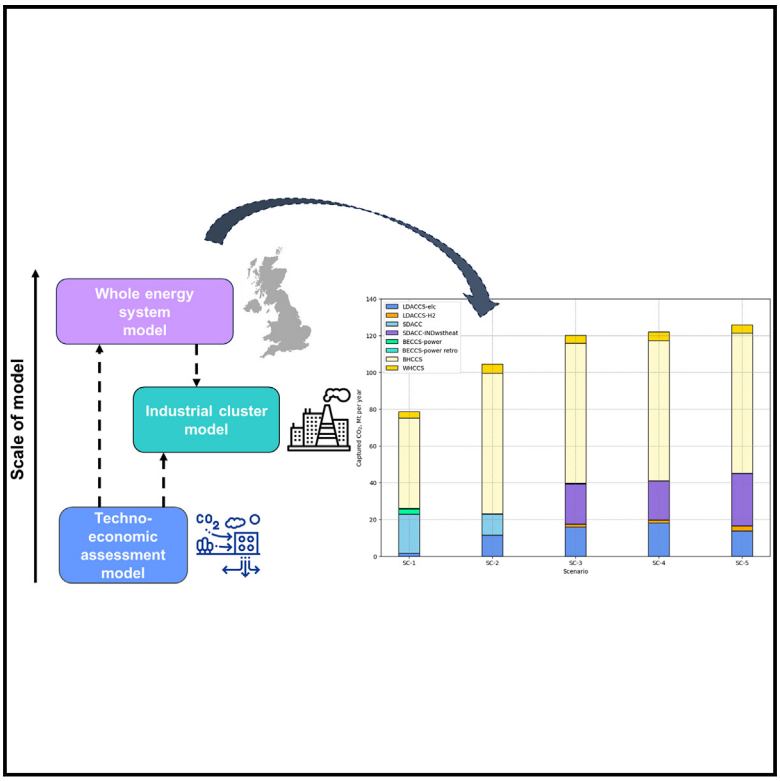
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Article

The role of negative emissions technologies in the UK's net-zero strategy

Graphical abstract



Highlights

- Carbon dioxide removal is enhanced by integrating DACCS into industrial clusters
- Industrial integration diminishes the cost of carbon avoidance
- Biomass availability poses a constraint to BECCS
- BECCS for hydrogen generation proves more viable than for electricity generation

Authors

Semra Bakkaloglu, Matthias Mersch, Nixon Sunny, Christos N. Markides, Nilay Shah, Adam Hawkes

Correspondence

s.bakkaloglu@imperial.ac.uk

In brief

This research unlocks the potential of capturing and storing CO_2 from the air (negative emissions technologies) to significantly boost a country's ability to achieve net-zero emissions. Focusing on the UK, the study finds that integrating NETs into industrial clusters to use waste heat could remove up to 134 million tonnes of CO_2 annually by 2050 in a cost-effective way. This approach combats existing emissions and helps counter future growth from transportation and industry, offering crucial insights for effective climate strategies.

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The role of negative emissions technologies in the UK's net-zero strategy

Semra Bakkaloglu,[1,4,*] Matthias Mersch,[2,3] Nixon Sunny,[3] Christos N. Markides,[2] Nilay Shah,[1] and Adam Hawkes[1]
[1]Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK
[2]Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK
[3]Centre for Environmental Policy, Imperial College London, London SW7 2AZ, UK
[4]Lead contact
*Correspondence: s.bakkaloglu@imperial.ac.uk
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SCIENCE FOR SOCIETY Understanding how to effectively mitigate climate change is crucial for the well-being of our planet and future generations. Negative emissions technologies (NETs) that take CO_2 out of the air are a vital component in this effort, but their effectiveness is still being debated. Our study examines NETs' potential in the UK, providing valuable insights for policymakers, industry leaders, and the public. We find that the UK could remove up to 126–134 million tonnes by 2050 if NETs are well integrated into industrial clusters where there is high waste heat potential. Key technologies include biomass gasification for hydrogen generation with carbon capture and storage (CCS) and direct air carbon capture and storage (DACCS) systems using industrial waste heat. These findings highlight the importance of integrating NETs into industrial strategies to meet climate goals effectively while addressing the increasing demand in the transportation and industrial sectors.

SUMMARY

The role of negative emissions technologies (NETs) in climate change mitigation remains contentious. Although numerous studies indicate significant carbon dioxide removal (CDR) requirements for Paris Agreement mitigation goals to be achieved, others point out challenges and risks associated with high CDR strategies. Using a multiscale modeling approach, we explore NETs' potential for a single country, the United Kingdom (UK). Here, we report that the UK has cost-effective potential to remove 79 $MtCO_2$ per year by 2050, rising to 126–134 $MtCO_2$ per year with well-integrated NETs in industrial clusters. Results highlight that biomass gasification for hydrogen generation with CCS is emerging as a key NET, despite biomass availability being a limiting factor. Moreover, solid DACCS systems utilizing industrial waste heat integration offer a solution to offsetting increases in demand from transportation and industrial sectors. These results emphasize the importance of a multiscale whole-systems assessment for integrating NETs into industrial strategies.

INTRODUCTION

Human activities continue to raise concentrations of greenhouse gases (GHGs) in the atmosphere, with increasingly evident impacts.[1] Although reducing GHG emissions rapidly remains crucial, most studies agree that emissions reductions alone will not be enough to limit warming to well below 2°C.[2,3] Consequently, carbon dioxide removal (CDR) technologies, also known as negative emissions technologies (NETs), are likely to be necessary to limit warming and/or return temperatures to well below 2°C this century.[4,5]

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global cumulative CDR from direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) is estimated to need to be in the range of 0–310 and 30–780 gigatonne (Gt) carbon dioxide (CO_2), respectively, during 2020–2100 to limit global warming to 1.5°C with no or limited overshoot.[6] Additionally, the International Energy Agency's (IEA's) Net-Zero scenario projects that DACCS and BECCS could globally remove 1.9 $GtCO_2$ per year by 2050.[7] By contrast, the National Academies of Science report[8] suggests NETs might have the potential to remove 10–20 $GtCO_2$ per year.[9]

NETs can be broadly divided into nature-based and engineered solutions. The former includes, e.g., afforestation and land-use change, while two possible engineered NETs are DACCS and BECCS, which both commonly feature in global climate change mitigation scenarios.[10] Results from another

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Global Change Analysis Model reveal that total annual CO_2 removal could reach approximately 10 $GtCO_2$ globally, incorporating BECCS, DACCS as well as nature-based solutions such as afforestation, enhanced weathering, soil carbon enhancement, and direct ocean capture with carbon storage.[11] Although global models are extensively employed in literature to estimate global CDR, there is a lack of studies addressing how to conceptualize, justify, and operationalize a CDR economy from the perspective of a single country.

DACCS directly removes CO_2 from the air by binding it to a selective solvent or sorbent.[12] Once enriched, the solvent or sorbent is regenerated, typically using heat and/or a pressure change. It releases a concentrated stream of the captured CO_2, which can then be compressed and injected into permanent storage, removing it from the atmosphere. Two main types of DACCS have been developed: one based on liquid absorbents (e.g., potassium hydroxide), which are regenerated in a high-temperature calciner process, and one based on solid sorbents (e.g., polymers functionalized with amines), which can be regenerated at lower temperatures.[12]

The solid low-temperature DACCS process is assumed to run solely on electricity, while the liquid high-temperature DACCS process is assumed to require natural gas to provide the heat. This is in line with the current commercial development and academic literature on DACCS. It should be noted that the liquid DACCS process can also be fully electrified.[13] However, since electricity prices are significantly higher than gas prices, this will result in higher operating costs. The natural gas driven process was shown to be more competitive.[13] More details on the two DACCS archetypes, including cost and performance characteristics, are provided in the experimental procedures.

BECCS, on the other hand, converts biomass to energy while capturing the CO_2 emissions from the process. Here, biogenic CO_2 is captured and permanently stored underground, thus effectively removing it from the atmosphere,[14] and providing negative emissions. BECCS can use a variety of biomass feedstocks and conversion processes to deliver electricity, heat, liquid or gaseous biofuel, or hydrogen.[15] Although BECCS is a promising NET, its role in net-zero transitions is uncertain, not least because it depends on the contentious issue of the quantity of future biomass availability, its costs, and traded off against its potential to provide CDR.[15]

BECCS is considered one of the most viable options for achieving large-scale negative emissions, with the least cost at mid-century,[16,17] while DACCS may become more prominent at a later time, especially in scenarios where biomass becomes increasingly unavailable.[17] According to the Sixth Carbon Budget Report by the Climate Change Committee (CCC), the UK should remove 44–112 $MtCO_2$ per year from the atmosphere by 2050 through natural or engineered methods to achieve its ambitious net-zero emissions goal.[18] Similarly, the UK government's net-zero strategy estimates that 75–81 CO_2 of removals per year will be needed by 2050 to offset residual emissions from hard-to-abate industries such as agriculture, transport (aviation and shipping), and industry.[19] Specifically, the Sixth Carbon Budget outlines the necessary DACCS range as 0–15 $MtCO_2$ per year, while the BECCS scale is expected to fall within 44–97 $MtCO_2$ per year by 2050.[10] These projections are contingent on the scenarios outlined by the CCC, which take into account societal and behavioral changes (such as dietary changes and waste reduction), technological innovations, and electrification efforts aligned with the goals of the Paris Agreement. However, a crucial element not considered in these scenarios is the integration of NETs with industry, particularly the utilization of available industrial waste heat to enhance CDR.

