ECOS 2023: How far should the UK go with negative emission technologies?

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Abstract

Negative Emissions Technologies (NETs), such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS), are potentially valuable to offset carbon emissions and therefore commonly deployed in global climate change mitigation scenarios. However, they are controversial and sometimes seen as a means of delaying or avoiding emissions reduction efforts. Nonetheless, the UK has set an ambitious target of engineering 57 Mt CO_2 per year of removals by 2050 to achieve net zero emissions[1]. This study uses the UK TIMES, technology-rich bottom-up energy system model to investigate the nationwide deployment of NETs in the energy system, while varying model parameters to provide an overview of decarbonisation in line with the UK's net zero ambitions. We investigated DACCS and BECCS NETs technologies with regards to technological uncertainties and sensitivities. We revised the TIMES model structure for NETs implementation to ensure proper integration with industry. Our analysis estimates that the UK can remove 78.5 Mt CO_2 by 2050 under the balanced Net Zero Scenario. However, by integrating an updated characterisation of removal technologies, and enabling tighter integration of DACCS into industrial clusters, we can achieve a removal capacity of up to 209 Mt CO_2 by 2050 based on our preliminary results. Additionally, a 50% reduction in DACCS cost could further increase the removal capacity to 218 Mt CO_2. This study provides valuable insights for policymakers and stakeholders in the UK and beyond, highlighting how NETs can be integrated in industrial strategy.

Keywords: DACCS, BECCS, NETs, Energy System modelling, UK-TIMES, Net-Zero

1. Introduction

The increasing concentrations of greenhouse gases (GHG) in the atmosphere due to human activities have led to the unprecedented challenge of climate change. While mitigation efforts such as reducing emissions are crucial, they alone are not enough to limit the rise in global temperatures to well below 2°C, as carbon dioxide removal scenarios are highly incorporated into modelling scenarios [2]. Negative emission technologies (NETs) have thus emerged as a potential solution to extract and store carbon dioxide from the atmosphere. Two promising NETs are Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS), which are a common feature of global climate change mitigation scenarios [1]

DACCS technologies remove carbon dioxide (CO_2) directly from the air using a chemical that selectively captures CO_2 molecules. Once the chemical is saturated with CO_2, the captured CO_2 is released and collected for processing. This process allows for CO_2 to be removed from the atmosphere and stored. DACCS can remove CO_2 directly from the atmosphere, regardless of the source of the emissions. This means that it can be used to remove CO_2 that has already been emitted, as well as to remove future emissions from sources that are difficult to decarbonise, such as aviation and shipping. DACCS technologies can be broadly classified into two categories: liquid absorbent (such as potassium hydroxide) and solid sorbents (such as amine-based solid sorbents). Liquid absorbent systems are

https://doi.org/10.52202/069564-0263

associated with high capital investment costs (CAPEX) and energy prices as they are operated at high temperatures, while solid sorbent DACCS is more sensitive to the adsorbent material costs and its performance with high CAPEX as well [3].

BECCS technologies, on the other hand, remove CO_2 from the atmosphere by using biomass production to generate energy and then capturing and storing the CO_2 emissions that are produced during the process. The CO_2 emissions produced during energy generation are offset by the CO_2 absorbed by the biomass during growth, and the captured CO_2 is stored underground, effectively removing it from the atmosphere, which can potentially provide negative emissions. BECCS technologies involve capturing CO_2 emissions from bioenergy facilities such as power plants, using carbon capture and storage (CCS) technology. The captured CO_2 is then stored underground. There are various types of BECCS systems that exist or are under development, including:

- Post-combustion capture: This technology involves capturing CO_2 emissions from the exhaust gas of a bioenergy facility after the combustion process.
- Pre-combustion capture: This technology involves converting biomass into a gas (syngas) before combustion. The CO_2 is then captured from the syngas before combustion.
- Oxy-fuel combustion: This technology involves burning biomass with oxygen instead of air. The resulting flue gas is mostly CO_2, which is then captured and stored.
- Chemical looping combustion: This technology involves using a metal oxide to react with biomass, producing a gas that is mostly CO_2. The metal oxide is then regenerated using air, producing a concentrated stream of CO_2 that can be captured and stored.

