Research Paper

Environment and Society Centre

November 2024

Why engineered carbon removals are at odds with energy security and affordability

Tackling the costs and risks in net zero strategies

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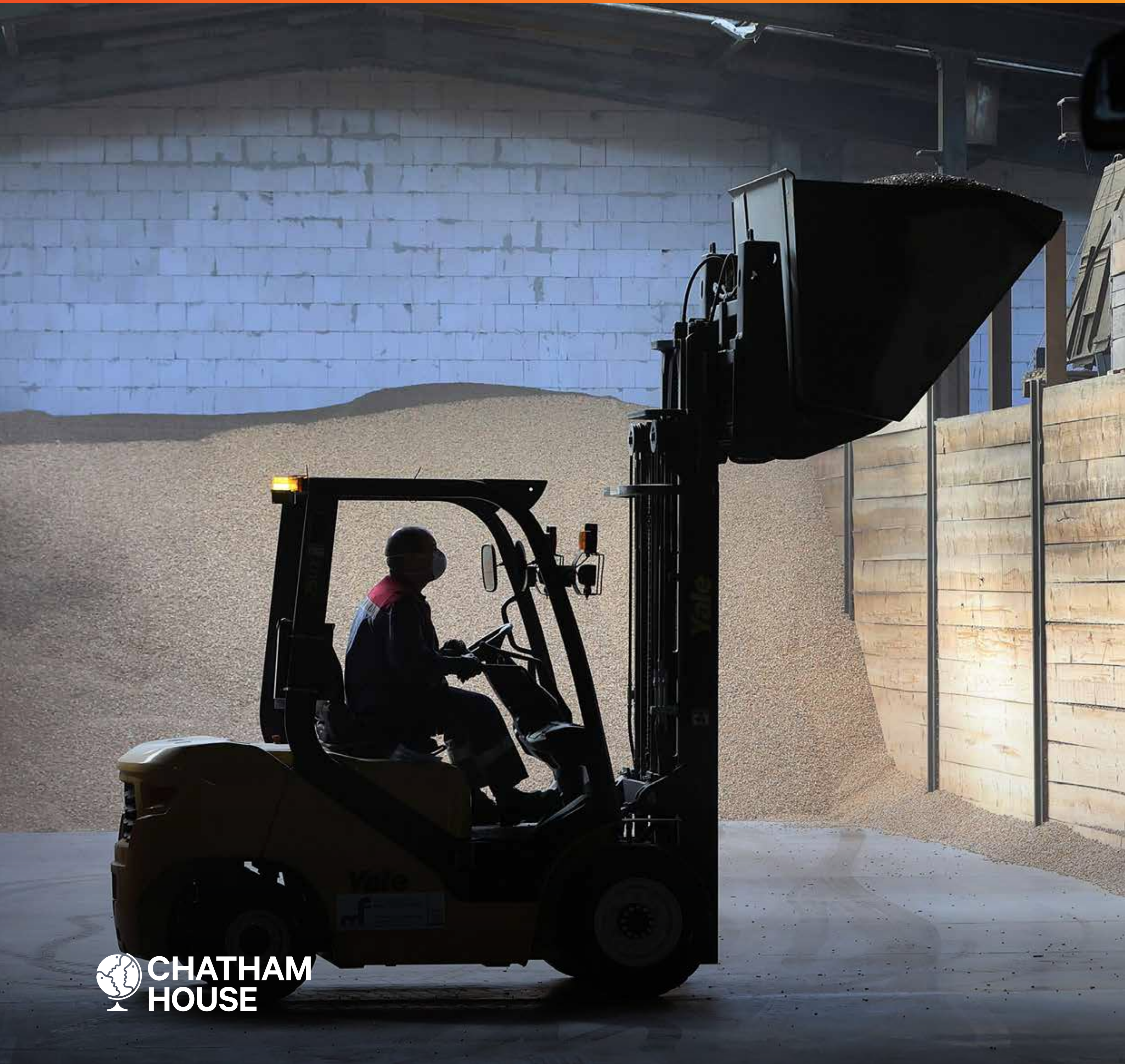

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Summary

— At the heart of net zero is a reliance on negative emissions, or carbon removals, to counterbalance emissions from sectors such as agriculture, shipping and aviation. However, the costs of engineered carbon removals – i.e. those reliant on technologies rather than nature-based solutions – could be prohibitive at the scale currently envisaged in many countries' net zero strategies. This paper investigates how greater international cooperation and reduced reliance on engineered removals could minimize the tensions between, on the one hand, rising energy security and affordability concerns and, on the other, the costs of pursuing net zero.

— The paper analyses the most recent cost estimates for bioenergy with carbon capture and storage (BECCS) and for direct air carbon capture and storage (DACCS). Assuming wood pellet prices corresponding to 2027 forward prices, and that BECCS is responsible for 99 per cent of the 2050 global deployment of engineered removals, as is the case within the IPCC's Sixth Assessment Report (AR6), it is calculated that costs could climb from the high end of a \$192–\$315 billion/yr range to up to \$460 billion a year.

— These high costs stem from the high heat energy input requirements of engineered removals; such inputs account for nearly 50 per cent of the cost of DACCS, and for at least 33 per cent of the cost of BECCS.

— In the context of high debt-to-GDP levels across many countries, and with military spending on the rise in a multi-polar world, the risk is that future engineered removals costs could become increasingly incompatible with policy imperatives that prioritize energy security and affordability. In such a scenario, the reliance on engineered carbon removals that many countries have already incorporated in their net zero planning would no longer be achievable. This in turn would widen the global 'emissions gap' – the gap between the emissions countries are likely to produce under their current commitments, and what is actually needed in line with the Paris Agreement goals – and increase the likelihood of triggering accelerated climate change.

— Greater international cooperation between countries is required to minimize the costs and risks associated with BECCS and DACCS. Such work will need to:

  — Acknowledge that countries do not possess the same geological and biophysical assets that would allow equal provision of sustainable, permanent and affordable CO_2 removal at scale, globally. Regions with geological storage sites will need to collaborate with regions with significant biomass resources.

  - Renew efforts to build international governance concerning the permanence of CO_2 within geological storage sites.
  - Establish new international standards around the entire supply chain to drive down costs, as well as regulating sustainability standards pertaining to biomass.
  - Facilitate the sharing of technological innovations to reduce costs.

- Greater transparency is needed between commercial developers of BECCS and DACCS, governments and the public regarding costs, allowing for the sensitivity of commercial information.

- Within net zero strategies, the split between emissions reductions and removals needs to be clearly defined, to reduce the risks of over-reliance on engineered carbon removal offsets that could fail to fully materialize. This split can be reviewed and amended over time as engineered removal technologies are deployed and more evidence of their performance becomes available.

- There is scope for costs and risks to be shared and minimized through a more collaborative international approach to BECCS and DACCS. Valuable lessons could be drawn from cooperation in the civil nuclear sector. But, as in the case of nuclear, even where costs are minimized, this does not mean that engineered removals are low-cost solutions.

- Not only do engineered carbon removals technologies critically rely on high energy input operational expenditure. As a largely retrofitted technology applied to at most hundreds of large power stations, BECCS deployment is unlikely to see the rapid cost reductions that have been achieved through mass production of modular technologies like solar panels, wind turbines and electric vehicle batteries.

- This means that greater focus must be placed on energy efficiency and demand management to reduce reliance on engineered removals, and simultaneously ease both energy security and affordability concerns.

01 Introduction

Decarbonization models and politicians are, due to their respective biases and assumptions, increasingly relying on engineered carbon removals, and this reliance is likely to grow.

At the heart of net zero is a reliance on negative emissions, both engineered and nature-based, to counterbalance what are deemed 'residual emissions' from sectors such as agriculture, shipping and aviation that are technically and economically very difficult to decarbonize. This counterbalancing of hard-to-abate fossil fuel and other greenhouse gas emissions is critical to efforts to close the global 'emissions gap'.[1]

Net zero policies must assess costs alongside environmental objectives. To achieve the required negative emissions, engineered removal technologies will need to be deployed on a mass scale. This scaling up cannot be achieved without substantial investments in infrastructure and equipment, along with durable revenues to cover ongoing operational expenses – including fuel inputs to the removal technologies.

Carbon removals are broadly classified into two groups: nature-based solutions including tree-planting; and engineered carbon removals, such as bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS), which rely on human-made technology. It is important to note that while carbon capture and storage (CCS) can be applied to fossil fuel generators, this results in emissions reductions, and not – as through BECCS and DACCS – carbon removals or negative emissions.

BECCS involves integrating carbon capture technologies with biomass energy production, which requires diverting vast amounts of heat from the burning of that biomass to run the CCS equipment. DACCS systems need large-scale infrastructure to take in ambient air and scrub the carbon dioxide (CO_2) from

1 The emissions gap is the gap between the emissions countries are likely to produce under their current commitments, and what is actually needed in line with the Paris Agreement goals.

it, requiring large amounts of heat and electricity. Both BECCS and DACCS then require the permanent storage of their captured CO_2 in underground geological features, including old oil and gas wells.

For many years, academics and policymakers have viewed the need to tackle fossil fuel emissions and decarbonize their economies through the lens of the 'energy trilemma', which asserts that there are three pillars for decision-makers to consider: sustainability, security and affordability. With the rise of geopolitical tensions and conflict in oil- and gas-producing regions, and historically low investment in upstream oil and gas, a new era of energy security and affordability concerns risks trumping the climate imperative of energy sustainability. It is through this shift in focus, and with net zero costs increasingly under scrutiny, that this paper examines whether the high energy input – and hence high cost – of engineered removals technologies needs to be managed under a more collaborative and cooperative international approach, where the costs and risks are shared and minimized.

Previous Chatham House work has investigated how the issues of biomass feedstock carbon debt and payback periods, as well as supply chain emissions, could reduce the net negativity of BECCS, and how land use tensions can arise at scale.[2] This paper acknowledges these issues (for a summary discussion, see Box 1), but broadly sets them aside, instead focusing on the direct costs of BECCS and DACCS.

The remainder of this chapter examines how countries have baked reliance on engineered removals into their climate action targets and policies, and why politicians are drawn to these technologies. Chapter 2 explores how present geopolitical shifts and conflicts, compounded by the impacts of declining investment in upstream oil and gas over the last decade, put energy costs in a highly volatile and potentially ongoing inflationary period. Chapter 3 investigates the future costs of BECCS and DACCS, arising from their large energy input requirements and the rising costs of wood pellets for BECCS. Chapter 4 makes the case that greater international collaboration around BECCS and DACCS could aid in delivering cost-optimal and risk-reduced deployment at scale of engineered removals, drawing on the example of international cooperation in the civil nuclear industry, and touches on how demand reduction could reduce reliance on BECCS and DACCS. The concluding chapter draws together the key themes and provides substantive recommendations for policymakers.

2 Quiggin, D. (2021), *BECCS deployment: The risks of policies forging ahead of the evidence*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/10/beccs-deployment; King, R. et al. (2023), *The emerging global crisis of land use: How rising competition for land threatens international and environmental stability, and how the risks can be mitigated*, Report, London: Royal Institute of International Affairs, https://doi.org/10.55317/9781784135430.

Why do the models used by the IPCC drive a reliance on engineered removals?

Integrated assessment models (IAMs) play a crucial role in shaping climate policy both globally and nationally. They serve as the foundation for the decarbonization pathways outlined by the IPCC, which governments rely on when setting their own climate targets and legislation. While the IPCC acknowledges that high reliance on engineered removals enables high consumption lifestyles,[3] its cost-optimizing models and associated optimistic assumptions tend to select them.

IAMs are tools used by researchers to analyse and evaluate the complex interactions between human activities, the economy, energy systems, land use and the environment. IAMs provide a framework for assessing the potential impacts of various policy interventions, technological changes and socioeconomic developments on key sustainability goals, such as climate change mitigation, energy security, air quality and economic growth.

It should, however, be noted that many of the academics who run the IAMs often go to lengths to reinforce that the models are not forecasts,[4] that they come with many caveats, and that their very varied outputs between the various IAMs are neither policy prescriptions nor a representative sample that can be statistically assessed as to the likely global decarbonization trajectory.

The decarbonization pathway outputs of IAMs informed the creation of the net zero goal of the 2015 Paris Agreement. IAMs are very clear that negative emissions should be additional to renewable deployment, not instead of, and should not be used to offset fossil fuel emissions. In essence, this means that reductions in emissions must be prioritized, with negative emissions only offsetting residual emission sectors. Often, however, the application of net zero targets within country-level targets, legislation and policies does not adequately define residual emission sectors, and there are growing calls to do this,[5] as well as for broader reforms of net zero,[6] including splitting out CO_2 reduction and removal targets.[7] Such reforms of net zero could ensure a greater real-world adherence to the IAMs' modelling outputs of negative emissions being additional to renewable energy generation, and not offsetting of fossil emissions.

The reliability of IAM outputs is contingent on the quality of the underlying assumptions. For example, in the case of BECCS, assumptions include factors such

3 Pathak, M. et al. (2022), 'Technical Summary', p. 114, in Shukla, P. R. et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157926.002.
4 Evans, S. and Hausefather, Z. (2018), 'Q&A: How 'integrated assessment models' are used to study climate change', Carbon Brief, https://carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change.
5 Buck, H., Carton, W., Lund, J. and Markusson, N. (2023), 'Why residual emissions matter right now', *Nat. Clim. Chang.*, 13, pp. 351–58, https://doi.org/10.1038/s41558-022-01592-2; Lund, J., Markusson, N., Carton, W. and Buck, H. (2023), 'Net zero and the unexplored politics of residual emissions', *Energy Research & Social Science*, 98, 103035, https://doi.org/10.1016/j.erss.2023.103035.
6 Rogelj, J., Geden, O., Cowie, A. and Reisinger, A. (2021), 'Net-zero emissions targets are vague: three ways to fix', *Nature*, 591(7850), pp. 365–68, https://doi.org/10.1038/d41586-021-00662-3.
7 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-climatepolicy-unconventional-mitigation.

as biomass feedstock production and yields and resulting land use change, energy production from biomass feedstocks, CO_2 capture rates, and supply-chain emissions.

IAMs aim to identify the most cost-effective means of achieving a specific temperature limit. Because of this emphasis on cost-optimization, many IAM scenarios heavily rely on BECCS.[8] In the 2018 IPCC special report *Global Warming of 1.5°C* (SR1.5),[9] 81 of the 90 scenarios relied on negative emission technologies (NETs).[10] Because BECCS is expected to both produce energy and remove atmospheric CO_2, IAMs may exhibit a bias towards selecting BECCS. Concerns arise because many cost assumptions within IAMs, including those related to BECCS, may be outdated.[11] Notably, the real-world costs of deploying traditional renewables like solar and wind have decreased significantly over the past decade, enabled by the modular nature and repetitive manufacturing of these technologies, with, for instance, around 70 billion solar cells expected to be produced in 2024.[12] Meanwhile, the cost of BECCS remains high and uncertain, as will be explored in the following chapters. In 2019, researchers noted that a paper published in 2015 reporting on the results from one IAM included solar PV and storage capital costs based on a 2008 analysis.[13]

The real-world costs of deploying traditional renewables like solar and wind have decreased significantly over the past decade, while the cost of BECCS remains high and uncertain.

An analysis conducted in 2020 offers valuable insights into the quality of BECCS parameters within IAMs.[14] The study highlights a lack of transparency in many assumptions, particularly regarding the technological aspects of BECCS, such as CO_2 transport and storage. Additionally, all six IAMs assessed in the study assume that the bioenergy used in BECCS facilities is carbon-neutral, meaning that the emissions generated during bioenergy production are offset over the biomass's lifetime growth period. Another study, published in 2021, has shown that some of the IAMs contain unrealistic land-use change allocations in their modelling architecture.[15] This is crucial, given that BECCS requires significant

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8 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), https://doi.org/10.3390/en12091747.
9 Masson-Delmotte, V. et al. (eds) (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, sustainable development, and efforts to eradicate poverty*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157940.
10 Carbon Brief (2018), 'In-depth Q&A: The IPCC's special report on climate change at 1.5C', 8 October 2018, https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c.
11 Ibid.
12 Quiggin, D. (2024), 'How modular renewables can reduce the costs of relying on carbon capture', Chatham House Expert Comment, [updated] 8 November 2024, https://www.chathamhouse.org/2024/10/how-modular-renewables-can-reduce-costs-relying-carbon-capture.
13 Ibid.
14 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), https://doi.org/10.1088/1748-9326/ab5c3e.
15 Bayer, A. et al. (2021), 'Diverging land-use projections cause large variability in their impacts on ecosystems and related indicators for ecosystem services', *Earth System Dynamics*, 12(1), pp. 327–51, https://doi.org/10.5194/esd-12-327-2021.

areas of land to produce its biomass fuel. The study states that some IAMs have 'highly regionalized land use and land cover changes with rates of conversion that are contrary to or exceed rates observed in the past'.