The concept of net zero is relatively well understood at a national level, but how it translates into sector level is much less clear. There has been a growing interest in integrating engineered NETs into industrial clusters, and that removal technologies are interesting not only because they appear to be crucial to the achievement of global Paris Agreement mitigation targets in IPCC scenarios,[1] but also at a national level to enable a smooth transition for the hard-to-decarbonize industries. UK industrial clusters are geographic areas with interconnected businesses that benefit from proximity. Integrating NETs into these clusters can offset and avoid emissions from various sources and offer economic advantages such as reducing system cost. Integration of NETs into industrial clusters has potential benefits such as the possibility to tap into existing CCS infrastructure, opportunities for waste heat utilization, possibly streamlined planning and permitting, and higher social acceptance, as well as a proximate market for co-products such as hydrogen.[20] In its industrial decarbonization strategy, the UK government has set a target to deploy at least two industrial-scale DACCS facilities by 2025 and to scale up deployment to reach 3 $MtCO_2$ captured per year by 2030, and to achieve a net-zero industrial cluster by 2050.[21] To support the deployment of these technologies, the government has launched a £1 billion Net-Zero Innovation Portfolio to fund the development and demonstration of innovative low-carbon technologies, including DACCS and BECCS.[1,22–26]

Here, we employ an integrated multiscale modeling approach focusing on the UK case study by utilizing a national-level energy system model accompanied by an industrial cluster-level model. This framework enables us to conceptualize, justify, operationalize, and ultimately understand the extent to which a single country can push the boundaries of CDR. Importantly, while much of the current literature relies on large-scale global models and integrated assessment models (IAMs),[11,13,27–30] our approach offers a supplementary viewpoint, delving into the intricate national and industrial dynamics involved in pursuing ambitious CDR. For this purpose, our first model focuses on individual technologies, providing detailed and updated technical potential and economic assessments for DACCS and BECCS. It aims to develop a suite of performance and cost models for various NETs options, taking into account technological uncertainties and sensitivities. The second model, a whole energy system model (WESM) for the UK[22–25] evaluates the potential for aggregate uptake of NETs. It focuses on the impact of integrating industrial clusters and provides a comprehensive UK-wide perspective on NETs deployment and its sensitivities. Finally, we apply an industrial cluster-scale model to delve into the nuanced role of NETs within industrial clusters. This model helps determine the optimal degree of NETs incorporation within these clusters. This study also aims to explore the impact of integrating industrial waste heat into DACCS increased demand from the industrial output and transportation sectors on the overall CDR. By

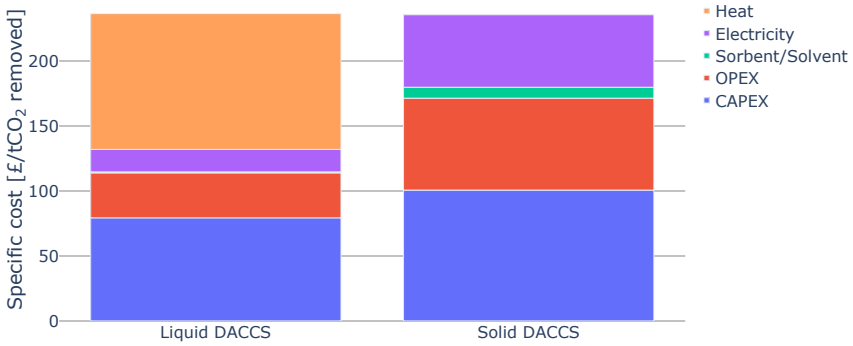


Figure 1. Breakdown of future costs of DACCS for a commercial Mt/a-scale plant

adopting this integrated approach, we aim to present cohesive insight on the role of NETs in the UK's transition to net zero. We find that total CDR could reach up to 126–134 $MtCO_2$ per year by 2050 through industrial waste heat integration into solid DACCS systems, with biomass gasification for hydrogen generation with CCS (BHCCS) being a major technology in NETs. We also report that rising demand across sectors necessitates greater deployment of solid DACCS, with the transportation sector (shipping and aviation) requiring more effort than the industrial sector. The findings of this study will be of significant interest to several key stakeholders. For the future of UK industry, the opportunities presented by NETs integration will have a major impact on siting choices, technology selection, and ultimately, profitability. Additionally, NETs manufacturers and policymakers will find valuable insights regarding the potential for NETs deployment, including optimal locations, integration strategies, and technology options for other countries.

RESULTS AND DISCUSSION

Techno-economic assessment model results

As costs and performance of NETs are still highly uncertain,[12] we conducted a techno-economic assessment of NETs based on data from the literature and an equipment-based costing model to assess the sensitivity toward different input parameters. Estimated ranges of capital investment cost (CAPEX) and fixed and variable operational cost (OPEX) of different DACCS and BECCS technologies are shown in the experimental procedures. Note that these values represent an optimistic future scenario for DACCS, as today's costs are much higher.[31]

To highlight key cost components, Figure 1 illustrates the cost breakdown for the solid low-temperature DACCS and liquid high-temperature DACCS per ton of CO_2 removed. The liquid DACCS archetype benefits from lower CAPEX and OPEX but incurs higher costs due to a higher heat demand and the requirement to reach about 900°C for solvent regeneration. The solid DACCS archetype, on the other hand, requires a higher initial capital investment but is more efficient in regeneration, here achieved via industrial-scale heat pumps, reducing fuel prices. It is important to note that the cost of heat and electricity depend strongly on the corresponding fuel prices and CAPEX on the cost of capital. The values shown in Figure 2 are indicative only.

Carbon removal credits from solid DACCS are currently sold at £1,100 per tCO_2,[32] while actual costs may be even higher.[33] To reach values close to the ones shown in Figure 1, significant reductions in CAPEX are required in conjunction with cheap electricity prices. Liquid DACCS is claimed to reach costs of \$94–\$232 per tCO_2 at commercial scale,[34] but the first commercial plant is still under construction.[35] The plant design is less capital intensive but relies on an efficient process and low fuel prices to reach such cost values. In the 2021 Global Assessment of DACCS report,[31] the IEA Greenhouse Gas Research & Development Programme (IEAGHG) estimates first-of-a-kind costs of \$407 and \$581 per tCO_2 for liquid and solid DACCS, respectively. The cost for 2050, after multiple implementations, is projected to be \$206 and \$233 per tCO_2, respectively.

To capture the strong dependence on fuel prices, we conducted a sensitivity analysis for both solid (see Figure 2A) and liquid (Figure 2B) DACCS systems to assess the impact of gas and electricity prices on capture costs. This is especially relevant given the fluctuations in energy costs since 2021.[36] As the solid DACCS system uses electricity as sole energy source, it shows no sensitivity toward changes in gas prices, unless gas-fired electricity is used. However, it is highly sensitive to variations in electricity prices, though this is attenuated by using a heat pump to efficiently supply the heat required for sorbent regeneration. Following the methodology of Sendi et al.,[37] the average coefficient of performance is assumed to be about 2. Nevertheless, electricity prices of £100 per MWh and higher result in capture costs of £300–£500 per tCO_2. The liquid DACCS system, on the other hand, is much more sensitive to gas prices (Figure 2B), which constitute a larger share of the overall cost (Figure 1). If gas prices exceed £100 per MWh, capture costs can be as high as £400–£700 per tCO_2, although such gas prices have rarely been observed historically. Note that, compared to current DACCS prices,[31] this is still quite inexpensive. As of March 2024, carbon removals using solid DACCS are sold for £1,200 per tCO_2,[38] while carbon removal credits for future DACCS projects are being sold for €400–€1,000 (£340–£860) per tCO_2.[38,39]

The costs of BECCS technologies, both present and future, are also uncertain, though less so than DACCS, as there is already industrial experience with commercial bioenergy and gasification facilities. Following a review of recent evidence in literature, the low, default, and high-cost ranges detailed in Table 2 in the experimental procedures are used in the further analysis. The results of techno-economic assessment model for DACCS and BECCS are implemented into the WESM.

