholesale electricity price of £40/MWh, the power revenues of the BECCS fleet would be

77 CCC (2019), *Net Zero: The UK's contribution to stopping global warming*.
78 European Environment Agency (2018), 'Efficiency of conventional thermal electricity and heat production in Europe', https://www.eea.europa.eu/data-and-maps/indicators/efficiency-of-conventional-thermal-electricity-generation-4/assessment-2.
79 Ahut Daggash and Fajardy (2019), *Bioenergy with carbon capture and storage, and direct air carbon capture and storage.*
80 nth of a kind: as technology improves from previous generations of plant design, the nth of a kind indicates an improved design in the future.
81 Department for Business, Energy and Industrial Strategy (2020), *The potential of bioenergy with carbon capture in the UK to 2050,* London: Department for Business, Energy and Industrial Strategy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/911268/potential-of-bioenergy-with-carbon-capture.pdf.

around £1.6 billion/yr. It is presumably due to these relatively high power revenues (due to the higher power efficiency) that the CCC defined a relatively low cost of removals (£158/tCO_2), which would likely take the form of a carbon price type subsidy.

Figure 8. Wheat straw based BECCS, under CCC net zero 'Further Ambition' scenario



Source: Compiled by the author; CCC (2019), *Net Zero: Technical Report*.
Note: Values in blue are stated by the CCC (2019), values in pink are inferred based on internal calculations.

5.2 Land required and supply chain emissions of wheat straw

Turning to the feedstock choice, it is also possible to calculate the wheat production and land requirement, on the basis that: wheat straw contains around 44 per cent carbon,[82] the CCC anticipate a capture rate of 95 per cent, and converting between carbon and CO_2, the 35.4 MtCO_2/yr target translates to the combustion of 23 Mt of wheat straw (assuming no emission associated with piping). Importantly, around 20–40 per cent of the wheat straw would need to be left on the agricultural land producing the wheat, or else leaching of carbon, nitrogen and phosphorus will cause the land to degrade and either additional fertilizers or organic manures would need to be applied. However, this is very much dependent on soil type and management

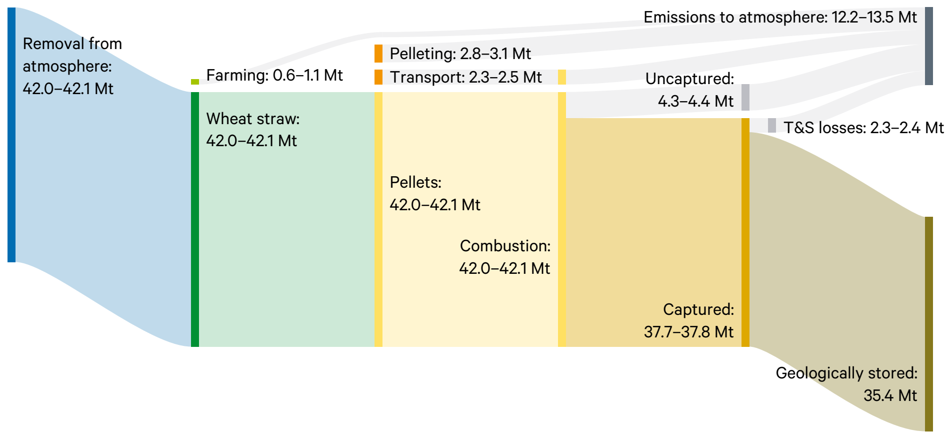
82 Emenike, O., Michailos, S., Finney, K. N., Hughes, K. J., Ingham, D. and Pourkashanian, M. (2020), 'Initial techno-economic screening of BECCS technologies in power generation for a range of biomass feedstock', *Sustainable Energy Technologies and Assessments*, 40, doi:10.1016/j.seta.2020.100743.

practices. As such, the 23 Mt of wheat straw would need to originate from a source of wheat straw of between 28 Mt and 32 Mt. Based on current wheat production, this translates to 21–25 Mt of wheat grain.[83] With current UK wheat grain production averaging around 13.5 Mt/yr, and a yield of 8.5 tonnes per hectare (ha),[84] if 100 per cent of the feedstock were provided by domestically grown wheat, an uplift of 57 per cent to 83 per cent of current production would be required, and 2.5–2.9 Mha of agricultural land (see Figure 8). This would represent 27–31 per cent of the UK's current agricultural land area, a substantial proportion that could have implications for food supply chains.