The efficiency of BECCS producing electricity from its biomass feedstock, for sale to its energy consumers, is central to its revenue base and economic competitiveness, and hence its selection by the cost-optimizing IAMs. As previous Chatham House analysis has shown, based on trials of BECCS technology, power-generation efficiencies from wood pellets are likely to be in the low 20–25 per cent range.[16] However, within four IAMs assessed by a 2019 study,[17] BECCS was assumed to have a 2020 power-production efficiency of 26–36 per cent, increasing to 31–39 per cent by 2030. Looking out to 2050, these IAMs assume the power-production efficiency of BECCS increases by less than 1 per cent per year, commensurate with empirical evidence as to how thermal power plants in Europe improved their efficiency between 1990 and 2010.[18] However, in order to meet the average assumed power efficiency in 2050 within these four IAMs, starting from where BECCS trials indicate the technology stands currently, production efficiency would need to increase by around 2 per cent annually.[19]

Not only are many of the modelling assumptions pertaining to engineered removals questionable, and potentially overly optimistic. Additionally, the severity of risks they assume need to be avoided may be under-represented. In their 2021 paper, economists Nicholas Stern and Joseph Stiglitz state: '[T]he estimates of damages from climate change in these IAMs is much smaller than is likely to occur.'[20] Stern and Stiglitz go further, identifying that there is 'a systematic bias towards reducing the strength of action on climate change, that results from underestimating the benefits and overestimating the costs of such action';[21] and concluding:

> The intuitions of the scientific community may well be right: the simplistic models of the economists have simply not captured essential aspects of the societal decision problem, and when they do so, the disparities in perspectives may be closed, if not eliminated.[22]

In 2022, the European Commission[23] highlighted research that showed that, of the IPCC scenarios (underpinned by the IAMs), only 5 per cent involved substantial energy demand reduction from current levels by 2100.[24] The research argued that IAMs have a techno-economic focus, and under-represent the potential for global energy demand reduction to contribute to carbon mitigation targets,

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16 Quiggin (2021), *BECCS deployment*.
17 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. 1254–67, https://doi.org/10.1016/j.energy.2018.12.131.
18 European Environment Agency (2021), 'Indicator 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.
19 Author's calculation.
20 Stern, N. and Stiglitz, J. (2021), *The Social Cost of Carbon, Risk, Distribution, Market Failures: An Alternative Approach*, Cambridge, MA: National Bureau of Economic Research, https://files.static-nzz.ch/2021/4/26/7e32b21f-81b9-4033-907c-7aaeba85e7a5.pdf.
21 Ibid.
22 Ibid.
23 European Commission (2002), 'Assessing the role of final energy demand in integrated assessment models', 28 September 2022, https://environment.ec.europa.eu/news/assessing-role-final-energy-demand-integrated-assessment-models-2022-09-28_en.
24 Scott, K., Smith, C. J., Lowe, J. A. and Garcia-Carreras, L. (2022), 'Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2 °C targets?', *Global Environmental Change*, 72, 102448, https://doi.org/10.1016/j.gloenvcha.2021.102448.

particularly in reducing dependence on CO_2 removal techniques. The European Commission also pointed to research that argues that the lack of demand reduction is limited due, in part, to 'an imperative to maintain GDP growth, which is typically closely coupled with energy demand'.[25]

Countries are already baking in reliance on engineered removals

With G20 countries accounting for almost 80 per cent of global fossil fuel emissions,[26] their decarbonization plans and relative reliance between technologies and demand-side action is crucial in assessing how likely it is that the world will be able to avoid overshooting the 1.5°C Paris Agreement target – and, by extension, avoid the risk of triggering runaway climate change.

The reliance of G20 members on engineered removals varies from country to country. Members have diverse climate targets and commitments, ranging from pledges to achieve net zero emissions by 2050 to more modest emission-reduction goals. Those with more ambitious targets tend to be more reliant on engineered removals in order to achieve those targets.

Several countries have included engineered removals within their nationally determined contributions (NDCs) under the Paris Agreement, and in their reporting to the UN Framework Convention on Climate Change (UNFCCC). However, the specific details and extent of the inclusion of engineered removals in NDCs vary significantly between countries. Some countries explicitly mention engineered removals as part of their mitigation strategies, while others incorporate them indirectly through national policies. As countries update and revise their NDCs over time, it's likely that more will incorporate engineered removals in their mitigation strategies.

A recent study,[27] published in 2024, found that relative to 2020, the most ambitious national targets imply that CO_2 removals, across all forms of greenhouse gas removal (GGR) types, increase by 0.5 $GtCO_2$ per year ($GtCO_2$/yr) by 2030, and 1.9 $GtCO_2$/yr by 2050. The same study found that these GGR scale-up pledges fall short of holding global temperatures to the 1.5°C Paris target, but that if countries were to pledge dramatically more ambitious emissions reductions while holding the GGR scale-up at the same levels, the emissions gap could be closed. This type of scenario is also consistent with low energy-demand scenarios.[28]

A further 2024 study,[29] found that NDC documents submitted to the UNFCCC indicate that countries plan to increase land-based GGRs from 2 $GtCO_2$/yr in 2020 to around 2.1 $GtCO_2$/yr in 2030 based on unconditional pledges, and to

25 Wilson, C. et al. (2019), 'The potential contribution of disruptive low-carbon innovations to 1.5 °C climate mitigation', *Energy Efficiency*, 12, pp. 423–40, https://doi.org/10.1007/s12053-018-9679-8.
26 Our World in Data (2024), 'CO_2 emissions', https://ourworldindata.org/co2-emissions (accessed 10 Jun. 2024).
27 Lamb, W. F. et al. (2024), 'Current national proposals are off track to meet carbon dioxide removal needs', *Nat. Clim. Chang.*, 14, pp. 555–56, https://doi.org/10.1038/s41558-024-01993-5.
28 Ibid.
29 Lamb, W. F. et al. (2024), 'The carbon dioxide removal gap', *Nat. Clim. Chang.*, 14, pp. 644–51, https://doi.org/10.1038/s41558-024-01984-6.

around 2.6 $GtCO_2$/yr based on conditional pledges.[30] Importantly, the study found that no country currently quantifies contributions from 'novel' GGRs, i.e. from engineered removals. However, several countries include engineered removals in their qualitative description of mitigation efforts within their NDCs.

Looking out to 2050, rather than 2030, only 31 countries have outlined long-term scenario strategies with quantifiable levels of GGR, 12 of which are EU member states. Based on these 31 countries, the study finds that projected CO_2 removals range between 2.5 $GtCO_2$ and 3.6 $GtCO_2$ in 2050, of which conventional land-based GGRs represent between 78 per cent and 73 per cent of removals, respectively.[31] Therefore, the upper-end projection of engineered removals is around 0.97 $GtCO_2$/yr of 'novel' GGRs, equivalent to 3.3 per cent of the fossil fuel emissions from G20 countries in 2023. This is largely driven by the US (52 per cent share), the EU (27 per cent) and Canada (21 per cent). However, it should be noted that this excludes various countries that are in the process of developing engineered removals technology roadmaps, among them China, Norway, Australia and Saudi Arabia.

The same study compared the country pledge analysis of land-based and engineered (or 'novel') CO_2 removal reliance against three scenarios, based on IAMs outputs, finding that depending on the level of demand reduction and renewables deployment, reliance on engineered removals ranged from zero to 3.5 $GtCO_2$/yr in 2050, equivalent to 11.9 per cent of the fossil fuel emissions from G20 countries in 2023. It should be noted that across all the illustrative mitigation pathways (IMPs) assessed by the IPCC, engineered removals are 2.75 (0.52–9.45) $GtCO_2$/yr for BECCS in 2050, and considerably less for DACCS, at 0.02 (0–1.74) $GtCO_2$/yr.[32] Combined, engineered removals would therefore, by 2050, be sufficient to sequester 9.4 per cent of 2023 fossil fuel emissions from G20 countries, with 99 per cent coming from BECCS. For comparison, negative emissions from agriculture, forestry and other land use (AFOLU) across the same IMPs in 2050 are 2.98 (0.23–6.38) $GtCO_2$/yr, meaning that negative emissions from BECCS and AFOLU are on a similar level.

Another important conclusion to draw from the 2024 study of NDC pledges[33] is that, even based only on the 31 countries' long-term scenarios that quantify levels of GGRs, the upper-end projection of 0.97 $GtCO_2$/yr of 'novel' GGRs in 2050 is more than one-third of the way towards the 2.77 $GtCO_2$/yr level within the IMPs assessed by the IPCC.

This review illustrates that, in 2050, engineered (or 'novel') CO_2 removal techniques, relative to 2023 G20 fossil fuel emissions, represent:

- 3.3 per cent, based on quantified country plans
- 9.4 per cent, based on IPCC illustrative mitigation pathways
- 11.9 per cent, based on pathways with a high reliance on engineered removals with limited demand reduction within societies

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30 A conditional pledge is one that countries would only undertake that pledge if a specific condition is met, for instance if international means of support are provided.
31 Lamb et al. (2024), 'The carbon dioxide removal gap'.
32 Pathak et al. (2022), 'Technical Summary', p. 114, in Shukla et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
33 Lamb et al. (2024), 'The carbon dioxide removal gap'.

Decision-makers understandably default to technological innovation to try to solve problems, while simultaneously aiming to deliver growth

Considering the revolutionary power of technology to change lives, mainly for the better, it is no wonder that politicians often, and rightly, turn to technology and innovation to resolve many of the world's problems.[34]

At the same time, technological innovation is fundamental to economic growth. Labour, capital and technological progress are the primary factors governing the rate of production, or economic growth, under the neoclassical growth model, also known as the Solow-Swan growth model.[35] Under the Solow-Swan model, the long-term growth prospects of an economy are determined by technological progress, as returns on capital diminish with no technological progress.[36]

Estimating the proportion of global GDP that is derived from technological innovation is extremely complex, and highly uncertain. However, technological innovation is widely recognized as a key driver of economic development and productivity growth. In its Global Innovation Index reports, the World Intellectual Property Organization (WIPO) highlights the role of innovation in driving economic growth and competitiveness across countries and regions.[37] And OECD data show that countries with higher levels of investment in research and development (R&D), technology adoption and innovation tend to exhibit higher rates of growth.[38]

Perhaps, then, it is no surprise that politics has to some extent influenced the scientific advice emerging from the IPCC,[39] resulting in a degree of breakdown of the old adage that policymakers 'follow the science'.[40] The most reported[41] and widely acknowledged instance of political influence over IPCC reports concerns the Summary for Policymakers,[42] which must be approved by governments. The approval session of the 2023 summary is reported to have seen a group led by Saudi Arabia push for an emphasis on carbon removals and CCS, while European countries pushed for statements that solar and wind electricity 'is now cheaper than energy from fossil

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34 Barry, A. (2001), *Political Machines: Governing a Technological Society*, London: Athlone Press.
35 Stern, D. I. (2011), 'The role of energy in economic growth', *Annals of the New York Academy of Sciences*, 1219, pp. 26–51, https://doi.org/10.1111/j.1749-6632.2010.05921.x.
36 Quiggin, D. (2014), 'Modelling The Expected Participation Of Future Smart Households In Demand Side Management, Within Published Energy scenarios', PhD thesis, Loughborough University, https://hdl.handle.net/2134/16220.
37 World Intellectual Property Organization (WIPO) (2023), *Global Innovation Index 2023: Innovation in the face of uncertainty*, Geneva: WIPO, https://tind.wipo.int/record/48220?v=pdf.
38 Guellec, D. and van Pottelsberghe de la Potterie, B. (2001), *R&D and Productivity Growth: Panel Data Analysis of 16 OECD Countries*, OECD Science, Technology and Industry Working Papers, No. 2001/03, Paris: OECD Publishing, https://doi.org/10.1787/652870318341.
39 Beck, S. and Mahony, M. (2018), 'The politics of anticipation: the IPCC and the negative emissions technologies experience', *Global Sustainability*, 1, e8, https://doi.org/10.1017/sus.2018.7.
40 Nick, H. (2020), 'Stick to the science: when science gets political', *Nature* podcast, https://www.nature.com/articles/d41586-020-03067-w.
41 Kaminski, I. (2023), 'Governments battle over carbon removal and renewables in IPCC report', Climate Home News, https://www.climatechangenews.com/2023/03/23/governments-battle-over-carbon-removal-and-renewables-in-ipcc-report.
42 For the 2023 summary, see IPCC (2023), 'Summary for Policymakers', in Core Writing Team, H. Lee and J. Romero (eds.), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC: Geneva, Switzerland, pp. 1–34, doi: 10.59327/IPCC/AR6-9789291691647.001.

fuels in many regions'.[43] Notably, too, France and Germany are reported to have 'cautioned that CDR [carbon dioxide removal] deployment at scale is unproven and risky', and to have asked for more detail on the limits and risks of CDR methods.[44]

But political influence over the mitigation pathways of the IPCC goes deeper, specifically over engineered removals, as reported by a 2018 study by academics at the University of Cambridge.[45] Due to the vast array of potential decarbonization pathways the world could take, contingent on the weighting ascribed to competing technologies, the IPCC defines Representative Concentration Pathways (RCPs) that represent the outputs of many IAMs. The selection of the RCPs is therefore open to judgment in order to condense the possible pathways down to a manageable number.

In 2007, the IPCC moved away from an older system and towards this RCP system, eventually landing on four pathways: RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5. At an expert meeting,[46] the decision to select RCP 2.6 over an alternative RCP 2.9 scenario proved controversial. The RCP 2.6 scenario had only been produced by one modelling group.[47] Both the pathways prescribed significant emissions reductions, but RCP 2.6 included a massive roll-out of BECCS by giving large expanses of land over to growing fuel crops.[48] An EU-funded project saw the two main European IAM teams invited to produce 2.6 pathways 'with which they were comfortable',[49] which ultimately led to the BECCS-heavy RCP 2.6 being selected and the proposed RCP 2.9 dropped. The Cambridge authors found:

> [T]he decision to include such a low stabilization pathway was influenced by policy-maker interest, not least from the EU which was actively asking new questions of the IAM community, but the decision in favour of 2.6 rather than 2.9 was arguably not just about avoiding prescriptiveness ('do this'), but about policy performativity – that is, concerns about the role of scientific assessments in defining the possibility space within which political actors can deliberate and make decisions.'[50]

We need to be increasingly aware that politics not only influences the IPCC Summary for Policymakers reports, but also the decarbonization scenarios themselves. The policy tail is wagging the science dog.

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43 Kaminski (2023), 'Governments battle over carbon removal and renewables in IPCC report', citing International Institute for Sustainable Development reporting.
44 Ibid.
45 Beck and Mahony (2018), 'The politics of anticipation: the IPCC and the negative emissions technologies experience'.
46 Ibid.
47 van Vuuren, D. P. et al. (2007), 'Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs', *Climatic Change*, 81(2), pp. 119–59, https://doi.org/10.1007/s10584-006-9172-9.
48 European Academies Science Advisory Council (2018), *Negative emission technologies: What role in meeting Paris Agreement targets?*, Halle: German National Academy of Sciences Leopoldina, https://easac.eu/publications/details/easac-net.
49 Beck and Mahony (2018), 'The politics of anticipation: the IPCC and the negative emissions technologies experience'.
50 Ibid.

02
A new net zero era, focused on energy security and affordability

The conflict and security dynamics of a multipolar world, combined with relatively low levels of upstream oil and gas investment, means net zero policies will remain under pressure from energy security and affordability realities.