Whole energy system modeling results

Reference scenario

In the reference scenario (SC-1), we evaluate the CO_2 removal potential of NETs based on their default techno-economic characteristics within the WESM, which represents a least-cost net-zero transition pathway for the UK (see experimental procedures

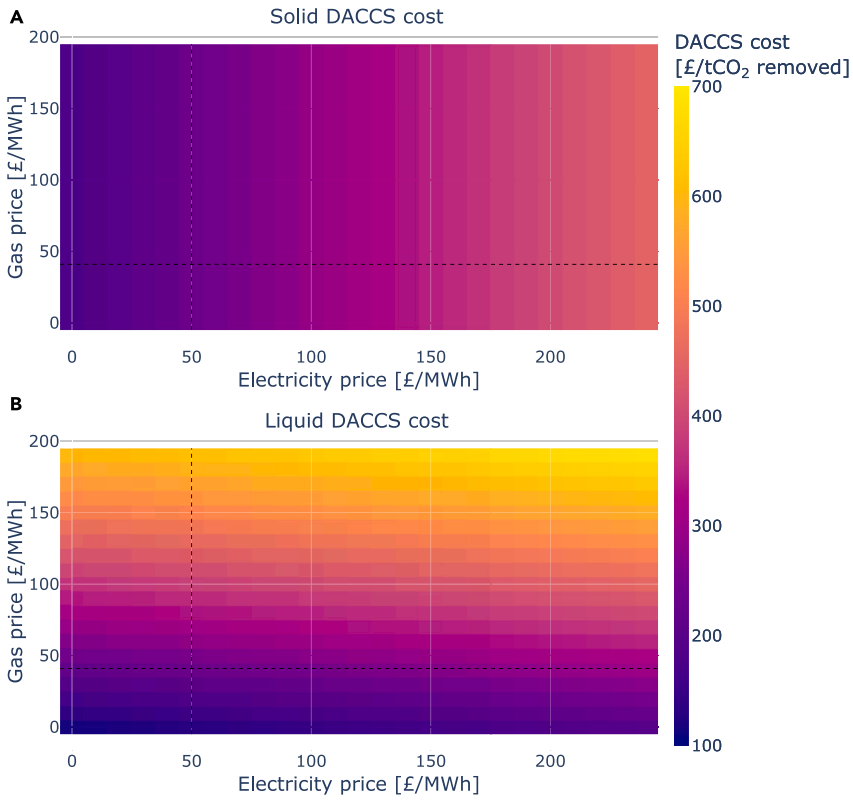


Figure 2. Sensitivity analysis of DACCS systems

(A) Solid DACCS (with heat pump).

(B) Liquid DACCS.

for default costs of NETs). The WESM is a bottom-up optimization model that depicts the whole energy system. Further details on the WESM are provided in the experimental procedures. Our analysis is based on the balanced net-zero scenario, which aligns with the UK net-zero strategy[19] and CCC balanced pathway.[44] The primary policy constraints on technologies, emissions, and commodities and system development objectives revolve around achieving a balanced mix of energy generation technologies with net-zero emissions by the year 2050 based on the least-cost solution. Under the balanced net-zero scenario, DACCS and BECCS remove 79 $MtCO_2$ per year in the UK by 2050 (Figure 3). The dominant technology is BHCCS (49 $MtCO_2$), followed by solid DACCS (21 $MtCO_2$), biomass combustion with CCS (BECCS power) (3.2 $MtCO_2$), waste gasification for hydrogen generation with CCS (WHCCS) (3.2 $MtCO_2$), and liquid DACCS powered by electricity (1.8 $MtCO_2$). These estimates are in line with the UK's net-zero strategy, which aims to deploy 75–81 $MtCO_2$ removal by 2050 to offset residual emissions.[19] Previous studies estimate that DACCS and BECCS can remove 19 and 51 $MtCO_2$ per year by 2050 to offset CO_2 emissions in the UK, based on the electricity systems optimization model.[45] Our results are consistent with these estimates. In the reference scenario, the total system cost is estimated to be around £4,100 per ton of CO_2 removed based on the calculation of overall system cost divided to total removed CO_2 (see Table 1).

Revised scenario—Input from the techno-economic models

We then integrated these optimistic future DACCS and BECCS cost estimates from the techno-economic model into the WESM (SC-2) to understand the potential differences in the scale and composition of the NETs portfolio by 2050. Figure 4 reveals that the cost-effective potential to remove CO_2 could increase to 103 Mt by 2050, following the aforementioned updated cost estimates. Similar to the reference scenario, BHCCS remains dominant, followed by solid DACCS powered by 40% electricity and 60% hydrogen in 2050, liquid DACCS powered by electricity, and WHCCS technologies. Compared to the reference scenario, the share of BHCCS is increased to 76 $MtCO_2$ by 2050 as the revised cost of BHCCS is lower than the default values, and because we are using a WESM, there is a demand for hydrogen across a range of sectors. Furthermore, the revised cost of solid DACCS is notably higher than the default values, leading to a reduction in its share. By contrast, the share of liquid DACCS is expected to increase due to its more cost-effective nature compared to the reference. Studies must use reliable techno-economic data to undertake an accurate assessment of the cost-effective potential to deploy NETs. Our assessment highlights that NETs may offer further opportunities for cost reduction compared to previously published studies.[19] Reassessing the techno-economic properties of NETs results in a total energy system cost reduction of 28%, amounting to £3,000 per ton of CO_2 removed in 2050.

Our techno-economic model also found that the cost of BHCCS is lower than the default cost, and BECCS power is more expensive than the default cost. As a result, the system prioritizes hydrogen production over electricity generation. BHCCS demonstrates superior efficiency when compared to BECCS,[43] resulting in additional energy available for substituting carbon-intensive gas and other applications. Considering the current decrease in the average power grid carbon intensity,[46] which in the UK is now lower than the carbon intensity of gas, the value of 1 megajoule (MJ) of hydrogen for displacing gas surpasses the value of 1 MJ of electricity for substituting other forms of electricity generation. This adjustment in costs results in emphasizing the cost-effectiveness of producing hydrogen from biomass as opposed to generating electricity. Previous studies have also arrived at similar results, indicating that the value of the negative emissions from BECCS can surpass the value of the electricity generated.[47,48] Also, Wolfram et al. reported that hydrogen deployment can reduce mid-century mitigation cost by 15%–23%.[49]

DACCS technologies integration into industrial clusters

Previous studies have identified both the importance of integrating NETs within an industrial sector in the energy systems

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Table 1. Overall results from the net-zero balanced scenario

Net-zero balanced scenario by 2050	CO_2 removal, Mt per year	Total system cost per kg of CO_2 removal
SC-1 default cost	79	4.1
SC-2 revised cost	103 [99–106]	3.0 [3.0–3.2]
SC-3 revised cost with industrial integration	118 [109–126]	2.6 [2.5–2.9]
SC-4 increase in industrial output demand	122 [111–127]	2.6 [2.5–2.8]
SC-5 increase in aviation and shipping demand	126 [113–134]	2.5 [2.4–2.8]

Notes: The brackets show the low- and high-cost estimates based on the low and high costs of each NET.

modeling[50] and the potential availability of 5–48 TWh of waste heat from the industrial sector in the UK.[51] This waste heat can be utilized by the solid DACCS systems,[12] as they can use waste heat at low temperatures (80°C–150°C). In this research, we also assessed the quantity of captured and stored CO_2 when integrating industrial waste heat into the solid DACCS system. The net-zero balanced scenario shows that 16.4–16.8 TWh per year of waste heat will be available from various industrial sectors, including chemical, food and drink, iron and steel, non-metallic minerals, paper and pulp, and other sectors, between 2050 and 2060 to be used by solid DACCS system. Our scenario 3 (SC-3) is based on integrating industrial waste heat into a solid DACCS system. The integration of available waste heat into the solid DACCS system increases the total removed CO_2 to 118 Mt by 2050 (see Figure 5). Although BHCCS remains the dominant technology (76 $MtCO_2$), the solid DACCS system removes nearly twice as much CO_2 (26 $MtCO_2$) compared to the revised cost analysis scenario (Figure 4), starting from 2050 to 2060. Solid DACCS is powered by 44% of available waste heat (31% from industry, 13% from electricity generation) and 56% by electricity in 2050, with its waste heat power increasing to 48% by 2060. The liquid DACCS, powered by electricity, represents the second-highest share for DACCS. It is evident that the integration of industrial waste heat into the solid DACCS system with revision of the techno-economic properties increases the total removed CO_2 amount by 14.4%. Additionally, the waste industrial heat integration to the system reduces the total energy system cost per ton of CO_2 removed by 38% compared to the reference scenario. This translates to total system cost reduction of around £2,600 per ton of CO_2 removed (Table 1).

Cost-sensitivity analysis

We also conducted an analysis of the impact of low and high costs (obtained from the techno-economic assessment, see experimental procedures) for each individual NET on the total CO_2 removals. This analysis is presented in Figure 6. According to the results of the low-cost analysis, the total removed CO_2 can reach 126 Mt by 2050 and 133 Mt by 2060, with a corresponding 2.1% reduction in system costs. In contrast to the low-cost scenario, which shows a smaller reduction in removed CO_2 compared to the central cost scenario, the high-cost scenario exhibits a significantly greater reduction in removed CO_2.

What would happen if the demand for transportation and industrial output increases?