The total capacities of NETs deployed in Integrated assessment models (IAMs) show considerable variation. For example, International Energy Agency's (IEA) Net Zero scenario estimate that BECCS and DACCs can globally remove 1.9 gigatons of CO_2 globally by 2050 [4]. The National Academies of Science report [5] estimates that NETs could potentially remove around 10-20 Gt of CO_2 per year by 2050, which is equivalent to around one-third of current global emissions [6]. According to the Sixth Carbon Budget report of Climate Change Committee (CCC), DACCS and BECCS deployed in the UK can remove 57 Mt CO_2 emissions per year in 2050 in the balanced net-zero scenario [1] (Figure 1).

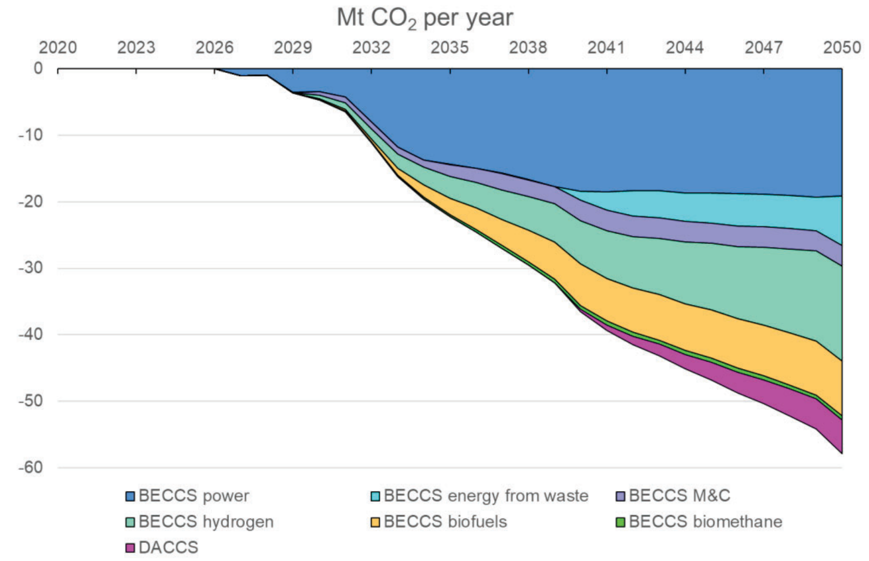

Figure 1. NETs deployment in the UK [7]

In recent years, there has been growing interest in integrating these NETs into industrial clusters in the UK. Industrial clusters are geographic regions of interconnected companies that accrue agglomeration effects from producing goods and services. By integrating NETs into these clusters, it is possible to reduce emissions from multiple sources while also generating economic benefits. Further benefits from co-locating NETs in industrial clusters include the potential availability of CCS infrastructure, potential integration of waste heat, a potentially easier permitting process, and higher social acceptance. The UK has set ambitious targets for the deployment DACCS and BECCS in its industrial clusters as part of its efforts to reach net-zero emissions by 2050.

The UK has set a target that DACCS capture up to 5Mt of CO_2 per year by 2050, and BECCS remove 22 Mt CO_2 per year by 2035 and 53 Mt CO_2 per year by 2050[1]. The government has also set a target to deploy at least two industrial-scale DACCS facility by 2025 and to scale up deployment to reach 3 million tonnes of CO_2 captured per year by 2030 and world's first zero cluster by 2050[8]. 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[9]. The government has also launched a consultation on the design of a UK Emissions Trading System and the potential inclusion of carbon removal credits, generated from NETs, which will provide a financial incentive for industries to reduce their greenhouse gas emissions and encourage the deployment of low-carbon technologies such as DACCS and BECCS.

The future energy system scenarios addressing the transition towards a Net-Zero have been carried out for UK by using the UK-TIMES model. This model is widely used for creating energy system decarbonisation pathways [10-13]. UK-TIMES covers the full energy system and is applied in this study to explore the role of DACCS and BECCS in achieving the UK's net-zero goal, particularly in offsetting industrial cluster emissions. Removal technologies are interesting not only because they appear to be crucial to the achievement of global Paris Agreement mitigation targets in IPCC scenarios, but also at a national level because they may create emissions space for some hard-to-abate industries to survive in a country, with important ramifications for "just" transitions and promoting "place-based" transitions. However, there are still challenges to overcome, including the high cost of these technologies and the need for supportive policies and regulations to encourage their deployment at scale. This paper explores the potential of DACCS and BECCS integrated into industrial clusters in the UK and assesses their potential to contribute to negative emissions targets.