The emergence of a multipolar world is reshaping geopolitics, challenging multilateral structures and disrupting established trade dynamics and supply chains. Nowhere is this more acutely evident than in the energy sector, where countries are already navigating the costs and new supply chains that necessarily come with the net zero energy transition.

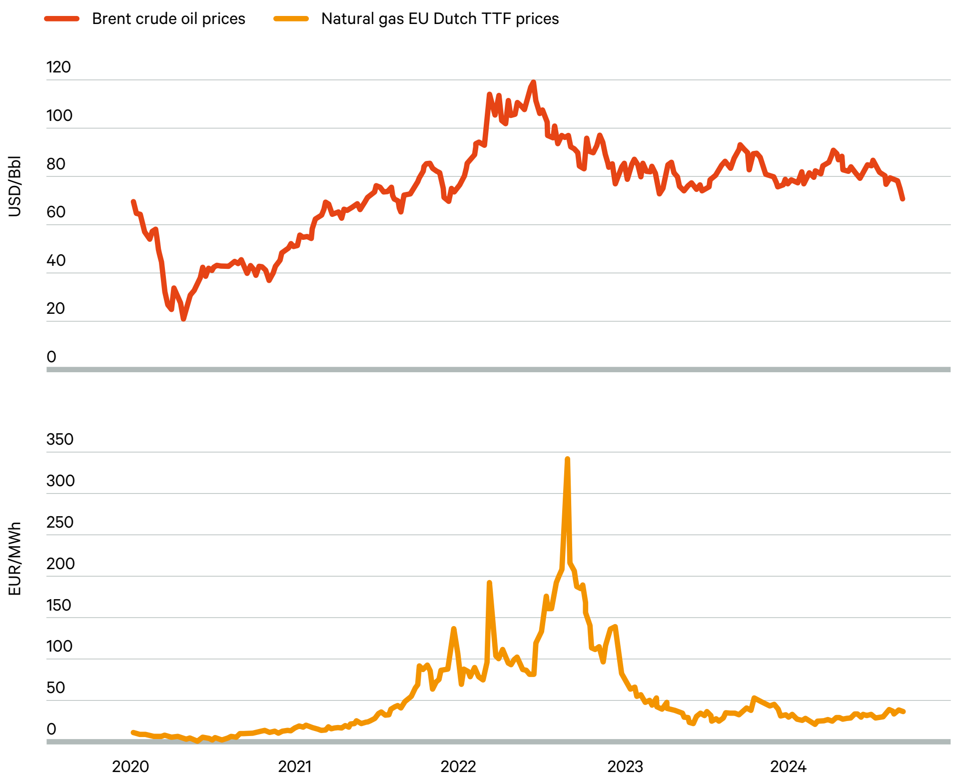
Since the oil price crash of 2014–16, too, there has been a period of historically low investment in upstream oil and gas, as a consequence of which oil- and gas-importing countries were already likely to face a protracted period of energy price inflation, due to baked-in constraints on global supply capacity.

This chapter explores how a refocusing on energy security and prices has emerged due to the new multipolar world, combined with historically low levels of investment in upstream oil and gas.

The new multi-polar world requires costs to be at the forefront of decision-making

In 2022, following Russia's full-scale invasion of Ukraine and the associated trade and geopolitical shocks, European gas prices increased 10-fold compared with prices in early 2021.[51] European countries that had hitherto relied on gas imported from Russia had to quickly diversify their gas supply, with a switch towards liquified natural gas (LNG) mainly from the US. European gas prices had, as of October 2024, fallen back to below their pre-war levels, while oil prices (Brent, average October 2024 prices) are equivalent to the 2021 yearly average price. However, an uptick in European natural gas prices during November was leading to renewed concerns regarding energy affordability over the 2024/25 winter.[52]

Figure 1. Oil and gas price movements, 2020–July 2024, in the context of Russia's 2022 invasion of Ukraine



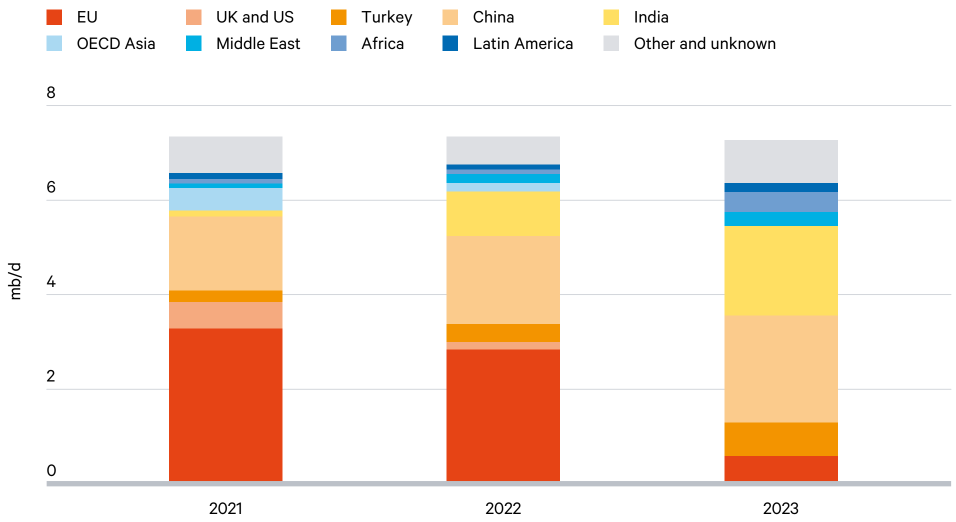
Sources: Trading Economics (2024), 'Brent Crude Oil: Brent Crude Oil (USD/Bbl)', https://tradingeconomics.com/commodity/brent-crude-oil; 'EU Natural Gas TTF: Natural Gas EU Dutch TTF (EUR/MWh)', https://tradingeconomics.com/commodity/eu-natural-gas.

51 Based on Natural Gas EU Dutch TTF prices, see Trading Economics (2024), 'EU Natural Gas TTF', https://tradingeconomics.com/commodity/eu-natural-gas (accessed 2 Nov. 2024).
52 Katanich, D. (2024), 'Winter is coming: Volatile energy prices set to return in Europe', Euronews, 23 November 2024, https://www.euronews.com/business/2024/11/23/winter-is-coming-and-volatile-energy-prices-are-set-to-return-in-europe.

At the start of 2024, the US Energy Information Administration (EIA) expected Brent crude to average $82 per barrel in 2024 and $79 per barrel in 2025, close to the 2023 average of $82 per barrel.[53] As of October 2024, European gas prices are stable, with countries rebuilding stocks in anticipation of the winter.[54] In the context of the recent upsurge in the Ukraine conflict, market analysts have commented that the gas 'market seems to have decided not to choose a direction for the moment'.[55]

Despite harsh Western-led sanctions, Russia continues to exert significant influence in the global oil market. Russia was the world's third-largest oil producer in 2023, after the US and Saudi Arabia, and the largest net exporter overall.[56]

Figure 2. Average daily Russian oil exports by country and region, 2021–23



Source: International Energy Agency (2024), 'Russia's War on Ukraine: Analysing the impacts of Russia's invasion of Ukraine on energy markets and energy security', https://www.iea.org/topics/russias-war-on-ukraine.

Russian oil export volumes in 2023 remained stable at 7.5 million barrels per day (b/d).[57] A slight decline in crude oil exports was offset by a corresponding increase in oil product exports. Overall exports to the EU, the US the UK and OECD Asia dropped 4.3 million b/d below pre-war levels. However, exports to India, China and countries in the Middle East almost entirely made up for exports lost due to sanctions (see Figure 2).

Nevertheless, Russia's monthly average revenue from commercial oil exports in 2023 fell by $4.2 billion compared with the previous year. This decline was due to price caps implemented by G7 countries and increased discounts on Russian crude more broadly.[58]

53 U.S. Energy Information Administration (2024), 'Short-term energy outlook', 9 January 2024, https://www.eia.gov/outlooks/steo/report/BTL/2024/01-brentprice/article.php (accessed 14 Jun. 2024).
54 Rocha, P (2024), 'European Gas Rises as Traders Focus on Topping Up Robust Stocks', 16 May 2024, Bloomberg New Energy Finance, https://www.bnef.com/news/sdkchgt0g1kw00.
55 Ibid.
56 International Energy Agency (2024), 'Russia's War on Ukraine: Analysing the impacts of Russia's invasion of Ukraine on energy markets and energy security', https://www.iea.org/topics/russias-war-on-ukraine.
57 Ibid.
58 Ibid.

From the European perspective, through the 2022 energy crisis, a combination of diversification policies, along with the switch to US LNG, reliable Norwegian supplies, sanctions, more renewable capacity, industrial gas demand declines, increased gas storage and a mild winter, shifted the bloc's dependence on Russian gas from around 40 per cent per year in 2020–21 to around 12 per cent in 2023.[59]

In 2022, EU countries together spent around €390 billion on energy subsidies, compared with €216 billion in 2021 and €200 billion in 2020.[60] The UK, for its part, spent around an additional £60 billion on gas,[61] and in excess of £50 billion on subsidies in 2022/23.[62] In July 2023, Bruegel estimated that some €651 billion had, since September 2021, been allocated and earmarked across EU countries, along with the UK and Norway, in order to minimize the impact of rising energy costs on consumers.[63]

Following the 10-fold increase in European gas prices, and the sharp fall back to near pre-war levels, LNG markets are fundamentally changed. One of the chief reasons for this is that the market has become more globalized, with increased demand for LNG and competition between Europe, China and other markets in Asia for US LNG,[64] which is a product of the shale oil and gas boom in the US. Over the period 2018–23, US LNG exports have quadrupled, and the EU's share has increased from an average of 28 per cent in the four years prior to 2022 to more than 60 per cent in 2022 and 2023.

Tensions remain acute in the Middle East, with recent heightened exchanges between Iran and Israel[65] compounding fears that the widening of the Israel–Hamas conflict could lead to regional instability, and jeopardizing the crucial Strait of Hormuz, via which one in every five barrels of global daily petroleum is transported.[66] During an emergency session of the UN Security Council in April 2024, Secretary-General António Guterres warned of the Middle East being at risk of full-scale conflict, and stating – 'neither the region nor the world can afford more war'.[67] The IMF also warned at this time of the increased risk that oil prices could rise sharply.[68]

While oil and gas prices have declined from their highest point in the early months of Russia's war on Ukraine, indications from forward markets are that for

59 Ibid.
60 Council of the European Union (2023), *Report from the Commission to the European Parliament and the Council: 2023 Report on Energy Subsidies in the EU*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0651.
61 Smeeton, G. (2024), 'Russia war anniversary – UK gas bill has now topped £100bn during gas crisis', 19 February 2024, Energy and Climate Intelligence Unit, https://eciu.net/media/press-releases/2024/russia-war-anniversary-uk-gas-bill-has-now-topped-100bn-during-gas-crisis.
62 Office for Budget Responsibility (2023), 'The cost of the Government's energy support policies', October 2023, https://obr.uk/box/the-cost-of-the-governments-energy-support-policies.
63 Sgaravatti, G., Tagliapietra, S., Trasi, C. and Zachmann, G. (2023), 'National fiscal policy responses to the energy crisis', Bruegel Datasets, 26 June 2023, https://www.bruegel.org/dataset/national-policies-shield-consumers-rising-energy-prices.
64 Flowers, S, (2022), 'How the Russia-Ukraine war is changing energy markets', Wood Mackenzie, 23 February 2023, https://www.woodmac.com/news/the-edge/how-the-russia-ukraine-war-is-changing-energy-markets.
65 Azizi, A. (2024), 'Which side will Arabs take in an Iran-Israel war?', Atlantic Council, 29 August 2024, https://www.atlanticcouncil.org/blogs/iransource/arabs-iran-israel-war.
66 McCormick, M. and Smyth, J. (2024), 'How US shale keeps sheltering America from the next oil price surge', *Financial Times*, 23 April 2024, www.ft.com/content/030dc3c8-0f25-483e-91aa-9dbd9abc5c4d.
67 United Nations (2024), 'Warning Middle East at Risk of Full-Scale Conflict, Secretary-General Urges All Parties to 'Step Back from the Brink', in Emergency Security Council Session', 14 April 2024, https://press.un.org/en/2024/sc15660.doc.htm.
68 Elliot, L. (2024), 'Middle East conflict risks sharp rise in oil prices, says IMF', *Guardian*, 16 April 2024, https://www.theguardian.com/business/2024/apr/16/middle-east-conflict-risks-a-sharp-rise-in-oil-prices-says-imf.

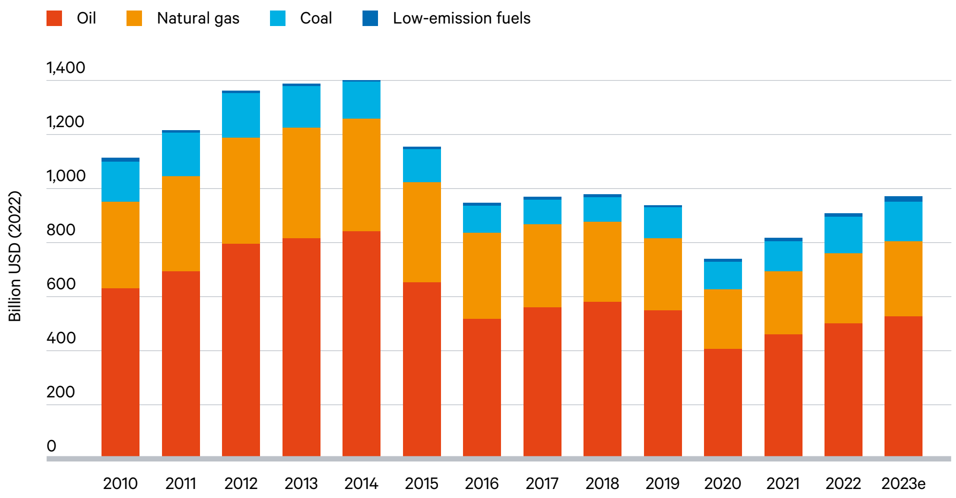
the foreseeable future prices in Europe will remain elevated compared with those in the US and China.[69]

Future oil and gas price rises cannot be ruled out, and many market analysts anticipate ongoing price volatility.[70] Even without considering a further escalation of Russia's military activity, along with wider Middle East tensions, and if the US can maintain its LNG export capacity, Russia has faced refining difficulties, and at the beginning of 2024 Ukraine targeted Russian refineries, leading to production declines.[71]

Historically low investment in upstream oil and gas means there is a structural inflationary trajectory of fossil fuel prices

Arguably, the shale oil and gas boom in the US has been one of the major drivers of the shifts in geopolitics over the last decade, as shale drilling techniques have helped the US become the world's largest producer of oil, consistently pushing Saudi Arabia into the second spot from 2017 onwards,[72] and meaning the US is less reliant on supplies from the Middle East. It has been this production revolution in the US that has prevented global oil prices going even higher during the war in Ukraine, and as the escalation of the Israel–Hamas conflict has fuelled wider instability in the Middle East. The scale of US output has also enabled record LNG exports to Europe, and has shielded European countries from otherwise even higher gas price inflation.

Figure 3. Global investment in fuel supply, 2010–23e



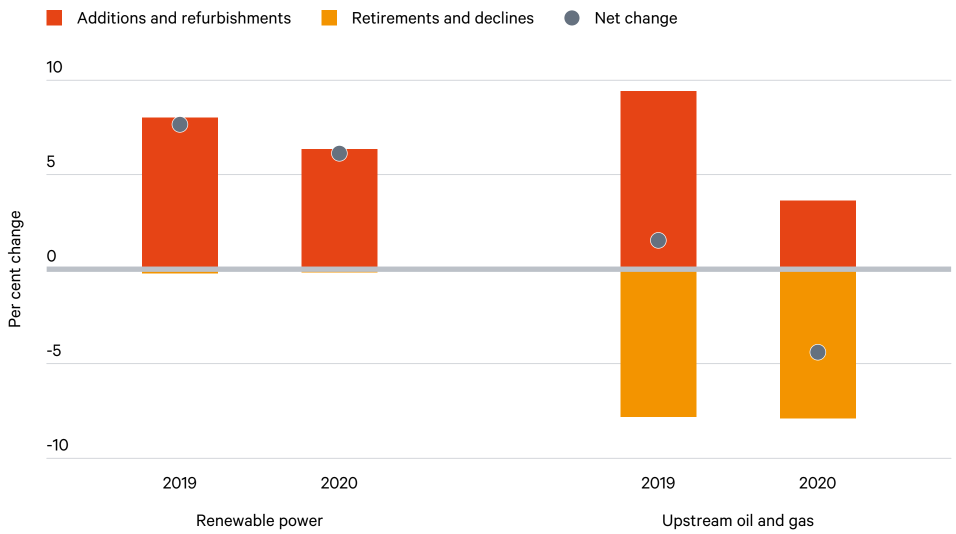
Source: International Energy Agency (2023), *World Energy Investment 2023*, https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf.