After evaluating the impact of industrial waste heat integration on overall CO_2 removal, we examine the system's response to changes in demand. The demand from the industrial and transportation sectors influences the demand for NETs,[52] as they are considered hard to abate. Here, we use model experimentation

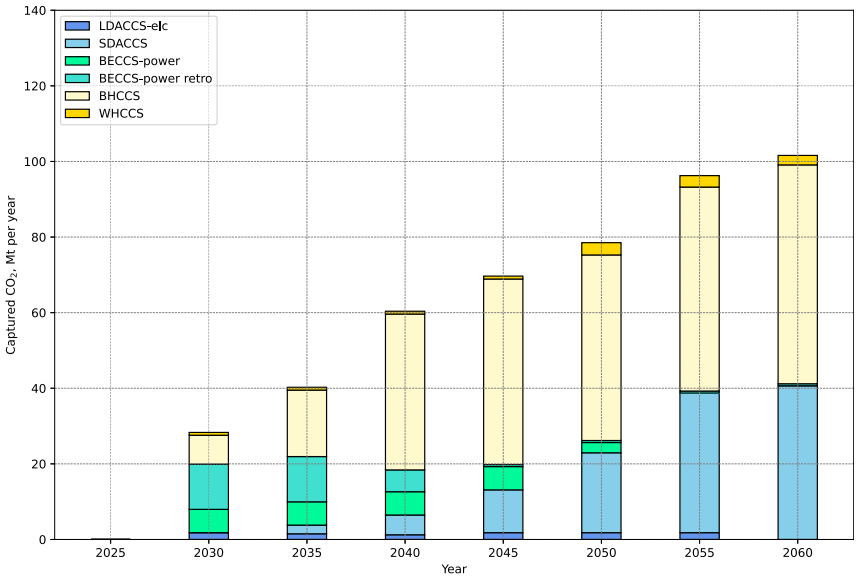


Figure 3. NETs results obtained from default techno-economic data in the whole energy systems model for the net-zero balanced scenario (SC-1)

BECCS-power, biomass combustion with CCS; BECCS-power retro, biomass combustion with CCS retrofitting; LDACCS-elc, liquid DACCS powered by electricity; SDACCS, solid DACCS; BHCCS, biomass gasification for hydrogen generation with CCS; WHCCS, waste gasification for hydrogen generation with CCS.

Table 2. Techno-economic parameters of BECCS and BHCCS

		CAPEX 2020 (£/kW)	CAPEX 2050 (£/kW)	Var. OPEX 2020 (£/kWh)	Var. OPEX 2050 (£/kWh)	Fix. OPEX 2020 (£/kW/a)	Fix. OPEX 2050 (£/kW/a)	EFF (%)	References
BECCS power	average	3,190	3,140	0.0046	0.0045	132	115	30	European Commission et al.,[40] BEIS,[41] and Bui et al.[42]
	low	2,720	2,720	0.0040	0.0040	69.3	58.4	33	
	high	3,440	3,250	0.0051	0.0050	194	172	27	
BHCCS	average	1,870	1,660	0.0078	0.0069	72.0	63.7	67	BEIS[43]
	low	1,140	1,000	0.0078	0.0069	43.7	38.6	68	
	high	2,610	2,310	0.0078	0.0069	100	88.7	66	

Notes: EFF, efficiency; Fix., fix cost; REF, references; Var., variable cost.

to evaluate the implications of increased demands in these sectors. Note that post-combustion CCS is expected to be deployed in industrial sectors, including cement, iron and steel, and chemicals, which will likely dampen the need for NETs. Here, we assume a 25% increase in demand for all industrial sectors, including steel and iron, pulp and paper, cement, chemicals, food and beverages, non-metallic minerals, non-ferrous metals, and other industrial sectors. This is because the industrial transition to a low-carbon future in the UK exhibits large uncertainty.[53] This assumption is our fourth scenario (SC-4). Additionally, we considered increased demand in the transportation sector, including domestic and international aviation and international shipping, by 25% by the year 2050, based on the average assumption of the shipping and aviation scenarios in the Sixth Carbon Budget report of the CCC.[10] We also considered the increase in the transportation sector demand in the scenario 5 (SC-5). The overall demand trajectory for all scenarios is provided in Figure S1.

In Figure 7, we present the estimated CDR potential of various NETs under a scenario of a 25% increase in demand for industrial output by 2050, using central cost estimation. The increase in industrial output demand (SC-4) results in the annual removal of 122 $MtCO_2$ for negative emissions (Figure 7). On the other hand, a greater demand in the shipping and aviation sector (SC-5) contributes to even greater CO_2 removal, amounting to approximately 126 $MtCO_2$ per year (Figure 8). It is preferable to emphasize that the liquid DACCS, powered predominantly by hydrogen (89%) and electricity (11%), removes 1.6 $MtCO_2$ in SC-4 and 2.6 $MtCO_2$ in SC-5 by 2050, diverging from other scenarios within the study as it is not used in other scenarios. Solid DACCS systems also play a significant role in both scenarios, capturing 21 $MtCO_2$ in SC-4 and 28.4 $MtCO_2$ in SC-5. The combined utilization of solid DACCS and liquid DACCS powered by hydrogen and electricity underscores the potential of these technologies to address the escalating CDR demands driven by the increasing requirements of both the transportation and industrial sectors. Moreover, the projected rise in transportation demand necessitates a greater emphasis on decarbonization efforts compared to the industrial sector. This disparity can be attributed to the relative ease of decarbonizing the industrial sector by transitioning from fossil fuels to hydrogen, as well as the substantially higher transportation sector CO_2 (48 $MtCO_2$) emissions

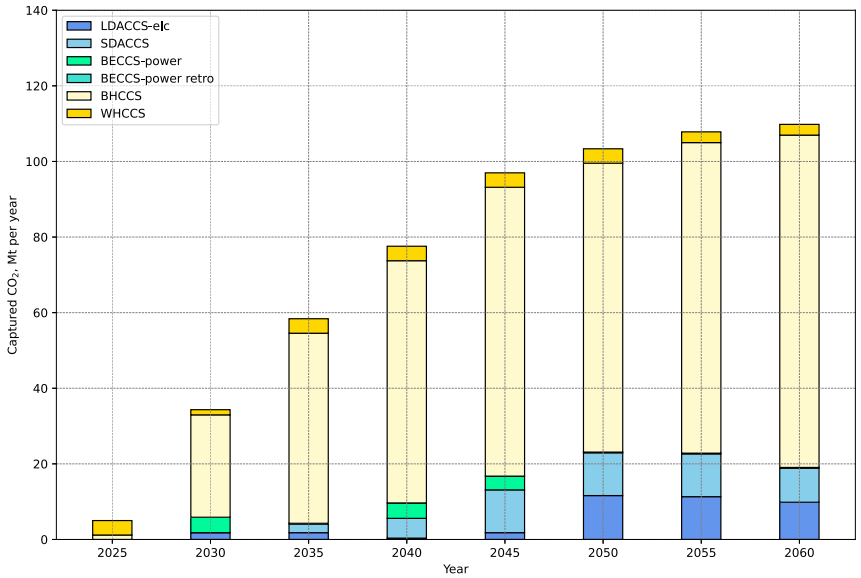


Figure 4. NETs results obtained from the revised techno-economic data in the whole energy systems model for net-zero balanced scenario (SC-2)

BECCS-power, biomass combustion with CCS; BECCS-power retro, biomass combustion with CCS retrofitting; BHCCS, biomass gasification for hydrogen generation with CCS; LDACCS-elc, liquid DACCS powered by electricity; SDACCS, solid DACCS; WHCCS, waste gasification for hydrogen generation with CCS.

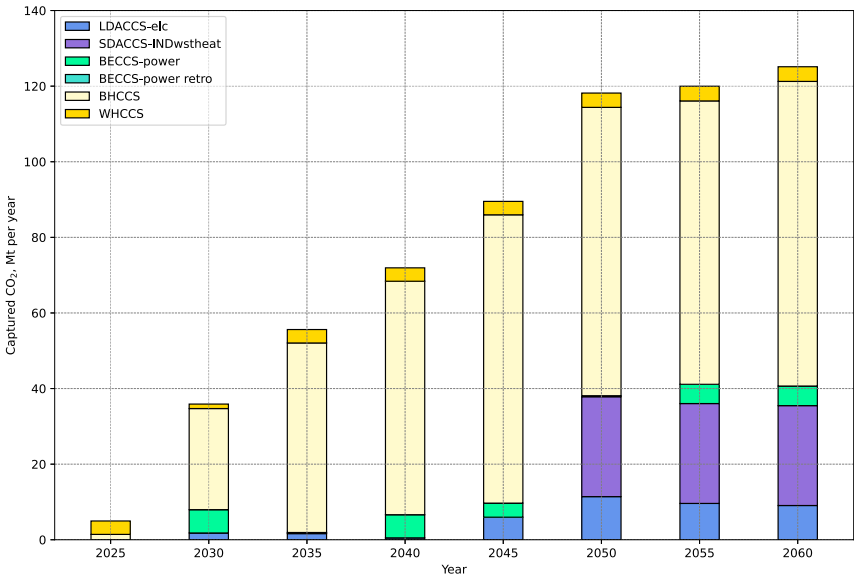


Figure 5. Amount of captured and stored CO_2 with solid DACCS integration of industrial waste heat in the net-zero balanced scenario (SC-3)

BECCS-power, biomass combustion with CCS; BECCS-power retro, biomass combustion with CCS retrofitting; BHCCS, biomass gasification for hydrogen generation with CCS; LDACCS-elc, liquid DACCS powered by electricity; SDACCS-INDwstheat, solid DACCS with industrial waste heat integration; WHCCS, waste gasification for hydrogen generation with CCS.

compared to the industrial emissions (8.3 $MtCO_2$). The 25% increase in both industrial output and transport sector demand leads to a 34% and 14% increase in CO_2 emissions, respectively. In contrast to industrial sector, the transportation sector poses more significant challenges in emission reduction, with biomass-derived fuels playing a substantial role in offsetting transport emissions and achieving net-zero goals. These findings align with current modeling results from Department for Energy Security and Net Zero (DESNZ), which emphasize the importance of BECCS for power, heat, and transportation as a major contributor to net-zero objectives.[52] However, as demand increases, bioavailability and sustainability limitations restrict the utilization of BECCS (see the paragraph below for further discussion). Therefore, more extensive deployment of DACCS systems is necessary (see Figure 9). Based on demand scenarios, the transportation sector requires a greater emphasis on decarbonization efforts compared to the industrial sector. This trend is reflected in the deployment patterns of DACCS technologies across scenarios, specifically solid DACCS (utilizing industrial waste heat) and liquid DACCS powered by electricity and hydrogen. Based on the cost-sensitivity analysis, the total removal of CO_2 amount could reach up to 134 $MtCO_2$ in 2050 (Table 1).