2. Methodology

2.1. DACCS

DACCS technologies pulls air from the surrounding environment and passes it through a pre-filter to remove any particles or contaminants. The air is then passed through a sorbent material, which selectively captures carbon dioxide (CO_2). The sorbent material can be a solid or liquid, depending on the specific DACS system design. Once the sorbent material is saturated with CO_2, it is heated to release the captured CO_2. This process is known as desorption or regeneration, pressure-swing or moisture swing system can also be utilised. The CO_2 is released as a concentrated stream that can be captured and compressed for storage. The captured CO_2 is compressed and transported to a storage site. The CO_2 can be stored in geological formations, such as depleted oil and gas reservoirs or deep saline aquifers, where it is securely stored underground to prevent it from entering the atmosphere.

There are four different DACCS systems defined in the default UK-TIMES model. We introduced an additional four DACCS systems with updated CAPEX and OPEX cost values (see Table 1). Technologies #1,2,3 and 7 already exist in the UK-TIMES model. We changed the commodities for technology #8 to connect with industrial waste heat, to represent industrial cluster integration. The existing data was adopted from a NAS study [5]. Additionally, we introduced new technologies #4,5,6 and 7 [3]. The capacity growth of all DACCS technologies is limited to 10% per year with a five-year seed value of 1 Mt CO_2 captured and stored.

Table 1. Techno-economical characteristics of selected DACCS technologies

#	DACCS Technologies	CAPEX [£/tCO_2], 2020	OPEX [£/tCO_2], 2020	Heat Req. [GJ/tCO_2]	Electricity Req. [GJ/tCO_2]	Lifetime [yr]
1	DACCS-Liquid solvent electric CCS[5]	630.7	25.8	10.68	1.2	30
2	DACCS-Liquid solvent electric NGA CCS[5]	630.7	25.8	10.68	1.20	30
3	DACCS-Liquid solvent electric hydrogen CCS[5]	630.7	25.8	10.68	1.20	30
4	DACCS-Solid sorbent electric CCS[3]	737.9	17.5	3.94	0.84	25

https://doi.org/10.52202/069564-0263

5	DACCS-Solid sorbent electric NGA CCS[3]	737.9	17.5	3.94	0.84	25
6	DACCS-Solid sorbent electric hydrogen CCS[3]	737.9	17.5	3.94	0.84	25
7	DACCS- Solid sorbent waste heat CCS[5]	714.4	10.8	3.94	0.84	30
8	DACCS- Solid sorbent waste heat CCS w/IND[5]	1,093.2	16.5	3.94	0.84	30

Notes: CAPEX: capital investment cost; CCS: carbon capture and storage; OPEX: operational and maintenance cost; Req.: requirement.

These CAPEX and OPEX values of DACCS are attributed to the year 2020. We have assumed a 50% reduction in CAPEX and OPEX by 2050 based on Fasihi et al [14]. As the liquid solvent requires high temperature (900°C) for the regeneration in the calciner, we did allow the integration of industrial waste heat (around 150°C) [15] with this technology.

2.2. BECCS

There are different types of BECCS systems, which vary based on the type of biomass feedstock, the conversion technology, and the carbon capture and storage (CCS) method used. Some of the different types of BECCS systems include:

1. Direct combustion BECCS: This involves the direct combustion of biomass to generate electricity or heat, with the resulting CO_2 emissions captured and stored using CCS technology.
2. Co-firing BECCS: In this system, biomass is co-fired with fossil fuels in power plants to reduce greenhouse gas emissions. The CO_2 emissions from the combustion process are captured and stored using CCS technology.
3. Gasification BECCS: This involves the gasification of biomass to produce a syngas, which is then combusted to generate electricity, heat or hydrogen. The resulting CO_2 emissions are captured and stored using CCS technology.
4. Anaerobic digestion BECCS: This system involves the anaerobic digestion of organic matter to produce biogas, which can then be used to generate electricity, heat or hydrogen. The CO_2 emissions from the combustion process are captured and stored using CCS technology.
5. Pyrolysis BECCS: In this system, biomass is heated in the absence of oxygen to produce a bio-oil and a solid char to produce hydrogen. The bio-oil can be used as a fuel, while the char can be used as a soil amendment. The resulting CO_2 emissions from the combustion of the bio-oil are captured and stored using CCS technology.