It should be noted that the genetic potential exists to raise wheat straw yields and minimize or eliminate additional land requirements. This is possible as current varieties of wheat have been selectively bred to exhibit shorter straw to prevent the crop becoming damaged in heavy winds and rain. As such, a switch to older varieties of wheat could produce more wheat straw, minimizing the additional land requirement.

Finally, given the carbon efficiency of wheat straw (Figure 7c) at 74–72 per cent (geologically stored), with 26–28 per cent emitted to the atmosphere, a removals target of 35.4 $MtCO_2$/yr indicates that 12.2–13.5 $MtCO_2$/yr would be emitted into the atmosphere (Figure 9). However, it is not clear from the CCC literature if the target accounts for these supply chain emissions or not.[85] If not, then the calculations as to the land requirement and uplift in wheat production would correspondingly increase in order to reach the target.

Figure 9. Supply chain emissions under the CCC further ambition scenario, assuming domestic wheat straw supplies 100 per cent of the feedstock. requirement, all in units of CO_2



Source: Based on the range of values of Figure 7c.

83 Fajardy and Mac Dowell (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?'.
84 UK Flour Millers (undated), 'The Flour Milling Industry Wheat', https://www.ukflourmillers.org/wheat.
85 CCC (2019), *Net Zero: Technical Report,* London: Climate Change Committee, https://www.theccc.org.uk/publication/net-zero-technical-report.

06 Minimizing the risks

With net zero separated into reduction and removal targets, and as BECCS and other GGRs prove themselves, their role, and our reliance upon them to avert climate change, could be expanded.

As the previous sections have highlighted, future reliance on BECCS is not necessarily flawed, but rather is fraught with complex trade-offs regarding feedstock choice, the supply chain embodied energy and emissions, as well as the optimization towards energy production or CO_2 removal. If handled poorly, these trade-offs will likely result in either competition with food production, high costs, impaired energy security, or a failure to meet the global carbon budget and ultimately prevent runaway climate change. This is particularly pertinent as countries' net zero pledges remain vague and potentially allow for offsetting traditional decarbonization with CO_2 removals.[86] In addition, the risks and trade-offs will be more acute as BECCS is scaled to the global level, which is likely to place significant pressure on biomass supply chains – not unimaginable given the number of countries now pledging net zero targets. This section discusses the potential solutions that could enable a future of BECCS (and more broadly GGRs) contributing to achieving net zero in a manner that minimizes the risks. Figure 10 illustrates these potential solutions (green box) that stem from the initial need for negative emissions (orange box) and the risks of BECCS (red box), as discussed in the previous chapters.

It is worth remembering that much of the optimism and hence increasing future reliance on BECCS stems from the IAMs and IPCC pathways. Furthermore, in the six IAMs that Butnar et al. (2020) reviewed, biomass is assumed to be carbon neutral, efficiency and capture rates are exogenous inputs, and the IAMs lack

86 Rogelj, Geden, Cowie and Reisinger (2021), 'Net-zero emissions targets are vague: three ways to fix'; ECIU (2021), *Taking stock: A global assessment of net zero targets*.

transparency around the technical functionality of BECCS.[87] In the real world, biomass supply chains embody non-marginal emissions and there is a clear trade-off between the efficiency and capture rate. While modellers and scientists treat models, such as IAMs, as 'experimental sandpits', policymakers tend see them as 'truth machines'.[88] A worst case scenario of poorly implemented BECCS policies could delay or deter emissions reductions, fail to deliver the removals currently being baked in by policymakers and net zero pledges, and result in 'imagined offsets' that fail to materialize, which one analysis indicates could result in an additional temperature rise of up to 1.4°C.[89]

In the real world, biomass supply chains embody non-marginal emissions and there is a clear trade-off between the efficiency and capture rate.