When comparing the responses of NETs in these five scenarios, it becomes evident that biomass technologies, particularly BHCCS, represent the primary NETs but have limitations

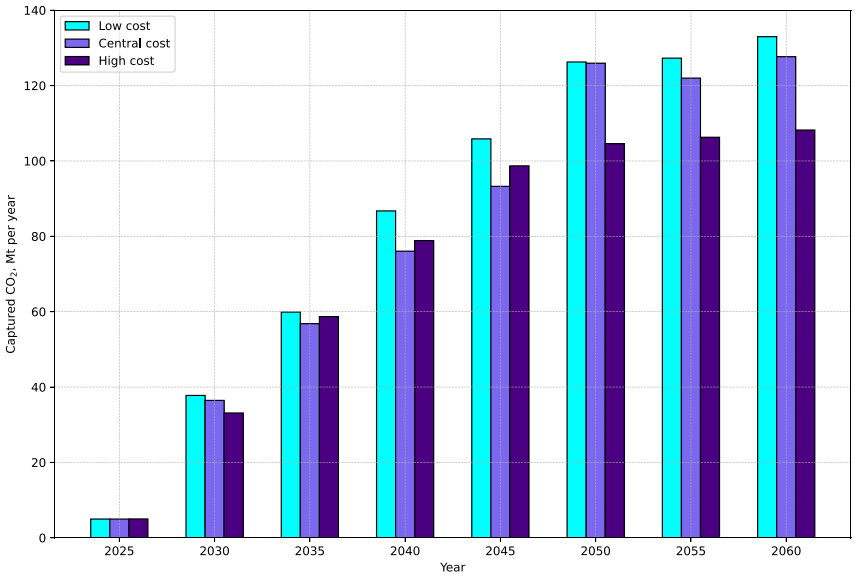


Figure 6. Sensitivity analysis of total removed CO_2 amount from NETs to differences in costs

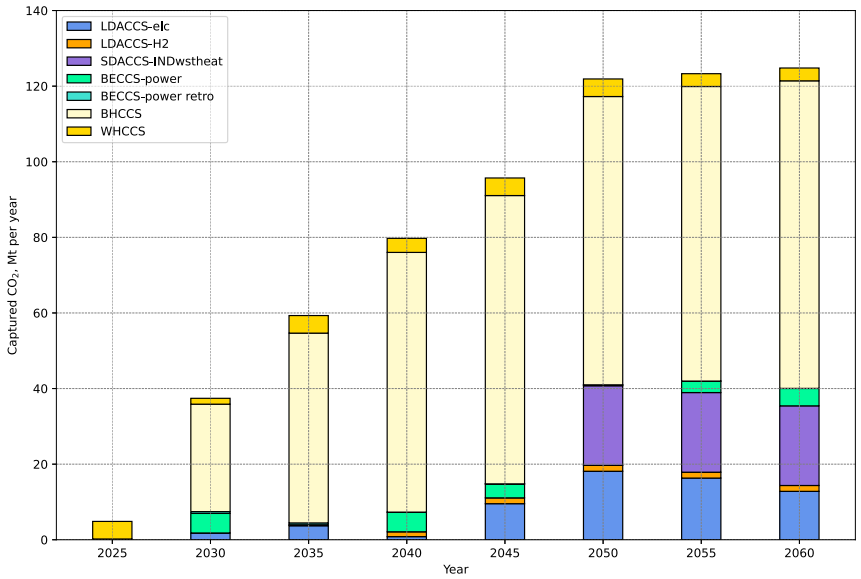


Figure 7. Total CO_2 removal from different NETs in response to a 25% increase in demand for industrial output by 2050, using central cost estimation in SC-4

Notes: INDwstheat, industrial waste heat integration. BECCS-power, biomass combustion with CCS; BECCS-power retro, biomass combustion with CCS retrofitting; BHCCS, biomass gasification for hydrogen generation with CCS; LDACCS-elc, liquid DACCS powered by electricity; LDACCS-H2, liquid DACCS powered by hydrogen; SDACCS-INDwstheat, solid DACCS with industrial waste heat integration; WHCCS, waste gasification for hydrogen generation with CCS.

including biomass availability and sustainability criteria,[52] capping their potential at 76 $MtCO_2$ per year. In contrast, the DACCS system exhibits greater potential to offset residual emissions (see Figure 8).[52] Previous modeling studies have highlighted the "highly uncertain and challenging to determine precisely" nature of sustainable biomass availability.[52] A recently published Biomass Sustainability report has estimated that the total sustainable UK biomass supply may range from 550 to 750 PJ in 2025 and 500–1,000 PJ in 2050, based on stable domestic biomass feedstock availability in the UK.[52] Biomass availability in the WESM is subject to constraints related to import growth rates and raw availability. The annual growth rate for biomass imports is restricted to 20%. Additionally, limitations exist on the availability of specific biomass type, including short-rotation forestry, solid organic waste, and agricultural residues. However, there is no restriction on importing low-quality pellet such as grass, waste straw, and wood waste. In total, the model restricts domestic and imported biomass availability to 340 and 147 PJ, respectively, by the year 2050, based on updates in 2020 to prevent over-harvesting of global biomass. Within these constraints, the total biomass utilization for BECCS in 2050 varies from 605 to 643 PJ across scenarios 1 and 5, respectively. This includes high-quality wood pellets (255 PJ) and low-quality pellets derived from grass (62 PJ), waste straw (218 PJ), and wood waste (110 PJ), which remains at its maximum within the WESM, primarily driven by the BHCCS

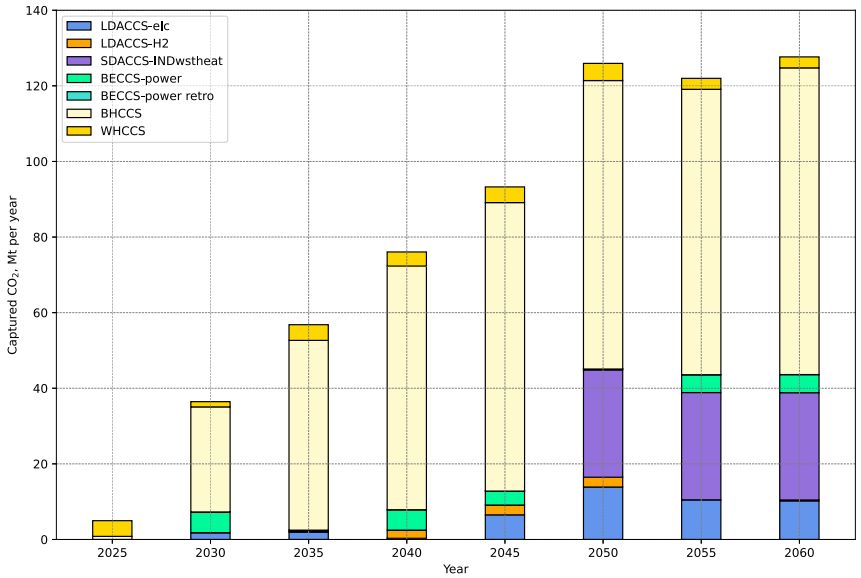


Figure 8. Total CO_2 removal from different NETs in response to a 25% increase in demand for transportation by 2050 using central cost estimation in SC-5

Notes: TRA, transportation (domestic and international aviation and international shipping); INDwstheat, industrial waste heat integration into DACCS.

BECCS-power, biomass combustion with CCS; BECCS-power retro, biomass combustion with CCS retrofitting; BHCCS, biomass gasification for hydrogen generation with CCS; LDACCS-elc, liquid DACCS powered by electricity; LDACCS-H2, liquid DACCS powered by hydrogen; SDACCS-INDwstheat, solid DACCS with industrial waste heat integration; WHCCS, waste gasification for hydrogen generation with CCS.