Each of these BECCS systems has its own advantages and limitations, depending on factors such as feedstock availability, energy efficiency, and cost-effectiveness. The UK-TIMES model utilises five different BECCS technologies (Table 5). The technologies with techno-economic properties are given in Table 2. The capacity growth of biomass technologies limited to 10% per year with maximum 20% of biomass import growth.

Table 2. Techno-economical characteristics of selected BECCS technologies

#	Technology name	CAPEX [£/kWh]	Var. OPEX [£/kWh]	Fix. OPEX [£/kWh]	EFF [%]	Lifetime year
1	Hydrogen Biomass gasification with CCS	0.254	-	0.018	46	30
2	Hydrogen Biooil SMR with CCS	0.151	-	0.010	54	30
3	Hydrogen Waste gasification with CCS	0.321	-	0.020	41	30
4	Biomass combustion with CCS	0.321	0.003	0.015	31	25
5	Biomass combustion with CCS-retrofit	0.208	0.004	0.009	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 fix operational and maintenance cost are for the year 2020.

2.3. TIMES model generator

The Integrated MARKAL-EFOM System (TIMES) model generator is maintained by International Energy Agency (IEA)- the Energy Technology Systems Analysis Programme (ETSAP) [16] to conduct in-depth energy and environmental analysis [17]. It is used for the analyse the possible future energy system scenarios [18]. The TIMES model is a bottom-up approach that uses a single or multi-regional model with a technology-rich database to analyse and plan energy systems at the national, regional, or city level. It is a techno-economic, partial equilibrium model-generator that assumes perfectly competitive markets and perfect foresight. Its source code, written in GAMS, is available for free download upon signing an ETSAP Letter of Agreement. In this study, we use the UK-TIMES which is built using the VEDA system (developed by UCL Energy Institute [19]) and it is now being utilised by His Majesty's Government departments to inform their climate policy analysis, including the 6th Carbon Budget [1].

The UK-TIMES model is a representation of the technology and fuel options available for various energy-consuming sectors when working towards the goal of decarbonisation. The decisions about these options are determined by what is the most cost-effective while taking into account various constraints that reflect the characteristics of the system. The model considers various factors, including the need to balance the supply and demand of energy over different periods of time, restrictions on the rate of technology deployment, and the availability of resources. One major advantage of this approach is that it trades off action between sectors, and captures interactions between sectors, allowing for more informed policy decision making. The UK-TIMES is structured in eight sectors, divided into three supply side and five demand sectors. The supply side consists of resources and trade, processing and infrastructure, as well as electricity generation transmission and distribution. The demand sectors include residential, services, industry, transport and agriculture. All sectors are calibrated based on the energy balance of the UK in the base year of 2010, and takes into account the existing portfolio of energy technologies in the Reference Energy System (RES). The UK-TIMES has flexible time periods and provides results for five-year periods until 2060. It consists of a total of 16 time-slices, with each of the four seasons being represented by a typical day divided into four time-slices.

The model aims to minimise the total system costs (least-cost solution), which includes investment cost, fixed and variable operation and maintenance cost, import cost, and export revenues for all modelled processes. The capacity of a particular technology remains until the end of its technical lifetime, and its salvage value is subtracted from the objective function if its economic lifetime goes beyond the modelling horizon. The inputs used to develop the UK-TIMES include exogenous service demand curves, supply curves, policies, and techno-economic parameters for each technology. Supply curves show the quantities of primary energy resources or imported commodities available at a specific cost. Techno-economic parameters are assigned to available and future technologies, including transformation and demand technologies. Technical parameters include efficiency and availability factor, while economic parameters include investment costs and interest rates. Policies may include the effects of legislation such as taxes and subsidies on specific technologies or fuels.