Many companies are planning on using CO_2 removals from BECCS to offset their emissions (see section 1.5). As a recent paper by prominent academics highlighted, 'Carbon offsetting is a widespread tool in efforts to achieve net zero emissions. But current approaches to offsetting are unlikely to deliver the types of offsets needed to achieve global climate goals'.[90] The report recommends that countries minimize the need for offsets, prioritize reducing emissions, and where offsets are used they should be of high quality, namely 'verifiable and correctly accounted for and have a low risk of non-additionality, reversal, and creating negative unintended consequences'.

This is likely to have three primary consequences, as per Figure 10. The first two are intimately connected: prioritizing reductions over removals and minimizing reliance on removals by ensuring the deployment of proven low-cost renewables, reducing energy demand, incentivizing green hydrogen and ensuring a diversity of future GGRs, inclusive of NBS. Secondly, in order to achieve high-quality offsets in the context of BECCS, both the carbon payback periods associated with the different feedstocks and their supply chain emissions need to be accounted for robustly. Given the issues highlighted in section 4.1, this would require the tightening of regulations and enforcement along the length of biomass supply chains. Furthermore, enforcement is likely to be significantly easier if countries ensure that the biomass they use is grown domestically.

Part of the solution could be to separate net zero targets into emission reductions targets and removals targets, which as a lead author to the 6th IPCC assessment report has indicated in a recent paper – could prevent 'offsetting the effects of both approaches'.[91] The authors go on to recommend a 90:10 split between reductions

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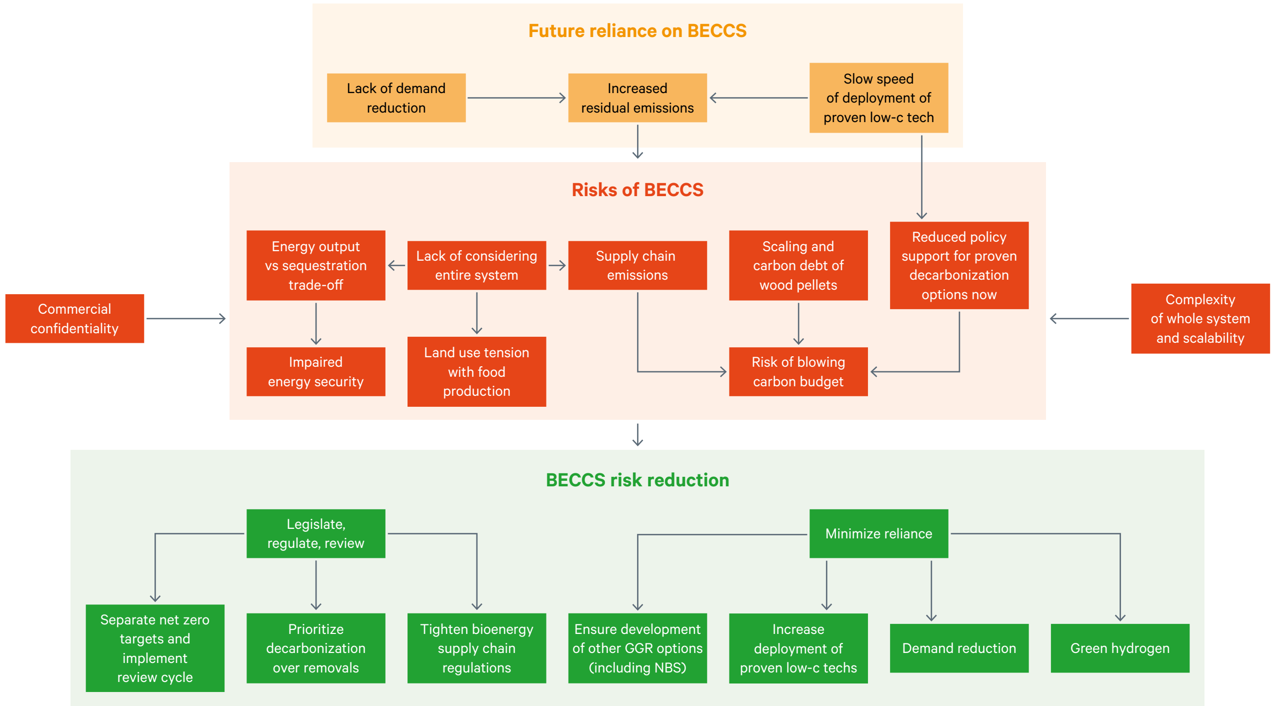
87 Butnar, Li, Strachan, Pereira, Gambhir and Smith (2020), 'A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): A transparency exercise'.
88 McLaren (2020), 'Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques'.
89 Ibid.
90 Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., Mitchell-Larson, E., Malhi, Y., Otto, F., Seddon, N. and Smith, S. (2020), *The Oxford Principles for Net Zero Aligned Carbon Offsetting,* Oxford: University of Oxford, https://www.smithschool.ox.ac.uk/publications/reports/Oxford-Offsetting-Principles-2020.pdf.
91 Geden, O. and Schenuit, F. (2020), *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*, Berlin: Stiftung Wissenschaft und Politik, https://www.swp-berlin.org/en/publication/eu-climate-policy-unconventional-mitigation.