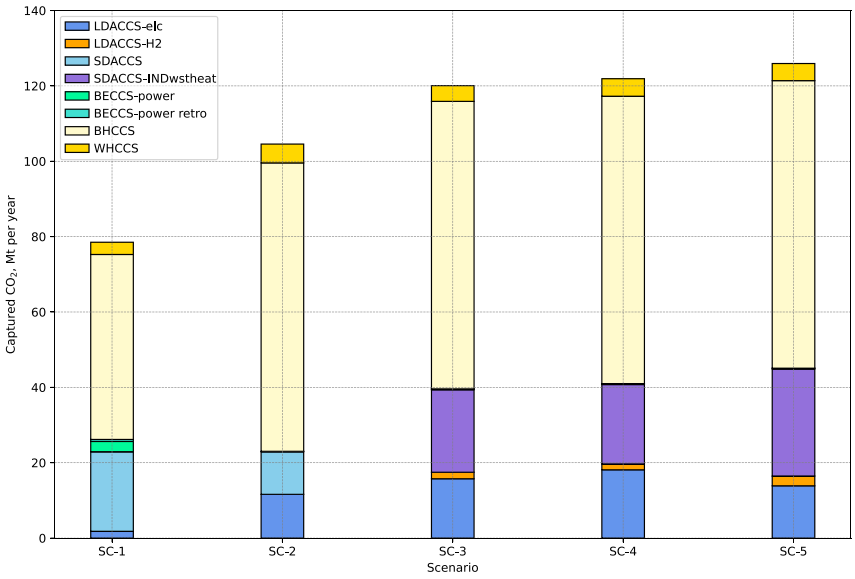


Figure 9. Total CO_2 removal from different scenarios by 2050, using central cost estimation

BECCS-power, biomass combustion with CCS; BECCS-power retro, biomass combustion with CCS retrofitting; BHCCS, biomass gasification for hydrogen generation with CCS; LDACCS-elc, liquid DACCS powered by electricity; LDACCS-H2, liquid DACCS powered by hydrogen; SDACCS, solid DACCS; SDACCS-INDwstheat, solid DACCS with industrial waste heat integration; WHCCS, waste gasification for hydrogen generation with CCS.

technology. BHCCS consistently plays a pivotal role in delivering the majority of negative emissions across all scenarios, underscoring its significance in achieving net zero by 2050. Notably, biomass prices (encompassing import and export) exhibit relative stability across scenarios 2–5, hovering around £237 per MWh. Scenario 1 presents a slightly lower price of £234 per MWh in 2050. These biomass prices incorporate both the biomass resource cost and associated palletization and distribution expenses. The details of price calculation for each type of biomass pellet along the biomass supply chain in the UK can be found in previous studies.[54]

Table 1 also displays the total system cost in pounds per kilogram of CO_2 removal. The trajectory of overall system costs per kilogram of CO_2 removal can be observed in Figure S2. It is evident that the total system cost has decreased with increasing CO_2 removal by revising the techno-economic costs as well as utilizing industrial waste heat. Industrial waste heat utilization accounts for up to 25% of the total system cost savings per kilogram of CO_2 removal. The demand changes do not impact the results, although SC-5 exhibits a slightly lower total system cost per kg of CO_2 removal due to its higher CDR amount.

Industrial cluster-level model results

Industrial clusters, where industries are spatially agglomerated, present unique opportunities for cost-effective decarbonization. Within these clusters, various industries can collaborate, share CO_2 infrastructure and storage, and benefit from centralized fuel (e.g., hydrogen) production. Refinery fuel gases, for instance, can serve as feedstock for hydrogen production, while available waste heat can power solid DACCS systems. The composition of industries within a cluster, as well as their business models, will determine the solution portfolio.

To understand the implications of our result at the industrial cluster level, we have chosen the Humber industrial cluster as our case study (see the experimental procedures for the industrial cluster model). Located in Yorkshire, the Humber industrial cluster is the largest in the UK in terms of industrial emissions, releasing more than 10 Mt of CO_2 annually, which accounts for more than 2% of the UK's total greenhouse gas emissions.[21] The primary industries in this cluster include steel, chemicals, cement, and oil refineries. Notably, the Zero Carbon Humber initiative aims to transform this industrial hub into the world's first net-zero emissions industrial cluster by 2040 through the development of CCS infrastructure and the production of blue and green hydrogen.[21] Our objective is to examine the most cost-effective energy supply mix for the Humber region while adhering to a net-zero emission constraint similar to the WESM (see Figure 10). Our Humber Region Industrial Cluster Model reveals that a cost-effective energy mix in a decarbonized Humber cluster relies on post-combustion CO_2 capture (~9 $MtCO_2$ per year) for tackling process emissions, fuel switching with hydrogen (~2 GW), and carbon offsets. Reforming with CCS outcompetes electrolytic production of hydrogen even at high gas prices. However, the share of hydrogen from gasification increases with the availability of biomass similar to the results obtained from the WESM. Importantly, decarbonization is associated with an energy penalty, and the overall energy conversion losses increase from approximately 3–14 TWh per year, which is in the line with WESM model results. This presents an opportunity for waste heat recovery and industrial integration (Figure 10).

We also assessed the system value of biomass in reducing the overall cost of carbon avoidance associated with reaching net zero in the Humber cluster as presented in Figure 11. This assessment assumed medium and high biomass prices of £180 and £250 per ton, respectively, based on reported biomass costs.[55,56] Consistent with the findings in the WESM, industrial cluster favors the adoption of BHCCS over DACCS, largely owing to the dual benefits of carbon avoidance and removal. As the availability of biomass increases, the industrial cluster prioritizes hydrogen generated from BHCCS technologies over blue hydrogen to achieve the lowest costs. Furthermore, when we integrate the available waste heat of 16.8 TWh per year from industrial cluster into the solid DACCS system based on the WESM model insights, the cost of carbon avoidance decreases by £50 per ton of CO_2 (see Figure 11).

Importantly, a small integration of biomass in the energy system offers significant value to the system. An increase in the uptake of biomass by approximately 2 TWh per year, or 3%–5% of

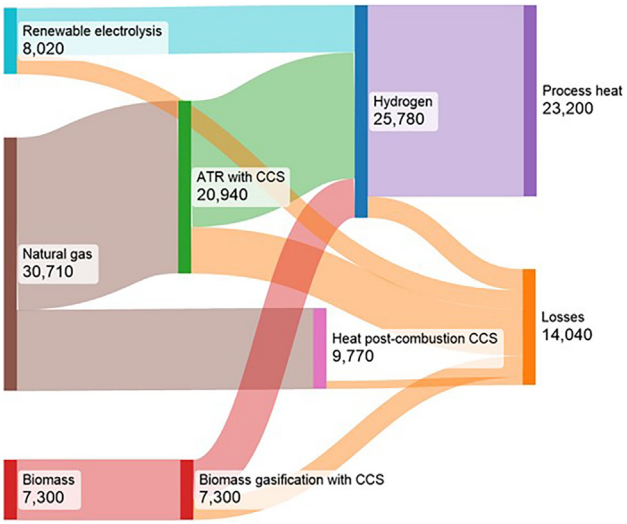


Figure 10. Sankey diagram showing the cost-effective energy mix of the Humber region with estimated energy flows represented in GWh per year

The produced energy is distributed as follows: process heat (23 TWh), heat for post-combustion CCS (8.8 TWh), and energy conversion losses (14 TWh).

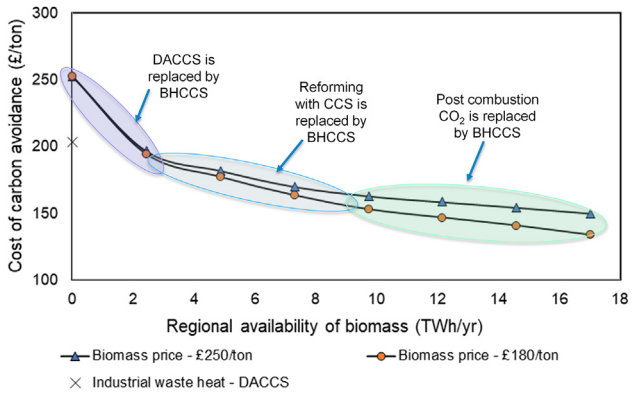


Figure 11. Cost of carbon avoidance in reaching net zero in the Humber cluster as a function of the availability of biomass at medium (£180 per ton) and high biomass (£250 per ton) prices

the overall energy supply in the cluster, reduces the cost of carbon avoidance from £252 to £195 per ton. This is largely owing to the displacement of DACCS to remove residual emissions from the cluster. At higher levels of biomass uptake, the overall system value is a function of the cost of biomass, with cheaper biomass sources offering the lowest costs of carbon avoidance. Nevertheless, the relative cost reductions diminish with an increasing supply of biomass, which suggests that biomass ought to be integrated into the system insofar as it presents material cost reductions without creating adverse impacts (land-use change, biodiversity loss, etc.) in the region.

Conclusions

This study shows that NETs can help the UK achieve its net-zero goal by 2050. The WESM reveals that the total CO_2 removed by NETs could reach up to 106 $MtCO_2$, or even 126 $MtCO_2$ if the existing NETs portfolio is supplemented with industrial waste heat fueling the solid DACCS technology. We find that the cost of carbon avoidance and total system is directly linked to industrial waste heat integration. Our findings also suggest that the UK may have to implement a wider variety of NETs to achieve a cost-optimal net-zero transition than previously believed, with BHCCS being the primary technology. The results strongly favor BHCCS over electricity generation BECCS, suggesting that the former technology should be prioritized in the UK's NETs strategy.