The outputs of TIMES models are region-specific and time-specific optimal investments, operations, and import/export levels. The model output includes not only the optimal solution but also costs, environmental indicators, marginal prices of commodities, and energy flows. UK-TIMES models both energy- and non-energy-related CO_2, CH_4, N_2O and HFC emissions, although non-CO_2 GHGs have not been explicitly considered in this study. Overall, the UK-TIMES VEDA model is a comprehensive tool for exploring different pathways to integrate DACCS and BESS into the UK's industrial clusters, providing insights into the costs, feasibility, and trade-offs associated with different options. In this study we have three main scenarios:

1. The default model runs: exploring the update of NETs without updates on technology characterisation.
    - We run the model with existing DACCS and BECCS technologies, including their techno-economic characteristics as described in sections 2.1 and 2.2.
2. The model runs where solid sorbent DACCS is integrated into industrial clusters.
    - We introduced four additional DACCS and integrated solid sorbent DACCS into industrial clusters, considering the low heat demand from industry/
3. The cost sensitivity of NETs deployment

https://doi.org/10.52202/069564-0263

- We changed the CAPEX of DACCS by ±50% to evaluate the cost sensitivity of DACCCS employment as well as NETs.

3. Results and discussion

3.1. Default results from the UK- TIMES model

Results show that 78.5 Mt CO_2 can be captured by DACCS and BECCS in the UK by 2050 under the balanced Net Zero Scenario (see Figure 2). The default DACCS (liquid solvent powered by electricity, electricity and gas, hydrogen; solid sorbent powered by waste heat from electricity generation without integration into industrial clusters) and BECCS (biomass incinerated gasification combined cycle (IGCC); hydrogen generation from biooil gasification with CCS; biomass gasification with CCS; waste gasification with CCS; electricity generation from biomass combustion with CCS) technologies are used to produce these results. In 2050, the most important technologies are:(1) hydrogen generation from biomass gasification with CCS, (2) solid sorbent DACCS, (3) hydrogen generation from waste gasification with CCS, and (4) biomass combustion with CCS for electricity generation following. The liquid solvent powered by electricity DACCS contributes the least to NETS.

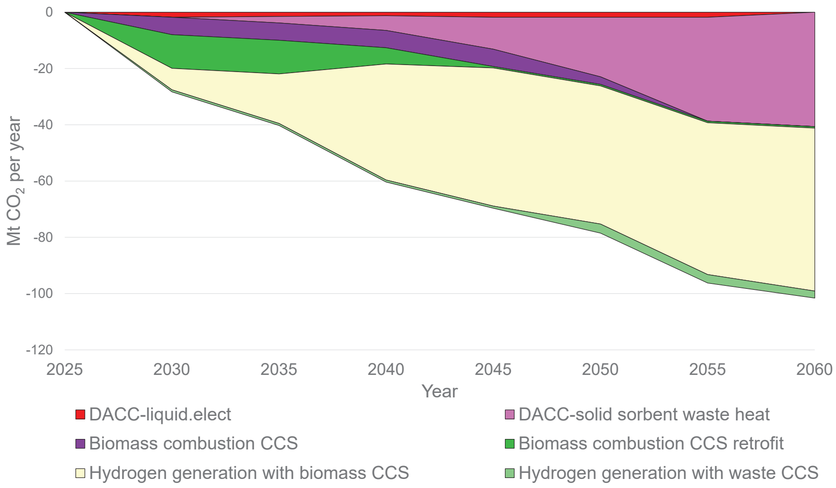

Figure 2. *NETs results from existing UK-TIMES model for Net Zero Balanced scenario*

According to the Net Zero balanced scenario, total positive CO_2 emissions would be 65 Mt CO_2 if DACCS, BECCS and natural negative emissions as well as industrial emissions sequestration are not taken into account (see Figure 3 for a breakdown of emissions by sector). It is evident that the positive emissions remain within the system, and it is not feasible to achieve the net-zero goal without the deployment of NETs, especially hard-to-abate sectors such as heavy industry, transportation, aviation and shipping. These sectors typically emit a large amount of greenhouse gases and require innovative and effective solutions to reduce their emissions and transition to a low-carbon economy.