69 Cornago, E. (2023), *EU climate and energy policy after the energy crunch*, Centre for European Reform, www.cer.eu/publications/archive/policy-brief/2023/eu-climate-and-energy-policy-after-energy-crunch.
70 Coleman, N. (2024), 'Russia defiant two years into war reshaping global energy', S&P Global, 22 February 2024, www.spglobal.com/commodityinsights/en/market-insights/latest-news/oil/022224-feature-russia-defiant-two-years-into-war-reshaping-global-energy.
71 Ibid.
72 Energy Institute (2024), *2024 Statistical Review of World Energy*, p. 21, https://www.energyinst.org/statistical-review.

However, both the historically low investment in upstream oil and gas globally since 2014,[73] and specifically anticipated production declines from depleting accessible shale reserves in US,[74] means that over the coming years supply constraints could contribute to another inflationary period for oil and gas prices across the US, Europe, China and beyond.

As shown in Figure 3, the two most significant oil price crashes of the last decade – in 2014–16, and the pandemic-induced crash in 2020 – contributed to significant declines in oil and gas upstream exploration and production investment. In 2020 prices dropped by almost one-third, relative to 2019 levels. Following the oil price crash in 2014, cuts in capital expenditure (capex) in global upstream oil and gas exploration and production were mitigated by declines in upstream costs. A 40 per cent reduction in nominal spending (between 2014 and 2019) resulted in a 12 per cent reduction in upstream activity.[75] Further cost reductions are consequently more limited, as many of the efficiency gains have already been realized. Low levels of upstream oil and gas investment meant that in 2019 and 2020 upstream oil and gas infrastructure retirements outpaced additions (Figure 4), and in 2021 the oil refining sector experienced its first decline in global capacity in 30 years.[76] As a result, the low levels of investment in the last few years are more likely to result in upward pressure on oil and gas prices.

Figure 4. Changes to energy-related capital stock in 2019 and 2020 as a share of total stock in the preceding year

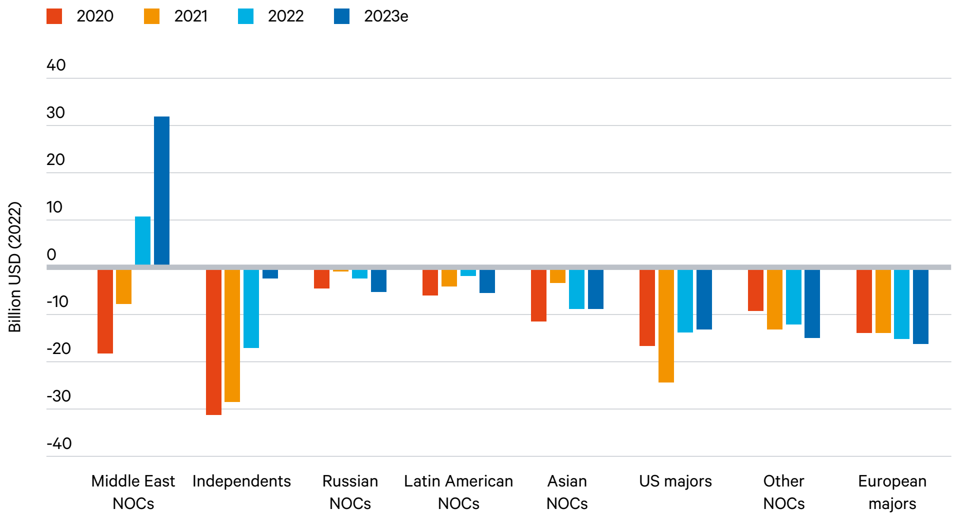


International Energy Agency (2020), 'Changes to the energy-related capital stock in 2019 and 2020 as a share of total stock in the preceding year', https://www.iea.org/data-and-statistics/charts/changes-to-the-energy-related-capital-stock-in-2019-and-2020-as-a-share-of-total-stock-in-the-preceding-year.

73 International Energy Agency (2020), *World Energy Investment 2020*, https://iea.blob.core.windows.net/assets/ef8ffa01-9958-49f5-9b3b-7842e30f6177/WEI2020.pdf.
74 Messler, O. (2024), 'Is U.S. Shale Production Finally Nearing Its Peak?', OilPrice.com, 21 March 2024, https://oilprice.com/Energy/Crude-Oil/Is-US-Shale-Production-Finally-Nearing-Its-Peak.html.
75 International Energy Agency (2020), *World Energy Investment 2020*.
76 International Energy Agency (2022), *World Energy Investment 2022*, https https://iea.blob.core.windows.net/assets/b0beda65-8a1d-46ae-87a2-f95947ec2714/WorldEnergyInvestment2022.pdf.

In 2023, the International Energy Agency (IEA) reported that 'record income in the oil and gas sector was used to increase shareholder returns and pay down debt'.[77] And as Figure 5 shows, only the national oil companies (NOCs) of producers in the Middle East are spending more than they were before the COVID-19 pandemic. Refinery capacity is increasingly being retired: in 2021, for instance, capacity equivalent to 1.8 million b/d was retired across North America, Europe and Asia, resulting in a net reduction in global refining capacity for the first time in 30 years.[78]

Figure 5. Change in upstream oil and gas capital investment relative to 2019, by company type, 2020–23e



International Energy Agency (2023), 'Change in upstream oil and gas capital investment relative to 2019 by company type, 2020-2023e', *World Energy Investment 2023*, p. 68, https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf.

Hesitancy about oil and gas supply investments is multifaceted, stemming from a mix of concerns about costs, uncertainty over longer-term demand, pressures from investors to focus on returns over production growth, and evolving climate policy. This is especially true of US shale oil and gas companies.[79] Not only is the US shale sector concentrating on shareholders' returns rather than production, it is also experiencing a persistent labour shortage in the main producing area, the Permian Basin.[80]

The fast depletion rate of shale oil and gas fields means that most of the production occurs over three to five years for the typical well, with a sharp drop in output after that. In the Permian fields, production is expected to peak in 2030. US EIA data show that new drilling technology has helped the US maintain and even slightly increase production recently, with output per rig increasing, while rig count has gone down,[81] due to less new drilling investment and activity.

77 International Energy Agency (2023), *World Energy Investment 2023*, https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf.
78 International Energy Agency (2022), *World Energy Investment 2022*.
79 Ibid.
80 Ibid.
81 U.S. Energy Information Administration (2024), 'Drilling Productivity Report', 13 May 2024, www.eia.gov/petroleum/drilling (accessed 11 Jun. 2024).

However, in a 2023 report from energy analyst firm Enervus, the lead author notes:

> The U.S. shale industry has been massively successful, roughly doubling the production out of the average oil well over the last decade, but that trend has slowed in recent years. In addition, we've observed that declines curves, meaning the rate at which production falls over time, are getting steeper as well density increases. Summed up, the industry's treadmill is speeding up and this will make production growth more difficult than it was in the past.[82]

Historically low investment in upstream oil and gas exploration and production has contributed to increasingly tight oil and gas markets, regardless of current geopolitical tensions, and it may not serve the West well to overly rely on US shale oil and gas production indefinitely. It is therefore not surprising that energy security and affordability has risen up the political agenda, and is competing with higher-cost components of net zero on the desks of decision-makers. Indeed, across Europe, the US and the UK, there has been increasing scrutiny over the costs of net zero.[83] This is compounded by the general inflation and cost-of-living increases across the world.[84]

82 Enervus (2023), 'EIR: Density drives steepening declines in U.S. shale', https://www.enverus.com/newsroom/eir-density-drives-steepeningdeclines-in-u-s-shale.
83 Salter, E. (2022), 'A new Tory faction is 'scrutinising' net zero – with tactics learned from Brexit', *Guardian*, 1 February 2022, www.theguardian.com/commentisfree/2022/feb/01/tory-faction-net-zero-brexit-green-policies; Murray, J. (2023), 'The government's assault on net zero has triggered a battle where no one wins', Business Green, 31 July 2023, https://www.businessgreen.com/blog-post/4121248/governments-assault-net-zero-triggered-battle-wins; Zurcher, A. (2020), 'US Election 2020: Biden seeks to clarify remark on ending oil', BBC News, 24 October 2020, www.bbc.co.uk/news/world-us-canada-54670269; Abnett, K. et al. (2023), 'Resistance to green policies around Europe', Reuters, 27 September 2023, www.reuters.com/business/environment/resistance-green-policies-around-europe-2023-09-27; Plunkett, S. (2023), 'Global push-back on Net Zero demands an industrial rethink', InnovationAus.com, 16 December 2023, www.innovationaus.com/global-push-back-on-net-zero-demands-an-industrial-rethink.
84 Economist Intelligence Unit (2023), *Worldwide Cost of Living 2023*, www.eiu.com/n/campaigns/worldwide-cost-of-living-2023; Atkins (2022), 'How is the cost of living crisis affecting net-zero policies?', Economics Observatory, 9 November 2022, www.economicsobservatory.com/how-is-the-cost-of-living-crisis-affecting-net-zero-policies; Picchi, A. (2023), 'Americans need an extra $11,400 today just to afford the basics, Republican analysis finds', [updated] 30 November 2023, www.cbsnews.com/news/inflation-households-need-extra-11400-these-states-its-even-higher.

03 Engineered removals are costly, however they are paid for

The high costs of BECCS and DACCS, because of their high energy input requirements, are likely to amplify the growing narrative that net zero is 'unaffordable'.

So far, this paper has explored how future reliance on engineered removal technologies – chiefly BECCS and DACCS – has increased, and that due to shifting geopolitics, conflict and historically low investment in upstream oil and gas, there has been growing scrutiny of the cost of net zero, and a recent shift in focus towards energy security and affordability. This chapter focuses on why BECCS and DACCS are likely to be a very expensive component of net zero and the energy transition. This raises the question of what might be the most cost-effective way of pursuing engineered CO_2 removals.

With the UK, in 2024, granting development consent for the world's largest BECCS facility,[85] it is interesting to note that the most recent analysis by the UK's Department for Energy Security and Net Zero on the costs of all electricity generators states:

> Costs for first deployment of both [BECCS and CCUS] technologies in the UK are expected to be revealed through bilateral negotiations which relate to specific

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85 Morby, A. (2024), 'Drax gets planning for world's largest carbon capture scheme', *Construction Enquirer*, 16 January 2024, www.constructionenquirer.com/2024/01/16/drax-gets-planning-for-world-largest-carbon-capture-scheme.

projects, informed by project specific analysis. The information and analysis used for this purpose is commercially confidential. Therefore, it is not available for generic cost assumptions.[86]

Given that the costs are yet to be fully understood, the risk is that future engineered removals costs could be incompatible with a focus on energy security and affordability, and that therefore the reliance countries have already built in cannot be fulfilled. This would widen the emissions gap and increase the likelihood of triggering accelerated climate change.

Engineered removals, deployed at scale, bring multiple risks in terms of land-use tensions, supply-chain emissions and carbon debt pertaining to BECCS (summarized in Box 1).[87] However, the primary near-term risk is that reliance on engineered removals technologies will be unduly costly, requiring subsidies paid for by taxpayers or energy consumers, or via carbon markets with costs again, ultimately, passed on to consumers via increased prices of goods and services.

Huge energy requirements

In its simplest terms, within both BECCS and DACCS systems, the CO_2 removal or separation process requires a chemical to bind to the CO_2 molecule. Because a significant volume of that chemical agent is required, it must be recycled around the system. This means that a significant amount of heat energy has to be applied to the chemical to allow it to release its CO_2, which is then subsequently buried underground. This is where the large energy requirement for both systems emerges.[88]

Given that the costs are yet to be fully understood, the risk is that future engineered removals costs could be incompatible with a focus on energy security and affordability, and that therefore the reliance countries have already built in cannot be fulfilled.

It is important to note that whereas DACCS will be a net energy consumer, BECCS is likely to be a net energy producer, albeit with significant amounts of energy being diverted to the CCS equipment.

DACCS removes carbon from ambient air via a chemical medium – typically an aqueous alkaline solvent or sorbent – in a similar manner to the solvents used in the CCS process of BECCS. The chemical medium is subsequently stripped

86 Department for Net Zero and Energy Security (2023), *Electricity Generation Costs 2023*, https://assets.publishing.service.gov.uk/media/6556027d046ed400148b99fe/electricity-generation-costs-2023.pdf.
87 For previous Chatham House work on these topics, see in particular Quiggin (2021), *BECCS deployment*; King et al. (2023), *The emerging global crisis of land use*.
88 Ibid.

of CO_2 by applying heat and then CO_2 dehydration and compression, allowing the medium to be reused to bind to more CO_2. The two main DACCS technologies are solid or liquid sorbents.[89]

The first and second laws of thermodynamics show that separating one gas from another requires a significant energy input. Because CO_2 is more concentrated within the flue gases of a power station, compared with that of ambient air, a BECCS system producing electricity will require less energy per unit of CO_2 captured, relative to a DACCS system which sucks in and processes atmospheric gases.

Importantly, the energy requirement of both BECCS and DACCS is primarily heat. While the heat energy input for BECCS will always be biomass, DACCS can, in theory, use various energy sources to produce the heat requirement. However, converting electricity to heat is a relatively expensive. As such, renewable heat sources will likely be needed for DACCS. While there are renewable heat sources such as from biomass and geothermal, these are much more limited in their current deployment and future availability than electricity-producing solar and wind.

Liquid DACCS (L-DACCS) relies on an aqueous solution (such as potassium hydroxide), and requires high temperatures of 300–900°C in the CO_2 separation process. Solid DACCS (S-DACCS) uses highly porous solid sorbents with a high surface area to adsorb the CO_2 molecules, and requires relatively lower temperatures of around 100°C. Because the energy input and hence costs of L-DACCS are higher, many of the DACCS projects in R&D and early commercialization phases are S-DACCS.

In Iceland, notably, operations began in May 2024 at S-DACCS specialist Climeworks' second large-scale commercial facility, Mammoth. Like the company's first facility, Orca, which entered production in 2021, Mammoth derives its heat source from the country's abundant geothermal resources.[90]

Within the relatively low-temperature S-DACCS system, to capture and store 1 million tonnes of CO_2 requires around 2 terawatt hours per year (TWh/yr) of energy.[91] This is equivalent to the output of a 230 MW gas turbine running constantly for a year. (For reference, the UK's largest gas power station has five 400 MW turbines.) Of this energy, more than 85 per cent is in the form of heat.[92] For the high temperature process of L-DACCS, the energy needed to capture and store 1 million tonnes of CO_2 increases to 2.4 TWh/yr, with more than 75 per cent being in the form of heat.[93]

In a BECCS system, the heat input to release the CO_2 molecule from the chemical solvent, within the CCS equipment, comes from diverting heat from the combusted biomass that would otherwise produce electricity,[94] this is commonly referred to as the energy penalty.

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89 Webb, P., Muslemani, H., Fulton, F. and Curson, N. (2023), *Scaling Direct Air Capture (DAC): A moonshot or the sky's the limit?*, Oxford Institute for Energy Studies, https://www.oxfordenergy.org/publications/scaling-direct-air-capture-dac-a-moonshot-or-the-skys-the-limit.
90 Climeworks (2024), 'Climeworks switches on world's largest direct air capture plant', 8 May 2024, https://climeworks.com/press-release/climeworks-switches-on-worlds-largest-direct-air-capture-plant-mammoth.
91 Webb, Muslemani, Fulton and Curson (2023), *Scaling Direct Air Capture (DAC)*.
92 Fasihi, M., Efimova, O. and Breyer, C. (2019), 'Techno-economic assessment of CO2 direct air capture plants', *Journal of Cleaner Production*, 224, pp. 957–80, https://doi.org/10.1016/j.jclepro.2019.03.086.
93 Ibid.
94 Quiggin (2021), *BECCS deployment*.