and removals, and that the reduction target should be seen as a minimum target, which if GGR methods (including BECCS) improved or demonstrated breakthroughs, could lead to net zero being achieved earlier. Another approach could see countries not only separating net zero targets, but also legislating a regular review cycle that adjusts the split between reductions and removals as BECCS (and other GGRs) is deployed and demonstrates its whole system operational performance, such as verifiable net negativity inclusive of supply chain emissions.

Currently the performance of BECCS is poorly understood, due in part to the understandable commercial confidentiality of the companies developing the technology. This, unfortunately, means there is a disconnect between the information available to policymakers – which is based on assumptions within models, such as the IAMs – when planning net zero inclusive of BECCS, and the risk that BECCS fails to meet the assumed level of performance. The review cycle of the split between reductions and removals could go further, including stringent key performance indicators that if met as BECCS is scaled up, could lead to BECCS being allocated a greater aggregate role within the net zero future.

Figure 10. Policy solutions for mitigating risks of BECCS



Source: Compiled by the author.

07 Conclusions and recommendations

BECCS may well prove to be invaluable in minimizing climate change, but policy action is needed to limit the inherent scaling risks. The UK is leading BECCS development, so must also demonstrate robust policy leadership.

The slow pace of global decarbonization has created an inevitable need to turn to removing CO_2 from the atmosphere to prevent the overshooting of carbon budgets and runaway climate change. A worst-case scenario of over reliant and poorly implemented BECCS policies could delay or deter emissions reductions, fail to deliver the removals being baked in by policymakers and net zero pledges, and result in 'imagined offsets' that fail to materialize. One analysis indicates that this could result in an additional temperature rise of up to 1.4°C.[92] The UK is leading efforts to develop policies and market frameworks to support BECCS. The UK must do so cognisant of striving towards realistic and robust targets, otherwise it would risk undermining global efforts to decarbonize.

This is particularly pertinent given the 'middle-of-the-road' 2050 IPCC global pathway towards 1.5°C compliant scenarios that envisages 1.5 $GtCO_2$/yr of BECCS removals, which if supplied solely by wood pellets would require a scaling of supply by more than 120 times, relative to what Drax currently combusts at its Selby facility. Due to the potential scaling pressures on wood pellet supply chains, the risk of carbon debt remains of concern. As one recent study points out, 'in the US coastal southeast there were fewer live and growing-stock trees and less carbon in soils with every year of milling operation than in the rest of the eastern US'.[93] As such, a diversity of feedstocks should be pursued.

92 McLaren, D. (2020), 'Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques'.
93 Aguilar, Mirzaee, McGarvey, Shifley and Burtraw (2020), 'Expansion of US wood pellet industry points to positive trends but the need for continued monitoring'.

In influential IAMs, particularly the six reviewed by Butnar et al. (2020), biomass is assumed to be carbon neutral, efficiency and capture rates are exogenous inputs to the models, and the models lack transparency.[94] In the real world, biomass supply chains embody non-marginal emissions and there is a clear trade-off between the efficiency and capture rate. While scientists treat models as 'experimental sandpits', policymakers tend see them as 'truth machines'.[95] Forging ahead with policy and market support mechanisms risks policy decisions leading the scientific and engineering evidence. In the UK, wheat straw may provide the optimal carbon efficiency: 74–72 per cent of CO_2 is geologically stored, and 26–28 per cent emitted to the atmosphere. As such, for a finite land area, wheat straw based BECCS would remove more CO_2 from the atmosphere. Based on the UK's CCC 2050 target for BECCS-to-power, if 100 per cent of the feedstock were provided by domestically grown wheat straw, an uplift of 57–83 per cent of current wheat production would be required, and 27–31 per cent of the UK's current agricultural land area, a substantial proportion that could have implications for food prices. This should be treated as an indicator, given that other agricultural residues could compliment wheat straw, and the genetic potential exists to raise wheat straw yields and minimize or eliminate additional land requirements.