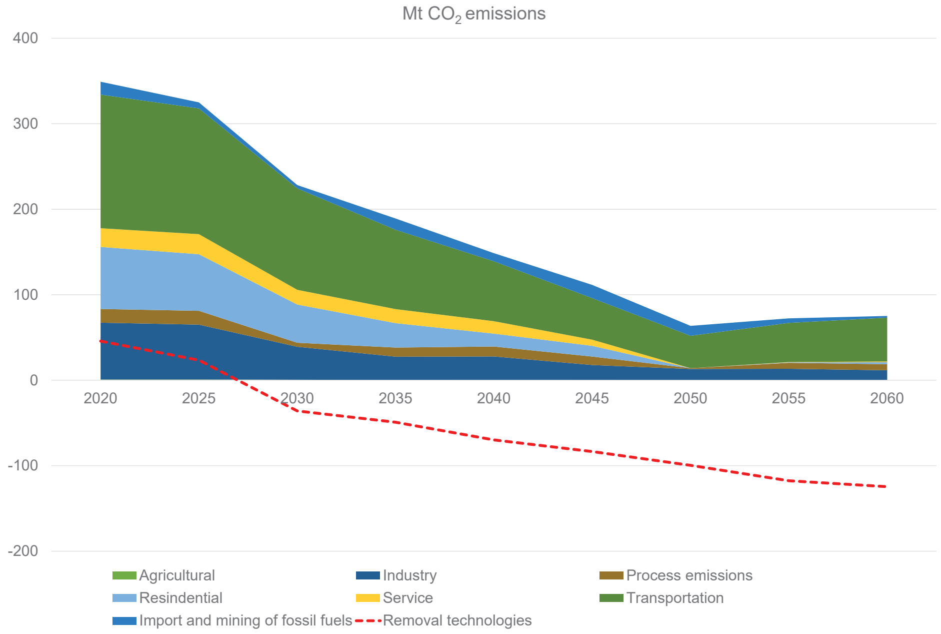

Figure 3. *Total CO_2 emissions from different sector in the UK.*

3.2. DACCS technologies integration into industrial clusters

According to Figure 2, the two leading DACCS technologies are solid sorbent waste heat DACCS and liquid solvent DACCS powered by electricity (as shown in Figures 2 and 3a) in the Net-Zero Balanced scenario. The UK-TIMES has not chosen other liquid solvent DACCS technologies powered by natural gas & electricity and hydrogen due to least-cost solution. In addition, we have included three other solid sorbent DACCS technologies, namely solid sorbent DACCS powered by electricity, natural gas & electricity, and hydrogen. Furthermore, we have explored the option of solid sorbent DACCS powered by low heat from industrial clusters, including the chemicals, food and drink, non-metallic minerals sectors, and other industrial low heat, in addition to waste heat from electricity generation processes.

We have found that DACCS can capture 22.9 Mt CO_2 by 2050 and up to 40.7 Mt CO_2 by 2060, mainly through the use of solid sorbent technology (as shown in Figure 4a), in the case where this DACCS is not integrated with industrial waste heat. There are 2 TWh (for 2050) to 19 TWh (for 2040) of low-grade heat available from industry that can be utilised in the DACCS system. By integrating solid sorbent DACCS with this available low temperature heat from industrial clusters, DACCS potential increases up to 180 Mt CO_2 by 2050 (Figure 4b) based on our preliminary results. Hence, the integration of DACCS technologies into industrial clusters can provide a fourfold increase in CO_2 removal in a net-zero scenario.