Our results from the integrated models also show that biomass availability is the limiting factor for BECCS deployment and negative emissions from BECCS technologies. It is worth noting that BECCS power has been deployed in all major assessments to date as a placeholder for all BECCS. However, this study departs from that convention and instead identifies the value of gasification and other BECCS routes for net zero. This is primarily due to the higher conversion efficiency of hydrogen and its ability to displace more carbon-intensive fuels than grid power (and avoiding the need to produce green hydrogen and the implications for further power generation). In other words, maximizing carbon avoidance per MJ of biomass energy is just as important as maximizing negative emissions. Moreover, since BECCS is constrained by biomass availability and sustainability, the rising demand across sectors necessitates greater deployment of DACCS. Solid DACCS, utilizing industrial waste heat, emerges as the cost-optimal solution, while liquid DACCS powered by electricity and hydrogen present promising pathways for additional CDR. Considering the demand disparity between the industrial and transportation sectors, it is evident that the transportation sector, particularly shipping and aviation, requires intensified decarbonization efforts. Therefore, we strongly advocate for increased investment in decarbonization strategies for the shipping and aviation sectors, including the development and implementation of DACCS systems. This study highlights the importance of considering the full range of DACCS and BECCS options and evaluating their impact on overall GHG emissions. By diversifying NETs pathways, we can maximize the potential for decarbonization and achieve net-zero emissions.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Any requests for further information should be directed to Dr. Semra Bakkaloglu (s.bakkaloglu@imperial.ac.uk).

Materials availability

This study did not generate new, unique materials.

Data and code availability

The UK The Integrated MARKAL-EFOM System (TIMES) model is available from University College London (UCL) at https://www.ucl.ac.uk/energy-models/models/uk-times. Several versions of optimization and dynamic simulation frameworks for modeling hydrogen and CO_2 process systems can be found here: https://github.com/act-elegancy/chain_tool.

Overview of methods

This study integrates three different models, including the techno-economic assessment of DACCS and BECCS, the WESM, and the industrial cluster model (Figure 12). The details of each model are explained below.

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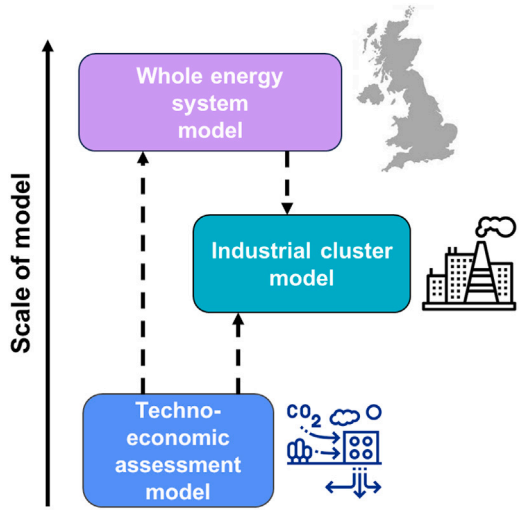


Figure 12. Integration of three models for comprehensive analysis, with the scale increasing from the techno-economic assessment model to the industrial cluster model and finally to the whole energy system model

Techno-economic assessment model

The costs of BECCS and especially DACCS are still highly uncertain, as they are emerging technologies. Therefore, we performed a thermo-economic assessment based on literature data, as well as a sensitivity study.

Cost ranges and data sources for BECCS technologies are summarized in Table 2. They are estimated based on data from the European Union (EC) commission,[40] the UK Department of Business, Energy & Industrial Strategy (BEIS),[41,43] and Bui et al.[42] Although estimated BECCS CAPEX in 2020 only vary by +8%/−15% from the average, the uncertainty in BHCCS CAPEX is significantly higher, varying by ±39%

DACCS costs and performance are also highly uncertain, as shown in Table 3. It is important to note here that all these values are optimistic projections for future costs when DACCS is deployed at scale. The performance of liquid high-temperature DACCS systems is modeled based on the comprehensive study by the National Academy of Sciences,[30] while solid low-temperature DACCS systems are modeled based on the data from Fasihi et al.,[57] Sendi et al.,[37] and, again, the National Academy of Sciences.[8] It is assumed that the solid low-temperature DACCS process is completely electrified (no natural gas demand), while for the liquid high-temperature DACCS process, the high-temperature heat is provided by natural gas combustion. For the latter, the ratio of energy provided from natural gas to energy provided from electricity is in the range of 6–7, showing that the process relies heavily on natural gas. As mentioned above, the liquid DACCS process can in principle be electrified, though this will result in higher costs due to the higher electricity prices.

The data shows that solid DACCS systems are expected to have higher upfront capital cost but potentially lower running cost as the energy demand is likely lower and heat is only required at about 100°C compared to the about 900°C required for the liquid DACCS system.

Whole energy systems model

TIMES model generator is maintained by the IEA to conduct in-depth energy and environmental analysis, commonly used to examine potential energy system scenarios.[59] It is a techno-economic, partial equilibrium, technology-rich, bottom-up model that operates on competitive market assumptions and perfect foresight. In our study, we utilized the UK TIMES model as our WESM, constructed with the VEDA system (developed by UCL Energy Institute)[60] and endorsed by various government departments, including its use in setting Carbon Budgets 5 and 6[10,61] and the net-zero strategy.[19]

UK TIMES model addresses the goal of decarbonization and the most cost-effective technology and fuel options for various energy-consuming sectors, considering various constraints. The model balances energy supply and demand over different time periods, technology deployment rates, and resource availability, facilitating informed policy decisions. The model encompasses eight sectors, divided into supply and demand sides, calibrated to the UK's 2010 energy balance with a focus on the existing energy technologies in the Reference Energy System (RES). UK TIMES provides results in 5-year increments until 2060, structured into 16 time slices.

The model's objective is to minimize total system costs, encompassing various economic factors, such as investment, operation and maintenance, import, export, and more. Supply curves define available resources at specific costs, and techno-economic parameters are associated with existing and future technologies. The model outputs optimal investments, operations, and import/export levels, providing insights into costs, feasibility, and trade-offs. It also addresses CO_2, CH_4, N_2O, and HFC emissions, offering a comprehensive analysis of integrating DACCS and BECCS into the UK's industrial clusters. The summary of UK TIMES sectoral assumptions can be found in can be found in annex A.2 of the Sixth Carbon Budget impact assessment.[62] The default cost of DACCS in 2020 is listed in Table 4, and another for BECCS in 2020 in the WESM is listed in Table 5. The techno-economic properties for 2050 are defined in the model based on the results of the techno-economic assessment provided in Table 3. The WESM then interpolates the costs between the defined values for 2020 and 2050 values at 5-year intervals.

WESM also considers land-use implications, including afforestation scenarios, into its modeling framework. This encompasses factors such as forestry biodiversity, reforestation with energy crops (e.g., eucalyptus,

Table 3. Techno-economic parameters of DACCS technologies

		CAPEX (£/tCO_2)	Variable OPEX (£/tCO_2)	Fix OPEX (£/tCO_2 per annum)	Lifetime (years)	Heat demand (GJ/tCO_2)	Electricity demand (GJ/tCO_2)	References
Liquid high-temperature DACCS	average	79.2	0.78	34.6	25	9.18	1.27	National Academies of Sciences Engineering and Medicine[58]
	low	55.5	0.78	26.7	25	5.29	0.79	
	high	103.1	0.78	42.5	25	10.69	1.68	
Solid low-temperature DACCS w/o heat pump	average	104.5	8.4	73.5	25	6.30	0.90	Sendi et al.,[37] National Academies of Sciences Engineering and Medicine,[58] and Fasihi et al.[57]
	low	73.2	8.4	56.7	25	4.10	0.84	
	high	136.0	8.4	90.3	25	11.62	1.08	
Solid low-temperature DACCS with heat pump	average	109.7	8.4	77.1	25	0	4.02	Sendi et al.,[37] National Academies of Sciences Engineering and Medicine,[58] and Fasihi et al.[57]
	low	76.9	8.4	59.5	25	0	2.87	
	high	142.8	8.4	94.7	25	0	6.84	

Table 4. Techno-economic characterization of DACCS in the WESM

#	DACCS technologies	CAPEX (£/tCO_2), 2020	OPEX (£/tCO_2), 2020	Heat Req. (GJ/tCO_2)	Electricity Requirement (GJ/tCO_2)	Lifetime (year)
1	DACCS-liquid solvent powered by electricity[8]	631	25.8	10.7	1.2	30
2	DACCS-liquid solvent powered by electricity and natural gas[8]	631	25.8	10.7	1.2	30
3	DACCS-liquid solvent powered by electricity and hydrogen[8]	631	25.8	10.7	1.2	30
4	DACCS-solid sorbent powered by electricity, gas, hydrogen, and waste heat from electricity generation[12]	738	17.5	3.94	0.84	25

paulownia, sitka spruce, willow, and miscanthus), and peatland restoration processes. It is important to note that the natural CO_2 removal associated with these land-use changes falls outside the scope of this study's results.