Based on the UK's CCC 2050 target for BECCS-to-power, if 100 per cent of the feedstock were provided by domestically grown wheat straw, an uplift of 57–83 per cent of current wheat production would be required, and 27–31 per cent of the UK's current agricultural land area, a substantial proportion that could have implications for food prices.

There are indications that first generation BECCS-to-power facilities will exhibit lower efficiencies than that envisaged by the CCC. Inefficient facilities would remove more CO_2 for an equivalent generating capacity, but would likely require a greater carbon removal subsidy as power revenues would be relatively lower than efficient equivalent facilities.

If BECCS is to play the crucial role that models, policymakers and net zero targets imply, then the carbon efficiencies and the energy output–capture rate trade-off needs to be at the heart of policy development, or else there is a risk that already tight carbon budgets become unresolvable, leading to runaway climate change. As such, policymakers should:

94 Butnar, Li, Strachan, Pereira, Gambhir and Smith (2020), 'A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): A transparency exercise'.
95 McLaren (2020), 'Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques'.

— Enforce tighter supply chain emission regulations that are well monitored and verified; likely to be more attainable if feedstocks are domestically grown.

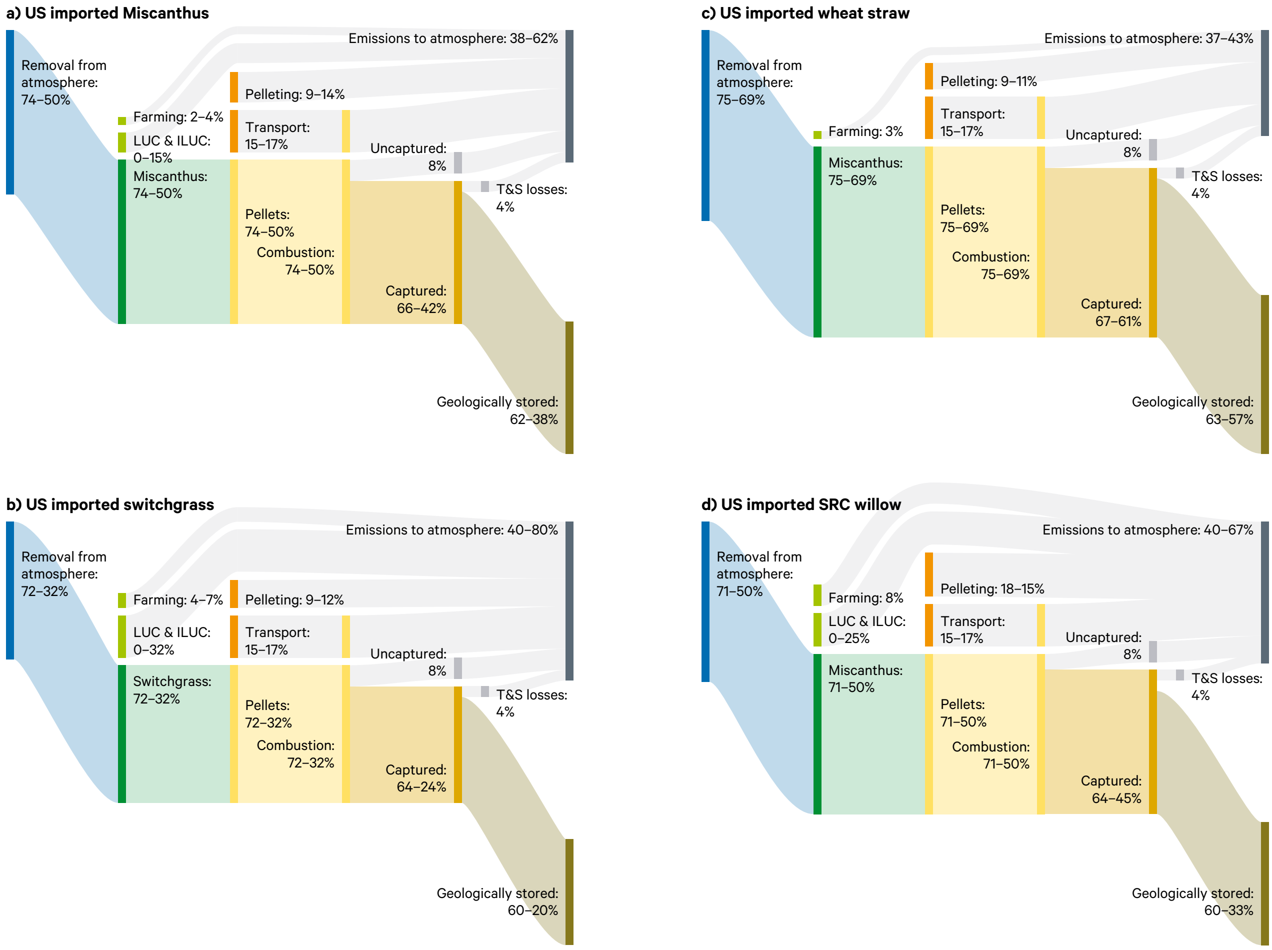
— Prioritize reductions over removals, ensuring that proven low-carbon technologies are deployed with earnest, options for demand reduction are given political priority, and green hydrogen is swiftly developed.