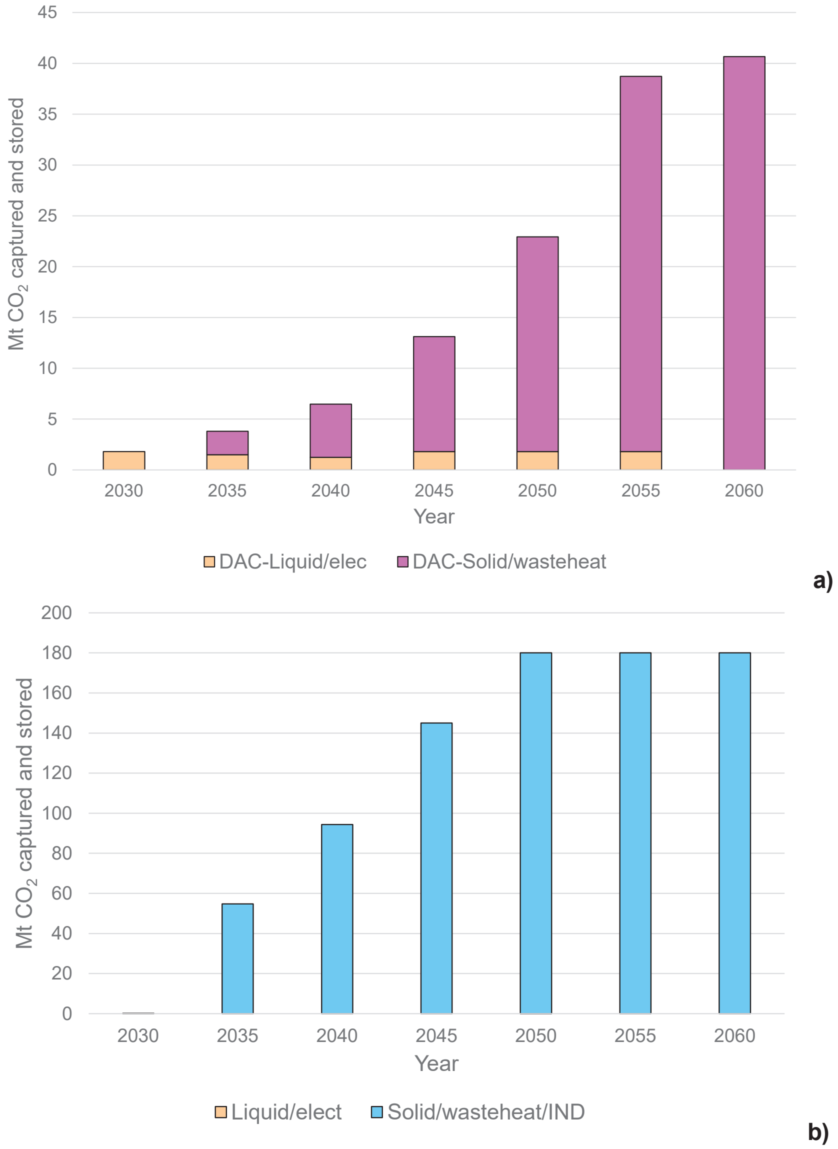

Figure 4. *DACCS technologies changes over time.* ***a)*** *Default results from Net-Zero Central scenario without industrial integration* ***b)*** *DACCS solid sorbent was integrated with industrial low heat. The same cost values are applied in both scenarios.*

It is important to note that increasing the deployment of DACCS will result in an increase in total positive CO_2 emissions (increase to around 178 Mt CO_2 in 2050) almost all sectors, primarily from the industrial, transport and process sectors due to the space created by NETs (see Figure A1 in the appendix). However, even though positive emissions will increase by 2.8 times, the integration of solid sorbent DACCS into the industry will provide a fourfold increase in CO_2 removal amount.

3.3. CAPEX cost impact on NETS

We have also explored the impact of capital cost (CAPEX) on the deployment of DACCS, given the uncertainty in the cost of DACCS in both the short and long term [3]. We varied the CAPEX by ±50% to estimate the amount of CO_2 that can be captured economically (as shown in Figure 5). When we increased the CAPEX, liquid solvent DACCS became less favourable, as CAPEX makes up a larger share of the total cost compared to solid sorbent DACCS technologies. As we decreased the CAPEX, liquid solvent DACCS was still utilised but to a lesser extent than solid sorbent which is integrated to industrial low heat. Although the model includes DACCS options with and without industrial integration (as listed in Table 1), solid sorbent DACCS with integration of waste heat from industrial clusters is the dominant technology. When we decreased the CAPEX, we could increase the amount of captured and stored CO_2 up to 180.4 Mt by 2050. A 50% decrease in CAPEX resulted in a 7% increase in the capacity for CO_2 removal, whereas a 50% increase in CAPEX decreased the CO_2 removal capacity by 21%.