The important consequence of the high heat energy input requirements of engineered removals is that they comprise nearly 50 per cent of the cost of DACCS,[95] and at least 33 per cent of the cost of BECCS.[96] It should be noted that the latter figure (i.e. for BECCS) is based on the UK government's 'low' cost of wood pellet price scenario; under the 'central' scenario, the figure would rise to at least 45 per cent of the cost.

Current and future abatement costs of engineered removals

A 2023 Oxford Institute for Energy Studies report estimates that current pre-subsidy costs for DACCS are around \$800–\$1,000/tCO_2.[97] This would mean that if DACCS were to provide 100 per cent of the engineered removals 2050 level within the IPCC's Sixth Assessment Report (AR6) (i.e. 2.77 GtCO_2/yr), some \$2.2–\$2.8 trillion would be required every year to finance DACCS. However, Climeworks expects costs to decline to \$400–\$700/tCO_2 by 2030, and to \$100–\$300/tCO_2 by 2050,[98] meaning that by 2050 the annual finance requirement could be in the range of \$277–\$831 billion.

The declines in costs anticipated by Climeworks are predicated on technological innovation,[99] but are also limited by the high fuel input costs. While it is unclear in which regions Climeworks expects its technology to be able to operate in these cost ranges, any suitable country will evidently require abundant and low-cost renewable heat sources, similar to the geothermal heat sources found in Iceland.

In January 2024, Drax, the main UK developer of BECCS, published guidance for the subsidy requirement to stimulate 'material deployment of BECCS' in the US,[100] stating that 'further increasing the 45Q tax credit [for carbon sequestration] to \$100–150/t CO_2 did not lead to a material deployment of BECCS but rather boosted the uptake of coal-CCS'; and that 'negative emission credits of 30 to 40 \$/tCO_2 sequestered is required for carbon dioxide removal technologies in addition to the 85 \$/tCO_2 provided by 45Q'. Therefore, a current subsidy for BECCS of around \$120/tCO_2 would be required. While biomass wood pellet prices have risen recently[101] (see below), some assessments, like the International Renewable Energy Agency's (IRENA) in 2021, envisage that BECCS costs may fall over time, reaching \$69–\$105/tCO_2.[102]

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95 See Webb, Muslemani, Fulton and Curson (2023), *Scaling Direct Air Capture (DAC)*, Figure 10: 2025 and 2050 carbon removal costs, 'energy use' and 'energy prices' as a share of total costs.
96 Based on current and forecast wood pellet prices, and using the central fuel cost in Appendix 2, Ricardo Energy & Environment (2020), *Analysing the potential of bioenergy with carbon capture in the UK to 2050: Summary for policymakers. Report for BEIS*, https://assets.publishing.service.gov.uk/media/5f3fe1f28fa8f55df267bc17/potential-of-bioenergy-with-carbon-capture.pdf.
97 Webb, Muslemani, Fulton and Curson (2023), *Scaling Direct Air Capture (DAC)*.
98 Ibid.
99 Ibid.
100 Mersch, M. et al. (2024), *The role and value of BECCS in the USA*, Drax, www.drax.com/wp-content/uploads/2024/01/Role-and-value-of-BECCS-in-the-US_Final_Report.pdf.
101 Harrison, T. and MacDonald, P. (2024), 'Drax's BECCS project climbs in cost to the UK public', 16 January 2024, https://ember-climate.org/insights/in-brief/draxs-beccs-project-climbs-in-cost-to-the-uk-public.
102 Lyons, M., Durrant, P. and Kochhar, K. (2021), *Reaching Zero with Renewables: Capturing Carbon*, Abu Dhabi: International Renewable Energy Agency, https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Capturing_Carbon_2021.pdf.

Assuming, as the IPCC does, that BECCS accounts for 99 per cent of the 2050 engineered removals sequestration rate, this would mean engineered removals would cost between $192 billion and $295 billion annually. However, if the costs of BECCS do not fall in line with current expectations, and the primary source of feedstock for BECCS is wood pellets (see Box 1), the high end of the range could be $315 billion annually. This is based on the mid-point of Drax's January 2024 estimate of the US subsidy requirement,[103] with wood pellets comprising 50 per cent of the global feedstock for BECCS.

For BECCS and DACCS respectively, 33 per cent and 50 per cent of ongoing costs are energy input operational expenditure.

Given the current heightened scrutiny of the cost of net zero, and the focus on energy security, potential costs of engineered removals, primarily BECCS, in the range of $192–$315 billion annually by 2050 need to be set in the context of current and projected global spending on the energy transition. Around $1.77 trillion per year is currently spent on the energy transition, globally.[104] To reach net zero in 2050, the IEA anticipates that around $4 trillion will need be needed every year between 2030 and 2050,[105] with the Energy Transition Commission anticipating that, on average, $3.5 trillion in capital investment will be needed each year between now and 2050.[106] This means that engineered removals would account for some 5.5–9.0 per cent of all clean energy investment in 2050, based on the IPCC 2050 removal potential of 2.77 $GtCO_2$/yr. It is important to emphasize that this range does not factor in the cost to energy consumers of the electricity produced by BECCS, or that, as explored in the next section, wood pellet prices have risen in recent years.

Emissions reductions of 2.77 $GtCO_2$/yr could be achieved for around $72 billion annually from electric vehicles (EVs), solar and onshore wind, based on their respective 2050 weighted abatement costs,[107] or 2 per cent of the average yearly spend to 2050. Here, it should be noted that as the global emissions gap widens CO_2 removal will become more important relative to mitigation. Importantly, because of the lifetimes of these assets, the majority of the costs are not ongoing operational expenditure (opex), unlike for BECCS and DACCS, where 33 per cent and 50 per cent, respectively, of their costs are energy input opex.

Not only do engineered removals require high fuel opex, which is undesirable in the context of the ongoing focus on energy security and price, BECCS deployment costs are unlikely to benefit from high learning rates. Technologies

103 Mersch et al. (2024), *The role and value of BECCS in the USA*.
104 Bloomberg New Energy Finance (2024), *Energy Transition Investment Trends 2024*, https://about.bnef.com/energy-transition-investment.
105 See 'Clean energy investment in the net zero pathway' figure, p. 22, in International Energy Agency (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*, www.iea.org/reports/net-zero-by-2050.
106 Energy Transition Commission (2023), *Financing the Transition: How to Make the Money Flow for a Net-Zero Economy*, https://www.energy-transitions.org/keeping-1-5c-alive/financing-the-transition.
107 Based on the abatement costs of solar, wind and EVs, weighted by their abatement potential. All values derived from figure 10, p. 27, in Farbes, J., Haley, B. and Jones, R. (2021), 'Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems', *Environmental Defense Fund*, https://www.edf.org/sites/default/files/documents/MACC_2.0%20report_Evolved_EDF.pdf.

with high learning rates, and therefore fast cost reductions, tend to be modular, with – as for solar panels, wind turbines and lithium-ion batteries for EVs, for instance – thousands to millions of units able to be produced each year.[108] Such technologies have already demonstrated, and continue to demonstrate, rapid cost reductions. BECCS, however, is generally being considered as a retrofitted technology, whereby large CCS infrastructure is fitted to existing bioenergy power stations or coal power stations with fuel switching. As such, at most hundreds of BECCS facilities are likely worldwide. This means the opportunity for engineers and contractors to learn from project to project, improve build efficiencies and drive down costs is more limited.

Box 1. BECCS feedstock choice, land-use tensions and the role of wood pellets

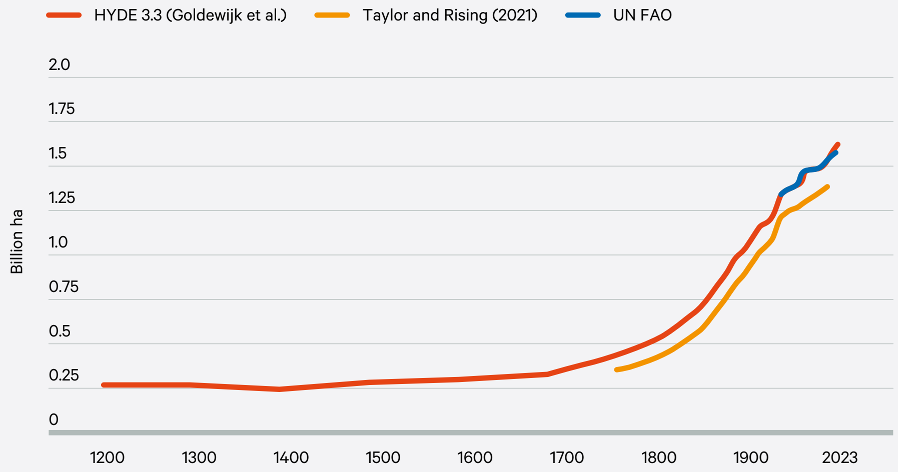
Most integrated assessment models (IAMs) assume BECCS will be powered by energy crops produced on cropland that is made available through sustainable intensification of agricultural practices. However, current trends in land use show that while total agricultural land use has peaked, cropland use is still rising globally (see Figure 6).[109] There are multiple reasons for this. One of the main drivers is that more animals are being fed from crops grown on croplands, rather than on pastureland, with almost half of global cropland currently used to produce animal feed. In relation to BECCS, this raises the question of whether there will be enough cropland to grow energy crops for BECCS without impacting food security and inflating food costs. A major 2023 Chatham House report shows that, in part due to demand for BECCS feedstocks, by 2050 the world could face an agricultural land deficit – the gap between the amount of farmland needed and that available – of 573 million hectares, almost twice India's land area.[110] Furthermore, the IPCC assesses that BECCS could require 25–46 per cent of the world's arable and cropland in 2100[111] in order to support 11.5 GtCO_2/yr of removals. By the same calculation, at the 2050 level of 2.75 GtCO_2/yr, 6–11 per cent of arable and cropland would be required for BECCS.

In 2020, solid biomass sources including wood chips, wood pellets and traditional biomass sources comprised 86 per cent of current supply of biomass globally; liquid biofuels accounted for 7 per cent; municipal and industrial waste sectors 6 per cent; and biogas 2 per cent. Looking specifically at biopower generated globally in the same year, 69 per cent was derived from solid woody biomass, and 17 per cent from municipal and industrial waste.[112] By 2050, the IEA forecasts that 55 per cent of all biomass supply will be woody biomass.[113]

108 Quiggin (2024), 'How modular renewables can reduce the costs of relying on carbon capture'.
109 Hannah, R. (2022), 'After millennia of agricultural expansion, the world has passed 'peak agricultural land'', Our World in Data, 30 May 2022, https://ourworldindata.org/peak-agriculture-land.
110 King et al. (2023), *The emerging global crisis of land use*.
111 Nabuurs, G-J. et al. (2022), 'Agriculture, Forestry and Other Land Uses (AFOLU)', in Shukla P. R. et al. (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York, Cambridge University Press, https://doi.org/10.1017/9781009157926.009.
112 World Bioenergy Association (2022), *Global Bioenergy Statistics 2022*, www.worldbioenergy.org/uploads/221223%20WBA%20GBS%202022.pdf.
113 International Energy Agency (2021), 'What does net-zero emissions by 2050 mean for bioenergy and land use?', 31 May 2021, www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use.

Given these land-use tensions, it is important to examine how the costs of BECCS could be impacted by wood pellets, rather than land-intensive energy crops, being the primary feedstock for BECCS.

Figure 6. Global cropland area is still increasing



Source: Hannah, R. (2022), 'After millennia of agricultural expansion, the world has passed 'peak agricultural land'', Our World in Data, 30 May 2022, https://ourworldindata.org/peak-agriculture-land.

Removals costs may increase as wood pellet costs rise

This paper has described how BECCS is relied on more than DACCS in the IAMs, and shown that the costs of the wood pellets to fuel BECCS power stations is the main cost component, comprising at least 33 per cent of the overall cost.[114] Given the limited scope for significant cost reductions to be driven by technological learning curves, due to the sheer size of the BECCS infrastructure and hence the inability to reduce costs by repeated learning (as has been the case for EV batteries, solar and wind), this section tackles the critical question of how wood pellet prices may impact the costs of BECCS into the future.

The main challenge in estimating the cost of a BECCS project lies in the unpredictability of the future price dynamics of wood pellets. Unlike many commodity markets that are characterized by high liquidity, the wood pellet market is relatively opaque, in that it is driven by numerous private bilateral agreements between companies. Consequently, the limited transparency in market price data for wood pellets means that there is significant uncertainty in projecting costs and hence subsidy requirements for BECCS projects. This opacity underscores the need for enhanced market transparency mechanisms as part of planning for future reliance on BECCS.

114 Based on current and forecast wood pellet prices, and using the central fuel cost in Appendix 2, Ricardo Energy & Environment (2020), *Analysing the potential of bioenergy with carbon capture in the UK to 2050: Summary for policymakers*.

Box 2. Calculating the costs implications of wood pellet prices

One of the only publicly available sources for current and forward wood pellet prices is Argus Media, which forecasts prices out to 2027,[115] resulting in a price of $208.50 per tonne (the mean of the 'bid' and 'ask' prices for North West Europe forward prices in 2027). These projections are from April 2024 and are the latest publicly available data.

In 2020, the UK government projected the costs of BECCS within three scenarios,[116] of low, medium and high wood pellet fuel costs. Table 1, below, shows the UK government's three scenarios and their corresponding levelized cost of electricity (LCOE) estimate. It should be noted that in the UK government documentation, the fuel costs scenarios are given for wood pellets 'pre-combustion'. The costs presented in this table have been converted to wood pellets 'post-combustion' using a BECCS net efficiency of 30.6 per cent.

Table 1. BECCS fuel costs (post-combustion) and levelized cost of electricity (LCOE) estimates, by the UK government

Scenario	Fuel cost (£/MWh)	LCOE (£/MWh)
Low	19	119
Medium	82	181
High	131	230

Source: Ricardo Energy & Environment (2020), *Analysing the potential of bioenergy with carbon capture in the UK to 2050: Summary for policymakers. Report for BEIS*, https://assets.publishing.service.gov.uk/media/5f3fe1f28fa8f55df267bc17/potential-of-bioenergy-with-carbon-capture.pdf.

Because Argus pellet prices are in units of $/t, and the UK government's fuel costs are in £/MWh, we have converted the Argus forward pellet prices for 2027 of $208.50/t both in terms of currency, and from the pre-combustion cost of the wood pellets, to the costs of the pellets per unit of electricity generated (MWh), or post-combustion.

- We assume a future USD to GBP exchange rate of 0.8
- Argus's methodology bases its prices on a higher heating value of 17GJ/t,[117] which is equivalent to 0.2117 t/MWh
- The UK government assumes a net efficiency of future BECCS plants of 30.6 per cent.[118]

This calculation results in a 2027 forward wood pellet price of £115/MWh (post-combustion). This value sits between the UK government's 'medium' (£82/MWh) and 'high' (£131/MWh) scenario pellet fuel costs (post-combustion), but closer to the 'high' scenario. Based

115 Argus Media (2024), 'Argus Biomass Markets', 24 April 2024, https://www.argusmedia.com/-/media/project/argusmedia/mainsite/english/documents-and-files/sample-reports/argus-biomass-markets-report-sample.pdf.
116 Ricardo Energy & Environment (2020), *Analysing the potential of bioenergy with carbon capture in the UK to 2050: Summary for policymakers. Report for BEIS*, https://assets.publishing.service.gov.uk/media/5f3fe1f28fa8f55df267bc17/potential-of-bioenergy-with-carbon-capture.pdf
117 Argus Media (2023), *Argus Biomass Markets: Methodology and specification guide*, last updated November 2023, www.argusmedia.com/-/media/Files/methodology/argus-biomass-markets.ashx.
118 Ricardo Energy & Environment (2020), *Analysing the potential of bioenergy with carbon capture in the UK to 2050. Summary for policymakers*, Table A1.1.

on the UK government's methodology, the £115/MWh wood pellet prices equate to a LCOE of £214/MWh.