Industrial cluster model

The mathematical framework expands on the list of technologies previously published by Sunny et al. and others to evaluate cost-effective designs that achieve net-zero greenhouse gas emissions in the Humber industrial cluster.[63] The model formulation is a mixed integer linear programming that optimizes the technology design and operation decisions to achieve the lowest costs in reaching net-zero. The model combines capital costs for technologies (production, transport, storage, and end-use technologies) alongside with their annual operating costs to provide a comprehensive description of project costs. In the model, each industrial emitter is allocated a distinct spatial node in the mathematical model. Altogether, 19 spatial nodes are used to describe 16 industrial sites (see Figure S3) and three offshore locations that can support long-term geological storage of CO_2 or offshore wind farms. Each industrial site is described with their heating requirements and process emissions, and these emissions must be avoided, captured, or offset to achieve CO_2 neutrality (see Table S1). Readers who are interested in the model formulation are encouraged to see Sunny et al.[63] and Küng et al.[64] for more details.

The model uses a snapshot representation of the investment time horizon to explore the different designs.[63–65] The material and energy balance constraints, together with the emission reduction constraints, enable different infrastructure designs to be explored. Under net-zero emission constraints, the model requires that:

- The heat demand of an industrial site is met by a technology capable of meeting that demand (i.e., gas boiler, electric heater, or H_2 boiler).
- Any emissions generated on-site from heating (if a gas boiler is used) or industrial processes are either captured using post-combustion CCS or offset using a NET.
- The thermal requirement of any post-combustion CCS facility is met by the heating technologies, and the electrical requirement may be met by renewable power generation, batteries, grid electricity imports, CCGT-CCS, or BECCS facilities.
- Any residual emissions from the post-combustion CCS facility and emissions associated with the fuel inputs must be offset using NETs such as solid DACCS, liquid DACCS, BECCS, or BHCCS.
- All heating technologies may provide heat for solid DACCS, but only gas and H_2 boilers can provide the high-temperature heat needed for liquid DACCS.
- If electricity or H_2 is produced, they must either be stored in dedicated grid-scale batteries or salt caverns, respectively, or used at every point in the operating horizon.

We assume that natural gas is associated with an indirect CO_2 footprint of 18 kg per MWh_{HHV}, which is representative of the leakages along the transport chain but not including production.[66] Renewable electricity generation is associated with a CO_2 footprint of 0 kg per MWh electricity, as all emissions originate from the production of the assets, which is outside the scope of this study. Grid electricity is associated with an approximate CO_2 footprint of 200 kg per MWh, which is representative of the supply in the year, 2022.[46] Imported biomass pellets are assumed to have a CO_2 footprint of 224 kg per ton of biomass.[67] The analytical superstructure is depicted in Figure 13. It is assumed that importing wood pellets from the US is utilized in BECCS to generate power in the region.[68]

The objective function is the total system cost associated with meeting the industrial demand for heat while simultaneously avoiding emissions from heating and carbon-intensive processes. A cost minimization approach is used with scenario-driven analysis to evaluate the value of the technologies in achieving net-zero greenhouse gas emissions cost-effectively. The overall performance of the designed system is evaluated using the following key performance indicators: cost of CO_2 abatement, % share of CO_2 avoided, % increase in natural gas consumption, total CO_2 injection rate, % share of RES in primary energy consumption, and % increase in primary energy consumption. A business as usual (BAU) scenario is defined assuming natural gas as fuel across the cluster with associated emissions. In the BAU

Table 5. Techno-economical characteristics of selected BECCS technologies

#	Technology name	CAPEX (£/kW)	Var. OPEX (£/kWh)	Fix. OPEX (£/kW/a)	EFF (%)	Lifetime (year)
1	hydrogen biomass gasification with CCS	2,807	–	196.5	46	30
2	hydrogen biooil SMR with CCS	1,560	–	109.2	54	30
3	hydrogen waste gasification with CCS	4,970	–	347.9	41	30
4	biomass combustion with CCS	2,810	0.003	132.3	31	25
5	biomass combustion with CCS-retrofit	1,820	0.004	78.9	89	25

Notes: CAPEX, capital investment cost for 2020; EFF, efficiency; Var., variable; Fix., fix; OPEX, operational and maintenance cost; Req., requirement; AD, anaerobic digestion; SMR, steam methane reforming. The variable and fixed operational and maintenance costs are for the year 2020.

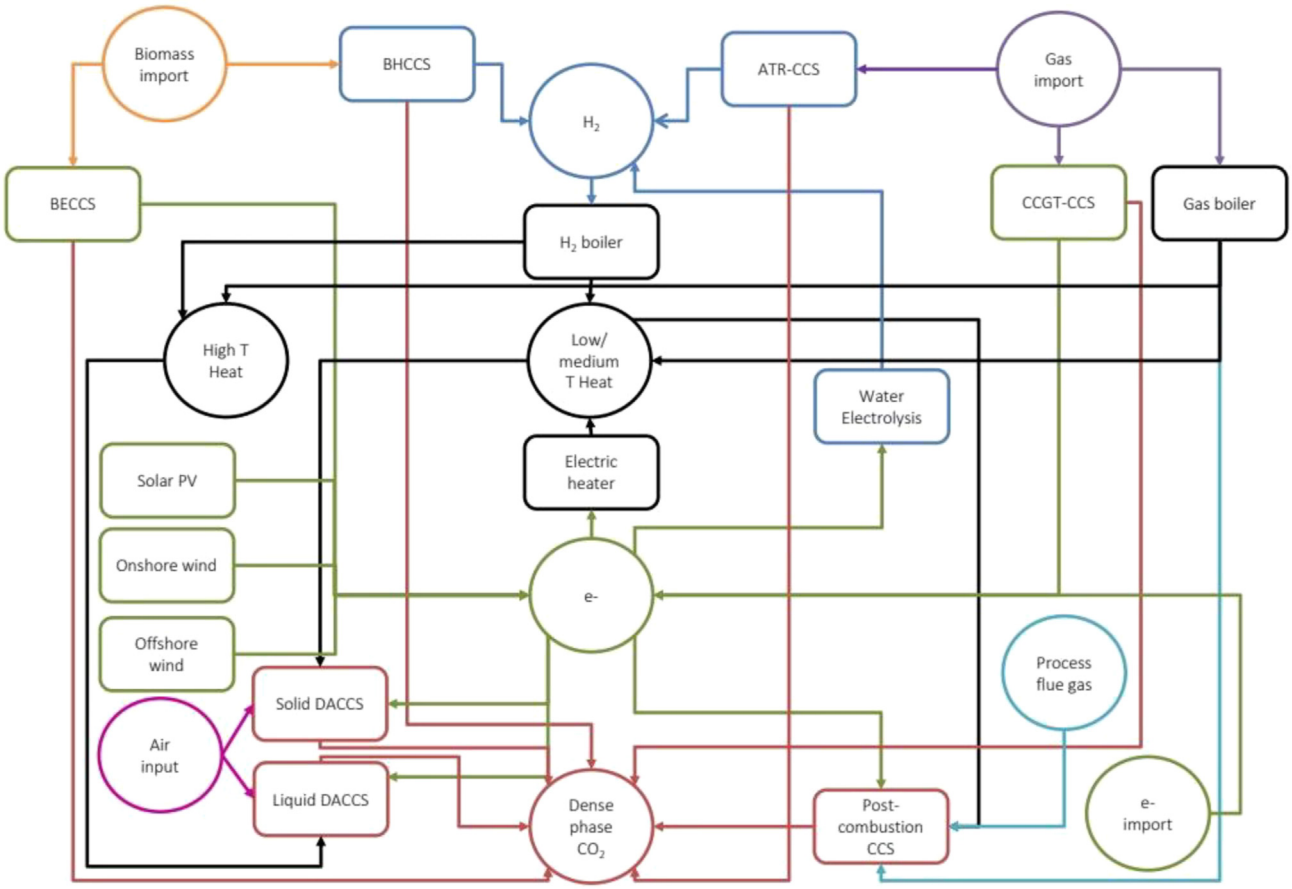


Figure 13. Analytical superstructure of industrial cluster model

scenario, no additional technology investments are needed to satisfy the demands in industry, as furnaces and heaters are already operational in sites. Thus, the overall performance of the BAU scenario is estimated using the annual natural gas consumption requirements. The KPIs used in this study measure the performance of the designed net-zero system relative to the BAU scenario.

The optimization decision variables are the following: (1) location and size of all conversion technologies illustrated in Figure 11; (2) location and size of electricity, H_2, and CO_2 storage facilities; (3) location and size of electricity, H_2, and CO_2 transport/transmission technologies; (4) operating strategy involving production, storage, and retrieval of all resources; and (5) import rates of natural gas, grid electricity, and biomass pellets. In this study, all system designs must achieve net-zero GHG emissions and heating demands, as imposed by the post-combustion CCS and DACCS technologies, where relevant.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100126.

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AUTHOR CONTRIBUTIONS

Conceptualization, S.B., M.M., N. Sunny, N. Shah, and A.H.; formal analysis, S.B., M.M., and N. Sunny; writing – original draft, S.B., M.M., and N. Sunny; writing – reviewing & editing, S.B., M.M., N. Sunny, N. Shah, C.N.M., and A.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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