— Legislators should consider separating net zero targets into reductions and removals, with an appropriate split that represents the current ambiguities in BECCS performance. Overtime, a regular review cycle could expand the role of removals as BECCS performance moves from being masked behind commercial confidentiality to meeting key performance indicators.

In assessing the merits of implementing a more stringent set of criteria for achieving net zero, policymakers should keep in mind that monitoring, reporting and verification of CO_2 is challenging enough, but that as the system becomes ever more complex the risks increase of a mismatch between what is claimed and real-world atmospheric CO_2 concentrations. Furthermore, all crises involve scarcity of some form or another. In the case of the COVID-19 pandemic, PPE and then vaccines became the commodity of scarcity, with profiteering, counterfeits and fraud swiftly following. The climate crisis is no different: the commodity of scarcity being the remaining units of the global carbon budget. But while PPE and vaccines are tangible goods, CO_2 in the context of removal offsets is, in many ways, a more gameable system, ripe for exploiting crisis driven profit.

Annex

Figure A1. Carbon efficiency of UK BECCS based on (a) miscanthus, (b) switchgrass, (c) wheat straw and (d) short rotation crop (SRC) willow, grown in the US and imported to the UK



Source: Based on data from Fajardy and Mac Dowell (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?'; *Drax (2020), Drax Group plc Annual report and accounts 2019*; and data from the MONET model.[96]
Note: The range of values is representative of decarbonized future supply chains and minimal LUC/ILUC (low carbon) and current supply chains (current energy systems) with high LUC/ILUC assuming grassland conversion to bioenergy (high carbon). It should be noted that the values for current supply chains (high carbon) for SRC willow are based on marginal land, rather than converting grassland, as the model indicates the feedstock would be net emitting unless marginal land or cropland is utilized.

96 Fajardy and Mac Dowell (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?'; Fajardy and Mac Dowell (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?'; Farjardy and Mac Dowell (2020), 'Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal'; Fajardy, Chiquier and Mac Dowell (2018), 'Investigating the BECCS resource nexus: Delivering sustainable negative emissions'; Fajardy (2020), *Developing a framework for the optimal deployment of negative emissions technologies*.

About the author

Dr Daniel Quiggin has expertise in the modelling, analysis and forecasting of national and global energy systems, having modelled various UK and global energy scenarios. He has worked as a civil servant on Brexit negotiations, as an analyst at Investec Asset Management within a commodities and resources investment team, and holds two master of science degrees, in Particle Physics and Climate Science, and a PhD in energy system modelling.

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Cover image: Timber supplies at EON's biofuel power station in Lockerbie, Scotland.
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