The required annual subsidy for BECCS is the difference between the LCOE and the wholesale electricity price. According to UK government projections,[119] the mean wholesale price of electricity between 2025 and 2040 is anticipated to be £62/MWh. Hence, in the UK, BECCS would require a top-up subsidy of £152/MWh. This is equivalent to an abatement price of $225/tCO_2$.[120]

Projecting the cost calculations shown in Box 2 forward to 2050 in order to estimate the global costs of engineered removals of BECCS and DACCS to achieve the IPCC's AR6 level of 2.77 $GtCO_2$/yr of removals requires, as previously, a number of assumptions. First, that wood pellet forward prices in 2027 are representative of those in 2050. Second, that costs in other countries would broadly be similar to those in the UK. And third, that wood pellets make up 50 per cent of the global feedstock for BECCS, with IRENA's 2021 forecast of \$69–\$105/tCO_2 assumed for the other 50 per cent of the global feedstock.[121] This third assumption partially accounts for feedstocks being cheaper in other parts of the world. On this basis, and with BECCS accounting for 99 per cent, and DACCS 1 per cent of the IPCC AR6 level of 2.77 $GtCO_2$/yr of removals, costs would climb from the high end of the range (\$192–\$315 billion annually by 2050) stated in the previous section, to up to \$460 billion per year. This in turn would represent 13 per cent of annual clean energy investment. This projected cost is 6.4 times the cost of wind, solar and EVs mitigating the same amount of CO_2.

Here, it is important to reiterate that as the global emissions gap widens CO_2 removal will be more important relative to mitigation, and that CO_2 removals should be additional to both renewable deployment and fossil fuel phase-out. It should also be noted that if countries go on to adopt more DACCS than BECCS, then based on Climeworks' own 2050 cost projections for DACCS (highlighted in the previous section of) \$100–\$300/tCO_2, the costs of engineered removals could be higher than the \$460 billion cost per year calculated.

Given that engineered carbon removals will likely require government subsidies, their cost implications should be viewed within the context of current high levels of countries' debt to GDP,[122] as well as the ongoing war in Ukraine, and tensions in the Middle East and Asia leading to military spending increasing by 6.8 per cent in 2023,[123] to reach \$2.4 trillion globally. A critical question, then, is whether engineered removals offer a means of addressing the tension between energy security and net zero, or whether these costs will exacerbate this tension.

119 Department for Energy Security and Net Zero (2023), 'Energy and emissions projections: 2022 to 2040', www.gov.uk/government/publications/energy-and-emissions-projections-2022-to-2040.
120 Assuming a capture rate of 90 per cent, 0.94 tCO_2/MWh of emissions from unabated biomass power generation, and a GBP to USD conversion rate of 0.8.
121 Lyons, M., Durrant, P. and Kochhar, K. (2021), *Reaching Zero with Renewables: Capturing Carbon*, Abu Dhabi: International Renewable Energy Agency, https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Capturing_Carbon_2021.pdf.
122 International Monetary Fund (2024), 'Central Government Debt', www.imf.org/external/datamapper/CG_DEBT_GDP@GDD/CHN/FRA/DEU/ITA/JPN/GBR/USA (accessed 27 Aug. 2024).
123 Tian, N., Lopes da Silva, D., Liang, X. and Scarazzato, L. (2024), *Trends in World Military Expenditure, 2023*, Stockholm: SIPRI, https://doi.org/10.55163/BQGA2180.

04 International cooperation to minimize the risks of reliance on engineered removals

There is scope for costs and risks of BECCS and DACCS to be shared and minimized through a more collaborative international approach. Valuable lessons could be drawn from cooperation in the civil nuclear sector. But even where costs are minimized, this does not mean that such technologies are low-cost solutions.

While engineered CO_2 removal technologies hold some promise for mitigating climate change, they currently, as explored in the previous chapter, bring significant cost challenges related to their high energy input requirement, particularly if relied on at scale. Addressing not just the cost, but also land-use tensions and supply-chain challenges (for a brief overview of these issues, see Box 1), will be crucial for unlocking their full potential while also minimizing the cost barriers and risks.

By leveraging shared expertise, resources and experiences across multiple countries, international collaboration plays an important role in reducing the costs and risks associated with deploying new, complex and innovative technologies to global challenges. Such cooperation can facilitate knowledge exchange, enable technology transfer, reduce duplication costs, and streamline supply chains via standardization. This chapter examines current cooperation initiatives concerned with engineered removals, and also looks at the record of international cooperation efforts in the civil nuclear sector, to draw lessons and provide recommendations as to how engineered removals technologies might be deployed at scale in a more cost-effective and risk-reduced manner.

The current status of international cooperation on engineered removals

Many multinational corporations – including Microsoft, Bank of America, Mitsubishi Industries, Airbus, JP Morgan Chase, UBS, Boston Consulting Group and Accenture – have forged corporate partnerships with BECCS and DACCS developers.[124] However, international cooperation between governments is more limited. What does exist is largely centred within the EU, coordinated by the European Commission.

The GeoEngineering and NegatIve Emissions pathways in Europe (GENIE) project was launched in 2021. Due to run until 2027, this €9.3 million collaboration focuses on the environmental, technical, social, legal, ethical and policy dimensions of greenhouse gas removals in a wider sense than just BECCS and DACCS, and is also investigating solar radiation management.[125] More specifically on BECCS and DACCS, the EU's key research and innovation funding programme, Horizon Europe, has a call for proposals, open until early 2025, that seeks to fund research projects with the goal of enabling 'cost-effective deployment of technologies such as DACCS and/or BECCS ideally linking them to industrial clusters with special emphasis of these technologies to safe CO_2 underground storage and CO_2 utilisation'.[126]

The Group of Negative Emitters (GONE) was launched in December 2023 at the UN Climate Change Conference (COP28) in Dubai, United Arab Emirates. Spearheaded by Denmark, along with Finland and Panama, GONE is a coalition of countries seeking to 'remove more planet-heating carbon dioxide than they produce',[127] drawing on both nature-based solutions such as afforestation, and technologies such as engineered removals.[128] The Carbon Management Challenge, co-sponsored by Brazil, Canada, Indonesia, the UK and the US, was launched in April 2023 'to accelerate the scale up of carbon capture, utilization and storage and carbon dioxide removal as necessary complements to aggressive deployment

124 Climeworks (2024), 'Our pioneering customers', https://climeworks.com/customers; Coalition for Negative Emissions (2024), 'Who are we', https://coalitionfornegativeemissions.org/who-we-are; George, S. (2024), 'Microsoft bets on BECCS in bid for carbon negativity', edie, 7 May 2024, www.edie.net/microsoft-bets-on-beccs-in-bid-for-carbon-negativity.
125 European Commission (2021), 'GENIE: GeoEngineering and NegatIve Emissions pathways in Europe', https://cordis.europa.eu/project/id/951542.
126 European Commission (2024), 'DACCS and BECCS for CO2 removal/negative emissions: HORIZON-CL5-2024-D3-02-12', https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2024-d3-02-12.
127 Meredith, S. (2024), 'The world's happiest countries are targeting net-negative emissions – despite a growing greenlash', CNBC, 1 May 2024, https://www.cnbc.com/2024/05/01/climate-crisis-worlds-happiest-countries-are-looking-beyond-net-zero.html.
128 Symons, A. and Keyton, D. (2023), 'Negative emitters: Denmark leads group of nations aiming to remove more CO2 than they emit', 11 December 2023, Euronews, www.euronews.com/2023/12/11/negative-emitters-denmark-leads-group-of-nations-aiming-to-remove-more-co2-than-they-emit.

of other zero-carbon technologies and energy efficiency'. The group brings together 20 countries plus the European Commission, with the ambition to advance 'carbon management projects that globally will reach gigaton scale by 2030'.[129]

The IEA's Technology Collaboration Programme (TCP) supports the 'work of independent, international groups of experts that enable governments and industries from around the world to lead programmes and projects on a wide range of energy technologies and related issues', in line with the IEA's shared goals of 'energy security, environmental protection and economic growth, as well as engagement worldwide'.[130] The TCP supports (among other technologies) work on breakthrough technologies like nuclear fusion power,[131] which – like BECCS – is yet to be deployed commercially. Notably, however, while the TCP supports many low-carbon technologies, it currently only has one relatively small work programme on GGRs.[132]

There are many academic and policy institutions, among them the Royal Society,[133] calling for greater international governance of geoengineering more broadly,[134] and the storage and permanence risks of geologically stored CO_2,[135] as well as a broad array of supply chain, feedstock, and other standards pertaining to BECCS and negative emissions more widely.[136] Indeed, since 2007, there have been calls for an international regulatory framework for risk governance of CCS.[137]

Nuclear power – a prime example to learn from

Civil nuclear power is an interesting analogue through which to explore how international cooperation might minimize the risks of scaling engineered removals and keep deployment costs manageable. Nuclear power is highly contentious and costly relative to other low-carbon technologies. Moreover, the storage of radioactive waste, like the geological storage of waste CO_2, requires careful consideration of its permanence and leakage risks.[138] Furthermore, the supply chains for uranium and plutonium encompass critical risks – albeit very different risks to those for woody biomass.

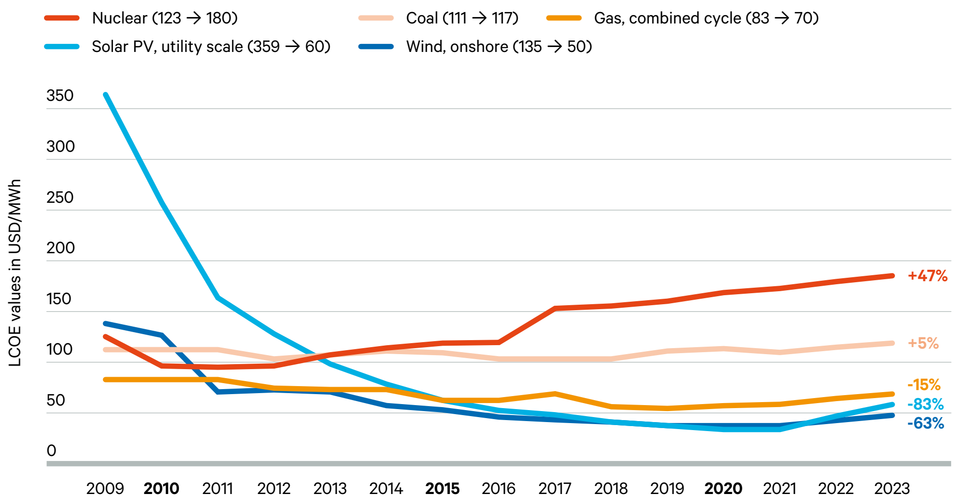
129 Carbon Management Challenge (2024), 'Participants', https://www.carbonmanagementchallenge.org/cmc.
130 International Energy Agency (2024), 'Technology collaboration: Advancing the research, development and commercialisation of energy technologies', www.iea.org/about/technology-collaboration.
131 International Energy Agency (2024), 'Fusion power: Fundamental and applied research including device-specific research and cross-cutting research such as materials and safety', www.iea.org/about/technology-collaboration/fusion-power.
132 IEAGHG (2024), 'Leading the way to net zero through carbon management', https://ieaghg.org.
133 Royal Society (2009), *Geoengineering the climate: Science, governance and uncertainty*, https://royalsociety.org/news-resources/publications/2009/geoengineering-climate.
134 Pasztor, J. (2017), 'The Need for Governance of Climate Geoengineering', *Ethics & International Affairs*, 31(4), pp. 419–30, https://doi.org/10.1017/S0892679417000405; Lebling, K., Schumer, C. and Riedl, D. (2023), *International Governance of Technological Carbon Removal: Surfacing Questions, Exploring Solutions*, Working Paper, World Resources Institute, https://doi.org/10.46830/wriwp.23.00013.
135 Maher, B. and Symons, J. (2022), 'The International Politics of Carbon Dioxide Removal: Pathways to Cooperative Global Governance', *Global Environmental Politics*, 22(1), pp. 44–68, https://doi.org/10.1162/glep_a_00643.
136 Torvanger, A. (2018), 'Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement', *Climate Policy*, 19(3), pp. 329–41, https://doi.org/10.1080/14693062.2018.1509044.
137 Shalini, V., Jenny, G. and Asbjørn, T. (2007), *An International Regulatory Framework for Risk Governance of Carbon Capture and Storage*, Resources for the Future, Washington, DC: https://www.rff.org/publications/working-papers/an-international-regulatory-framework-for-risk-governance-of-carbon-capture-and-storage.
138 Royal Society (2022), 'Locked away – Geological carbon storage', https://royalsociety.org/-/media/policy/projects/geological-carbon-storage/geological-carbon-storage_briefing.pdf.

Importantly, it should be noted that the costs of nuclear power have remained stubbornly high over the decades. As shown in Figure 7, nuclear, on a levelized cost of electricity (LCOE) basis, increased by almost half between 2009 and 2023, to reach £180/MWh in the latter year (having exceeded £150/MWh every year since 2017). Over the same period, and on the same basis, solar and wind have declined in cost by more than 80 per cent and 60 per cent, respectively.[139]

In 2010, the World Nuclear Association (WNA) set up a working group on Cooperation in Reactor Design Evaluation and Licensing (CORDEL), a collaboration aimed at achieving greater international standardization in reactor design. With harmonization of reactor design comes not only increased confidence in safety, but also, it is intended, minimization of costs.[140] As the WNA states: 'Gains in safety assurance and cost reduction will inevitably occur when feedback from worldwide nuclear operations is systematically focused on perfecting a small number of standard designs which have been certified and approved by a recognized competent authority in the country of origin.'[141]

This approach of international standardization of technology design, to either minimize otherwise even higher costs, or actually drive them down, would be a beneficial approach in engineered removal technologies.

Figure 7. Comparative costs of low-carbon and traditional power sources, 2009–23



Source: Schneider, M., Froggatt, A. et al. (2023), *World Nuclear Industry Status Report 2023*, p. 415 (Fig. 64), https://www.worldnuclearreport.org/World-Nuclear-Industry-Status-Report-2023.

The approach of standardization to minimize or reduce costs is also demonstrated at the national level. For instance, the French National Audit Office has shown how EDF leveraged the standardization of the French fleet, with vertically integrated

139 Schneider, M., Froggatt, A. et al. (2023), World Nuclear Industry Status Report 2023, p. 415 (Fig. 64), https://www.worldnuclearreport.org/World-Nuclear-Industry-Status-Report-2023.
140 World Nuclear Association (2020), 'Cooperation in nuclear power', [updated] 18 November 2020, https://world-nuclear.org/information-library/current-and-future-generation/cooperation-in-nuclear-power.
141 Ibid.

supply chains, leading to significant cost reductions.[142] Standardization across countries requires industrial organization and homogenized supply chains to speed up transactions, resulting in increased manufacturing productivity via the production of a greater number of identical components. Increased volume production via standardization also increases supply chain competition, and enables long-term contracting.[143] Standardization also enables operational efficiency and learning. The nuclear engineering company Assystem anticipates that a substantial programme of standardizing nuclear builds could reduce the costs of nuclear power in the West to £60–70/MWh.[144] In the case of BECCS, however, it is important to emphasize that vertical integration of biomass feedstock supply chains could bring increased risks.

Beyond the WNA and the CORDEL initiative, a significant body of international and bilateral agreements, multilateral organizations and technology sharing supports the industry.[145] In the period 2000–15, according to a 2019 study of some 500 cooperation agreements, and over 200 memorandums of understanding and joint statements, the US and Russia dominated international technological cooperation.[146] The study's authors found that the US was particularly dominant in areas of safety and security, and Russia in construction of nuclear power plants, reactor and fuel supply, and decommissioning and waste.

The most significant safety-related collaboration internationally is via the World Association of Nuclear Operators (WANO), formed in 1989 as a response to the Chernobyl disaster three years earlier. The International Atomic Energy Agency (IAEA), with 126 member states, is the main international organization for peaceful use of nuclear energy and technology, and is an autonomous intergovernmental organization within the UN system. The IAEA covers international cooperation across reactor operations, the nuclear fuel cycle, radioactive waste management, human health and radiation protection, and safeguards. The OECD Nuclear Energy Agency (NEA), representing 33 countries with 84 per cent of the world's nuclear capacity, assists member countries in developing the scientific, technological and legal bases required for nuclear power, and the costs of decommissioning.[147] At the downstream end of the nuclear fuel cycle, established in 1998 and with 11 country members, is the International Association for the Environmentally Safe Disposal of Radioactive Materials (EDRAM). At the regional European level, the European Atomic Energy Community (Euratom) establishes a single market for the trade in nuclear materials and technology.[148] In September 2011, the Nuclear Power Plant Exporters' Principles of Conduct was established to ensure best practices in the export of nuclear power plants. These principles focus on safety, physical security,

142 OECD Nuclear Energy Agency (2020), *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*, www.oecd-nea.org/upload/docs/application/pdf/2020-07/7530-reducing-cost-nuclear-construction.pdf.
143 Ibid.
144 Rooney, M., Roulstone, T., Locatelli, G. and Lindley, B. (2021), *Fusion Energy: A Global Effort – A UK Opportunity*, London: Institution of Mechanical Engineers and Blackburn: Assystem, www.assystem.com/en/publications/reportfusion-energya-global-effort-a-uk-opportunity.
145 World Nuclear Association (2020), 'Cooperation in nuclear power'.
146 Jewell, J., Vetier, M. and Garcia-Cabrera, D. (2019), 'The international technological nuclear cooperation landscape: A new dataset and network analysis', *Energy Policy*, 128, pp. 838–52, https://doi.org/10.1016/j.enpol.2018.12.024.
147 World Nuclear Association (2020), 'Cooperation in nuclear power'.
148 Institute for Government (2017), 'Euratom', 7 July 2017, www.instituteforgovernment.org.uk/article/explainer/euratom.

environmental protection and spent fuel management, systems of compensation for nuclear damage, non-proliferation and safeguards, and business ethics.[149] The initiative has a notable focus on countries with an emerging interest in pursuing civil nuclear energy development.[150]

International cooperation is needed to address the risks of engineered carbon removals, especially given concerns regarding, in the case of BECCS, supply chains, land-use tensions, deforestation and carbon debt, and for both DACCS and BECCS, the permanence risks of geologically stored CO_2. The need for international collaboration will be all the more acute as the technologies are scaled up. Valuable lessons could therefore be drawn from cooperation in the civil nuclear sector.

International collaboration can reduce the risks and collectivize the costs

A study published in 2020 by researchers at Imperial College London[151] clearly sets out the benefits of international collaboration in driving down costs of BECCS. Their study explored the cost-optimal deployment of BECCS between the EU, Brazil, China, India and the US. The researchers identified that a cooperative and collaborative approach to CO_2 removal, based on equitable burden-sharing and CO_2 storage trading, is needed in order to meet global removal targets at least cost. This is principally because countries do not possess an equal share of sustainable biomass and geological features to provide sustainable, permanent and affordable CO_2 removal. This means that there are significant differences in life-cycle removal costs of BECCS between regions. As such, they identify that collaboration is required in setting up the systems and markets to enable the trading of negative emissions credits and biomass in order to sustainably and affordably meet global targets for CO_2 removal.[152]

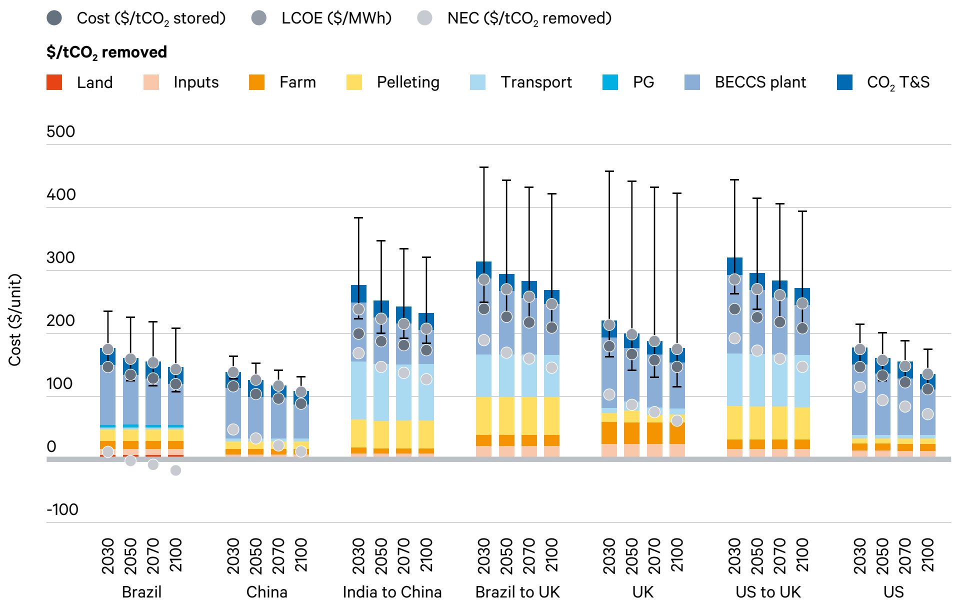
As shown in Figure 8, the cost of BECCS CO_2 removal varies according to region, due to variations in how the supply chain is configured, and the researchers identified feedstock yield as a key determinant of cost.[153] This is particularly starkly illustrated in the biomass yield differences between Brazil and the UK. Not only did biomass feedstock yield impact costs, but the researchers also found that labour costs and the costs of electricity strongly influenced the required CO_2 removal subsidy or costs of removal credits within a trading system to make BECCS systems economically viable.

The same study's authors found that for 2100, the forecast regional differences in BECCS costs ranged between \$85/tCO_2 in South China, within an optimistic biomass supply chain scenario, up to \$450/tCO_2 in the UK under a pessimistic biomass supply chain configuration, with up to a 50 per cent increase in cost in the

149 Carnegie Endowment for International Peace (2011), 'World's leading nuclear power companies adopt principles of conduct', https://carnegieendowment.org/posts/2011/09/worlds-leading-nuclear-power-companies-adopt-principles-of-conduct.
150 Ibid.
151 Fajardy, M. and Mac Dowell, N. (2020), 'Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal', *One Earth*, 3(2), pp. 214–25, https://doi.org/10.1016/j.oneear.2020.07.014.
152 Ibid.
153 Ibid.

case of the UK importing biomass from Brazil.[154] Hence, the cost-optimal BECCS deployment is achieved with low-cost regions providing CO_2 removal for regions where BECCS costs are higher. The researchers concluded that 'full inter-regional collaboration in biomass and negative emissions trading led to highest chance of meeting global targets at the lowest cost'.[155]

Figure 8. Breakdown of BECCS cost in selected regions, 2030–2100 forecasts



Source: Fajardy, M. and Mac Dowell, N. (2020), 'Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal', *One Earth*, 3(2), pp. 214–25, https://doi.org/10.1016/j.oneear.2020.07.014.

The importance of regional cooperation around CO_2 geological storage, to lower costs for all, can be seen within the EU's 2024 Net Zero Industry Act (NZIA). The NZIA includes a target for the EU to develop at least 50 million tonnes per year of CO_2 storage capacity by 2030 in geological storage sites, including depleted oil and gas fields and saline aquifers.[156] In 2024, too, a North Sea regional agreement between Norway, the Netherlands, Belgium, Denmark and Sweden was established that will allow these countries to collaborate on the cross-border transport and geological storage of captured CO_2.[157] This North Sea regional grouping sits in parallel with the European Commission's North Seas Energy Cooperation project (NSEC).[158] The UK, while (like Norway) not a member of the EU, signed a memorandum of understanding with NSEC in 2022, and carbon storage is seen as an important area of collaboration between the UK and the EU.[159]

154 Ibid.
155 Ibid.
156 European Union (2024), 'Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724', June 2024, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401735.
157 State of Green (2024), 'Northern European collaboration for CO2 transport and storage in place', 16 April 2024, https://stateofgreen.com/en/news/northern-european-collaboration-for-co2-transport-and-storage-in-place.
158 European Commission (2022), 'The North Seas Energy Cooperation', https://energy.ec.europa.eu/topics/infrastructure/high-level-groups/north-seas-energy-cooperation_en.
159 Heussaff, C., McWilliams, B. and Tagliapietra, S. (2024), 'Identifying areas for EU-UK energy and climate cooperation', Bruegel, 26 September 2024, https://www.bruegel.org/analysis/identifying-areas-eu-uk-energy-and-climate-cooperation.

Short-term demand management could allow decarbonization to catch up and reduce reliance on engineered removals

Focusing on demand reduction in the short term could allow time for supply-side decarbonization efforts to catch up. As the IEA states:

> [T]echnology alone is not enough: net zero emissions in 2050 cannot happen without the consent and active support of people. In part, this involves one-off events that are not counted as behavioural changes but involve a mixture of low carbon technologies and people's engagement, such as buying an electric vehicle (EV) or insulating a loft. However, behavioural changes – meaning adjustments in everyday life that reduce wasteful or excessive energy consumption – are also needed. They are especially important in richer parts of the world where energy intensive lifestyles are the norm.[160]

By prioritizing demand-side actions, such as improving building insulation, promoting use of public transport and adopting energy-efficient appliances, countries could achieve emission reductions at lower costs and with fewer barriers to implementation than those explored in this paper with regard to engineered removals, and by virtue reduce the risks of large-scale reliance on engineered carbon removals. As underscored by the IPCC in 2022:

> Mitigation strategies that focus on lowering demand for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or pathways with high consumption and emissions that are ultimately compensated by large quantities of BECCS.[161]

And, as was highlighted in Chapter 1, across the influential IAMs only 5 per cent involved substantial energy demand reduction from current levels by 2100,[162] reflecting the IAMs' techno-economic focus, and the fact that these models under-represent the potential for global energy demand reduction to contribute to carbon mitigation targets, particularly in reducing dependence on CO_2 removal techniques.

The IPCC classifies future emissions reduction mitigation strategies from the demand side into 'avoid', 'shift' and 'improve' options. As can be seen in Figure 9, the behavioural change elements of avoid and shift total around 7 tonnes CO_2e per capita,[163] which should be assessed within the context that per capita emissions from fossil fuels and industry are around 15 tonnes CO_2 in the US, a little over 7 tonnes CO_2 across the EU and 8 tonnes CO_2 in China.[164] Indeed, across three end-use sectors (buildings, land transport and food), the IPCC indicates with a high

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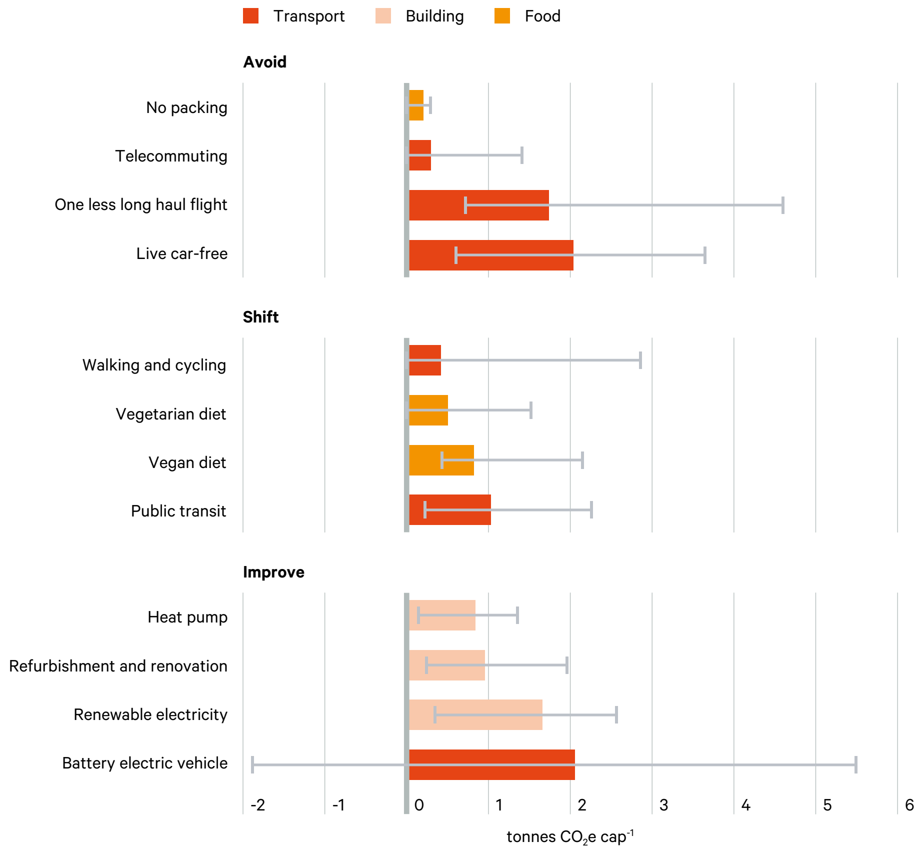
160 International Energy Agency (2021), 'Do we need to change our behaviour to reach net zero by 2050?', https://www.iea.org/articles/do-we-need-to-change-our-behaviour-to-reach-net-zero-by-2050.
161 Pathak (2022), 'Technical Summary', p. 141, in Shukla et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
162 Scott, Smith, Lowe and Garcia-Carreras (2022), 'Demand vs supply-side approaches to mitigation'.
163 Pathak et al. (2022), 'Technical Summary', Figure TS.20(b), in Shukla et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
164 Our World in Data (2023), 'Per capita CO_2 emissions', https://ourworldindata.org/grapher/co-emissions-per-capita (accessed 12 Jun. 2024).

level of confidence that the demand side could reduce emissions of direct and indirect CO_2 and non-CO_2 greenhouse gas emissions by between 40 and 70 per cent globally by 2050.[165]

Figure 9. Low-carbon lifestyles can be classified into avoid, shift and improve options



Source: Pathak, M. et al. (2022), 'Technical Summary', Figure TS.20(b), in Shukla, P. R. et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, https://doi.org/10.1017/9781009157926.002.

Critically, however, governments remain reluctant to invest in or promote demand-side action, particularly where public behaviour change is required. The IPCC notes: 'Policies that are aimed at behaviour and lifestyle changes carry a perception of political risks for policymakers, which may explain why policy instruments focus more on information provision and adoption of incentives than on regulation and investment.'[166]

165 Creutzig, F. et al. (2022), 'Demand, services and social aspects of mitigation', in Shukla P. R. et al. (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York, Cambridge University Press, https://doi.org/10.1017/9781009157926.007.
166 Ibid., p. 565.

In this context, international technical, social and policy data sharing on demand could benefit governments that are currently wary of implementing demand-side policies. Sharing on demand initiatives could also help normalize the behavioural aspects of energy transition across countries. Best- as well as worst-practice examples of policymaking, communication and implementation would help governments avoid pitfalls – and thus the associated political risk of public backlash. It may also help prevent high-profile policy failures, which can damage narratives of the overarching need for public engagement on climate action, and jeopardize governments' ability to reach their legally binding national and multilateral commitments to emissions reductions.

05 Discussion, conclusions and recommendations

Policymakers will need to reduce the costs and scale of reliance on engineered removals by focusing on the demand side, reforming net zero policies and collaborating internationally on negative emissions approaches.

The ‘energy trilemma’ requires decision-makers to consider the three pillars of sustainability, security and affordability. This research paper has examined whether the high energy input, and hence the high cost, of engineered CO_2 removal technologies stands up to scrutiny in a context in which governments are prioritizing considerations of energy security and affordability. It also makes the case that governments need to think of more collaborative, cooperative and multilateral approach to BECCS and DACCS, where the costs and risks are shared and minimized. But even where costs are minimized, this does not mean that these technologies are low-cost solutions.

The emergence of a multi-polar world over the last few years has reshaped geopolitics, and disrupted established trade dynamics and supply chains. Nowhere is this more acutely evident than in the energy sector, where countries are already navigating new supply-chains costs that necessarily come with the net zero energy transition. The geopolitical shifts and ongoing conflicts compound the consequences of a period of historically low investment in upstream oil and gas exploration and production. Future oil and gas price rises cannot be ruled out, and many market analysts anticipate ongoing price volatility.[167]

167 Coleman (2024), ‘Russia defiant two years into war reshaping global energy’.

For all these reasons – and compounded by wider inflation and cost-of-living concerns across the world[168] – urgent questions of energy security and affordability have risen up the political agenda, and are competing on the desks of decision-makers with the more expensive elements of net zero strategies. Indeed, in the EU, the US and the UK, the costs of net zero are coming under increased political pressure.[169]

Based on NDC documents submitted to the UNFCCC, the upper-end projection of engineered removals is around 0.97 $GtCO_2$/yr of engineered removals in 2050, equivalent to 3.3 per cent of the fossil fuel emissions from G20 countries in 2023. This is largely driven by the US (52 per cent share), the EU (27 per cent share) and Canada (21 per cent share). Across all the IMPs assessed by the IPCC, engineered removals constitute 2.75 (0.52–9.45) $GtCO_2$/yr for BECCS, and 0.02 (0–1.74) $GtCO_2$/yr for DACCS, in 2050.[170] Combined, engineered removals would therefore, by 2050, be sufficient to sequester 9.4 per cent of 2023 fossil fuel emissions from G20 countries, with 99 per cent coming from BECCS.

The primary near-term risk is that reliance on engineered removals technologies will be highly expensive, requiring subsidies paid for by taxpayers or energy consumers, or via carbon markets.

The high heat energy input requirements of engineered removals represent nearly 50 per cent of the cost of DACCS,[171] and at least 33 per cent of the cost of BECCS.[172] The risks of relying on engineered removals, primarily BECCS, at the scale G20 countries have indicated are multifaceted. However, the primary near-term risk is that reliance on engineered removals technologies will be highly expensive, requiring subsidies paid for by taxpayers or energy consumers, or via carbon markets with costs again, ultimately, passed on to consumers via increased prices of goods and services. This could have a disproportionate impact on low-income households, either as consumers or taxpayers, depending on how subsidies are paid for.

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168 Economist Intelligence Unit (2023), *Worldwide Cost of Living 2023*; Atkins (2022), 'How is the cost of living crisis affecting net-zero policies?'; Picchi, A. (2023), 'Americans need an extra $11,400 today just to afford the basics, Republican analysis finds'.
169 Salter (2022), 'A new Tory faction is 'scrutinising' net zero – with tactics learned from Brexit'; Murray (2023), 'The government's assault on net zero has triggered a battle where no one wins'; Zurcher (2020), 'US Election 2020: Biden seeks to clarify remark on ending oil'; Abnett et al. (2023), 'Resistance to green policies around Europe'; Plunkett (2023), 'Global push-back on Net Zero demands an industrial rethink'.
170 Pathak et al. (2022), 'Technical Summary', p. 114, in Shukla et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
171 See Webb, Muslemani, Fulton and Curson (2023), *Scaling Direct Air Capture (DAC)*, Figure 10: 2025 and 2050 carbon removal costs, 'energy use' and 'energy prices' as a share of total costs.
172 Based on current and forecast wood pellet prices, and using the central fuel cost in Appendix 2, Ricardo Energy & Environment (2020), *Analysing the potential of bioenergy with carbon capture in the UK to 2050: Summary for policymakers*.

Not only do engineered removals entail high opex fuel input costs, which are undesirable for any government currently concerned with energy security and price, BECCS deployment costs, in particular, are unlikely to benefit from high learning rates. Technologies with high learning rates, and therefore fast cost reductions, tend to be modular, with thousands to millions being produced each year, such as solar panels and wind turbines, as well as lithium-ion batteries for EVs.[173] All of these technologies have demonstrated – and continue to demonstrate – rapid cost reductions. BECCS is generally being considered as a retrofitted technology, with large CCS infrastructure being fitted to existing bioenergy power stations and coal power stations with fuel switching. As such, at most hundreds of BECCS facilities are likely, meaning that the opportunity for engineers and contractors to learn from experience, improve build efficiencies and drive down costs is more limited than for their modular competitors.

Assuming wood pellet prices remain at a similar level to the 2027 forward price illustrated in Chapter 3, and that BECCS is responsible for 99 per cent of the 2.77 $GtCO_2$/yr sequestration level within the IPCC's AR6, by 2050 engineered carbon removal costs could climb from the high end of the $192–315 billion/yr range, to up to $460 billion per year. This in turn would represent 13 per cent of annual clean energy investment. This is 6.4 times the cost of wind, solar and EVs mitigating the same amount of CO_2. It should be noted, however, that as the global emissions gap widens CO_2 removal will become more important relative to mitigation, and that CO_2 removal should be additional to both renewable deployment and fossil fuel phase-out.

The significantly large costs of engineered carbon removals should be set within the context of historically high levels of countries' debt to GDP,[174] as well as the ongoing war in Ukraine, and tensions in the Middle East and Asia leading to military spending increasing by 6.8 per cent in 2023,[175] reaching $2.4 trillion globally.

The risk, therefore, is that the future costs of engineered removals may be incompatible with the new energy security and affordability era, and therefore the reliance that countries have already built in cannot be fulfilled. This would widen the emissions gap and increase the risk of triggering accelerated climate change.

While engineered CO_2 removal technologies hold some promise for mitigating climate change, the very real cost challenges, particularly when relied on at scale, mean that addressing supply-chain and build-cost barriers will be crucial for unlocking their full potential.

173 Quiggin (2024), 'How modular renewables can reduce the costs of relying on carbon capture'.
174 International Monetary Fund (2024), 'Central Government Debt' (accessed 20 Jun. 2024).
175 Tian, Lopes da Silva, Liang and Scarazzato (2024), *Trends in World Military Expenditure, 2023*.

International collaboration

A cooperative and collaborative approach to CO_2 removal, based on equitable burden-sharing and CO_2 storage trading, is needed to meet global removal targets at least cost. This is principally because countries do not all possess the same geological and biophysical assets to help them provide sustainable, permanent and affordable CO_2 removal.

Many multinational companies have already forged corporate partnerships with BECCS and DACCS developers.[176] However, international cooperation between countries remains limited; what does exist is largely centred within the EU, coordinated by the European Commission.

International cooperation projects play a crucial role in reducing the risks and costs associated with deploying new and innovative technologies. Cooperation between countries can facilitate knowledge exchange, enable technology transfer, reduce duplication costs and streamline supply chains via standardization.

Nuclear power, like engineered removals, is highly contentious and costly relative to other low-carbon technologies. Moreover, the storage of radioactive waste, like the geological storage of waste CO_2, requires careful consideration for its permanence and leakage risks. Furthermore, the supply chains of uranium and plutonium encompass critical risks, albeit very difficult to those concerning woody biomass for BECCS.

In 2010, the World Nuclear Association set up the CORDEL working group, with the aim of achieving greater international standardization in nuclear reactor design. Harmonization of reactor design not only brings increased confidence in safety, but also lowers construction costs.[177] France's National Audit Office reported that EDF was able to leverage the standardization of the French fleet, with a vertically integrated supply chain, resulting in significant cost reductions.[178]

Standardization between countries requires industrial organization, resulting in increased manufacturing productivity via the production of a greater number of identical components. Increased volume production via standardization also boosts supply-chain competition, and facilitates long-term contracting.[179] Standardization also enables operational efficiency and learning. This highlights the potential for international collaboration, via programmes akin to CORDEL, to reduce the costs of engineered removals. Moreover, greater efforts need to made towards an international regulatory framework for risk governance of carbon capture and storage.

176 Climeworks (2024), 'Our pioneering customers'; Coalition for Negative Emissions (2024), 'Who are we'; George (2023), 'Microsoft bets on BECCS in bid for carbon negativity'.
177 World Nuclear Association (2020), 'Cooperation in nuclear power'.
178 OECD Nuclear Energy Agency (2020), *Unlocking Reductions in the Construction Costs of Nuclear*.
179 Ibid.

Based on the experience of various global collaboration efforts around innovative but highly expensive technologies, greater international cooperation around engineered CO_2 removal technologies has the potential to minimize costs and scaling risks through various mechanisms:

- Governments can provide incentives for innovation and facilitate collaboration between public and private sectors by encouraging investment in R&D.
- Collaborative R&D efforts enable countries to pool resources, expertise and infrastructure. This is crucial given that countries do not possess equal geological and biophysical assets in order to provide sustainable, permanent and affordable CO_2 removal.
- International research collaborations also enhance the robustness and credibility of engineered removal technologies, by subjecting them to peer review, validation and independent assessment.
- International collaboration allows countries to share the financial burden and risks associated with developing and deploying engineered removals at scale. Pooling financial resources reduces individual countries' exposure to high upfront costs and uncertainty, making engineered removals more economically viable and attractive for investment.
- By coordinating supply chains, standardizing processes and sharing infrastructure, countries can reduce production costs, streamline operations, foster a skilled workforce and enhance scalability.
- International harmonization of policies, regulations and standards can ensure consistency and coherence across jurisdictions, and reduce regulatory uncertainty and compliance costs for industry.

We need to rethink ever-increasing energy demand

Focusing on reducing demand in the short term could allow time for supply-side decarbonization efforts to catch up, and thus decrease the scale of dependence on engineered removals. Measures that reduce demand – among them energy efficiency improvements, lifestyle changes and behavioural shifts like those shown in Figure 9 – can lead to rapid reductions in emissions.

As was highlighted in Chapter 4, in 2022 the IPCC stated:

> Mitigation strategies that focus on lowering demand for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or pathways with high consumption and emissions that are ultimately compensated by large quantities of BECCS.[180]

180 Pathak et al. (2022), 'Technical Summary', p. 114, in Shukla et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

The IPCC classifies future emissions reduction mitigation strategies from the demand side as 'avoid', 'shift' and 'improve' options. As shown in Figure 9, the behavioural change elements of avoid and shift amount to around 7 tonnes CO_2e per capita;[181] for context, per capita emissions from fossil fuels and industry are around 15 tonnes CO_2 in the US, a little over 7 tonnes CO_2 across the EU, and 8 tonnes CO_2 in China.[182] Indeed, across three end-use sectors (buildings, land transport and food), the IPCC indicates with a high level of confidence that the demand side could reduce emissions of direct and indirect CO_2 and non-CO_2 greenhouse gas emissions by between 40 and 70 per cent globally by 2050.[183]

Net zero needs reform

While the pursuit of net zero has created a broad church, and many companies in sectors where CO_2 abatement costs are high have signed up, there exists an ambiguity within national-level net zero targets. Often, governments do not stipulate a precise split between emissions reductions through conventional low-carbon technologies, and CO_2 removals via GGRs, inclusive of engineered removals. As such, a moral hazard exists whereby the world's future reliance on engineered removals and all GGRs could exceed what is technically feasible, and at the same time reduce collective action to deploy proven and cost effect low carbon technologies that already exist.

Net zero commitments, while essential, require reforming in several ways to ensure their effectiveness and credibility over the coming years, particularly if reliance on GGRs increases. As a priority, net zero legislation needs to define the split between emissions reductions and removals; this split could change over time, and be reviewed by an independent body. In the UK, for instance, this body could be an entity like the Climate Change Committee, which could undertake yearly reviews. As engineered removals costs increasingly become clearer, and are no longer withheld for reasons of commercial confidentiality, the scaling risks ought to become better understood and managed, meaning that reliance on the technologies could justifiably grow. Conversely, if engineered removals fail to meet key performance indicators, reliance on removals within net zero commitments should be commensurately reduced.

Reforming net zero strategies to prioritize emissions reductions at source, rather than relying on CO_2 removal offsets or credits based on yet-unproved engineered removal technologies, is essential in order to avoid greenwashing, and to ensure that net zero targets are credible and effective in addressing climate change. This in itself is important if major policy failures are to be avoided, trust in government is to be maintained, and more harmful backlash against net zero policies is to be averted.

181 Pathak et al. (2022), 'Technical Summary', Figure TS.20(b), in Shukla et al. (eds) (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
182 Our World in Data (2023), 'Per capita CO_2 emissions' (accessed 12 Jun. 2024).
183 Creutzig et al. (2022), 'Demand, services and social aspects of mitigation', in Shukla et al. (2022), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Summary of recommendations

- Greater international cooperation between countries is required to minimize the costs and risks associated with large-scale reliance on BECCS and DACCS. Such cooperation will need to:
  - Acknowledge that countries do not possess the same geological and biophysical assets that would allow equal provision of sustainable, permanent and affordable CO_2 removal at scale, globally. Regions with geological storage sites need to collaborate with regions with significant biomass resources.
  - Renew efforts to build international governance concerning the permanence of CO_2 within geological storage sites.
  - Establish new international standards around the entire supply chain to drive down costs, as well as regulating sustainability standards pertaining to biomass.
  - Facilitate the sharing of technological innovations to reduce costs.
- Greater transparency is needed between commercial developers of BECCS and DACCS, governments and the public regarding costs, allowing for the sensitivity of commercial information.
- Within net zero strategies, the split between emissions reductions and removals needs to be clearly defined, to reduce the risks of over-reliance on engineered carbon removal offsets that could fail to fully materialize. This split can be reviewed and amended over time as engineered removal technologies are deployed and more evidence of their performance becomes available.
- Greater focus needs to be placed on energy efficiency and demand management in order to reduce reliance on engineered removals, and simultaneously ease both energy security and affordability concerns.

Acronyms and abbreviations

AFOLU	agriculture, forestry and other land use
BECCS	bioenergy with carbon capture and storage
capex	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, usage and storage
CDR	carbon dioxide removal
CO_2e	carbon dioxide equivalent
CORDEL	Cooperation in Reactor Design Evaluation and Licensing
DACCS	direct air carbon capture and storage
EDRAM	Environmentally Safe Disposal of Radioactive Materials
EIA	[US] Energy Information Administration
EVs	electric vehicles
Euratom	European Atomic Energy Community
FAO	Food and Agriculture Organization of the United Nations
GENIE	GeoEngineering and Negative Emissions pathways in Europe
GGR(s)	greenhouse gas removal(s)
GONE	Group of Negative Emitters
$GtCO_2$	gigatonne(s) of carbon dioxide
$GtCO_2$/yr	gigatonnes of carbon dioxide per year
IAEA	International Atomic Energy Agency
IAM(s)	Integrated Assessment Model(s)
IEA	International Energy Agency
IMP(s)	illustrative mitigation pathway(s)
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	levelized cost of electricity
L-DACCS	liquid DACCS
LNG	liquified natural gas
NDC(s)	nationally determined contribution(s)
NEA	Nuclear Energy Agency
NETs	negative emission technologies
NOCs	national oil companies
NZIA	Net Zero Industry Act
OECD	Organisation for Economic Co-operation and Development
opex	operational expenditure
R&D	research and development
S-DACCS	solid DACCS
TCP	Technology Collaboration Programme
UNFCCC	United Nations Framework Convention on Climate Change
WANO	World Association of Nuclear Operators
WIPO	World Intellectual Property Organization

About the author

Dr Daniel Quiggin is a senior research fellow in the Environment and Society Centre at Chatham House. He specializes in analysis of how national and global energy systems will evolve to 2050. His current research and policy engagement focuses on negative emissions under net zero policies, climate risks and impacts, the role of demand reduction within the energy transition, and the trade of lithium-ion battery raw materials.

Previously, Daniel worked as a senior policy adviser at the Department for Business, Energy & Industrial Strategy, on the post-Brexit policy implications for the energy sector's trade of goods and services. At Investec Asset Management, he helped develop a global renewable energy investment strategy, and modelled the investment potential of various renewable sectors across all major economies.

Acknowledgments

This research was produced with support from the Packard Foundation. Thanks to Tim Searchinger at the World Resources Institute, and Richard King at Chatham House, for their invaluable feedback, as well to as the anonymous peer reviewer.

ISBN 978 1 78413 620 8
DOI 10.55317/9781784136208

Cite this paper: Quiggin, D. (2024), *Why engineered carbon removals are at odds with energy security and affordability: Tackling the costs and risks in net zero strategies*, Research Paper, London, Royal Institute of International Affairs, https://doi.org/10.55317/9781784136208.

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