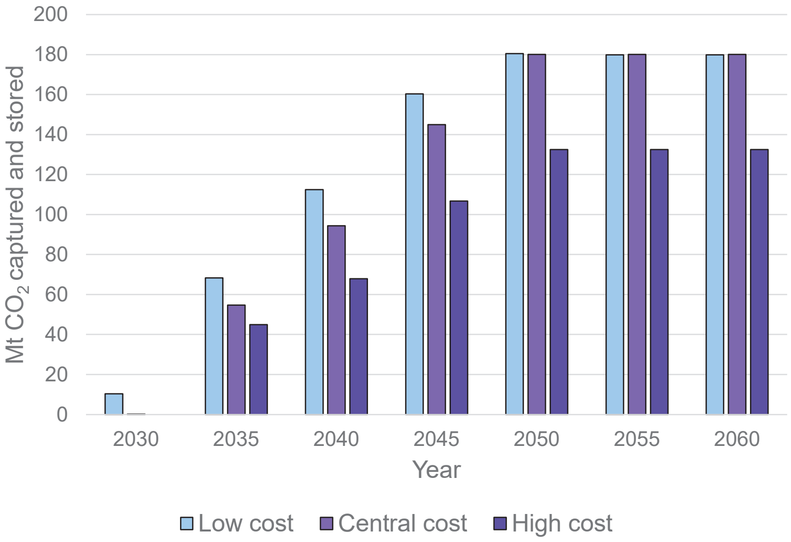

Figure 5. *The impacts of DACCC capital costs on DACCS capacity. The low cost and central scenarios utilise solid sorbent DACC with industrial waste heat integration and liquid solvent electricity powered DACCS. The high-cost scenario only considers the solid sorbent DACCS with industrial cluster integration.*

We have also assessed the overall NETs removal amount based on the range of DACCS CAPEX. A 50% decrease in DACCS CAPEX increases the total NETs removal capacity up to 219 Mt CO_2 by 2055 and 218 Mt CO_2 by 2050 (as shown in Figure 6). This removal capacity is expected to further increase as the BECCS CAPEX also decreases.

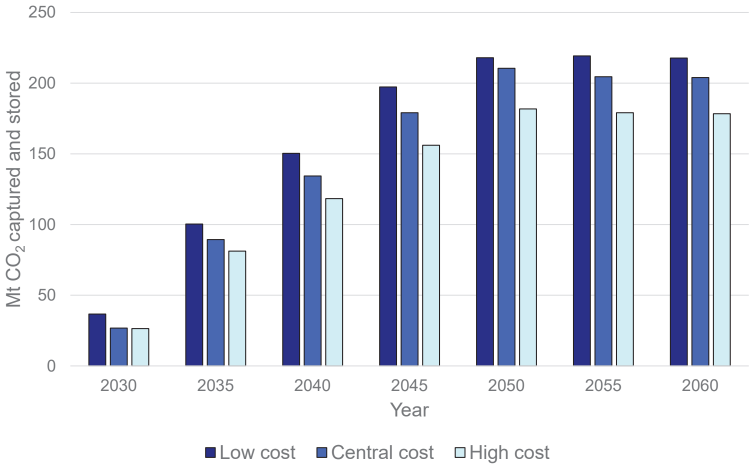

Figure 6. *The impact on DACCS's CAPEX on overall NETs deployment*

https://doi.org/10.52202/069564-0263

4. Conclusion

This study demonstrates the potential of Negative Emissions Technologies (NETs) to help achieve the United Kingdom's net zero ambition by 2050, with a particular focus on Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS). By integrating additional NETs into industrial clusters and reducing costs, it is possible to significantly increase CO_2 removal amount from the atmosphere. Our findings indicate that solid sorbent DACCS powered by waste heat, ideally industrial low-temperature heat, is the leading DACCS technology. We also discovered that by integrating the solid sorbent DACCS into industrial low heat and reducing the CAPEX of DACCS by 50%, NETs can remove up to 219 Mt CO_2. We anticipate that lowering the CAPEX of BECCS will further increase this removal capacity. Our study underscores the importance of investing in and expanding NETs to combat climate change and achieve a sustainable future. These insights are of great value to policymakers and stakeholders in the UK and beyond.

5. Acknowledgements

This work was supported by the UK Engineering and Physical Research Council (EPSRC) through the Integrated Development of Low-Carbon Energy Systems (IDLES) programme [grant number EP/R045518/1].

6. Appendixes

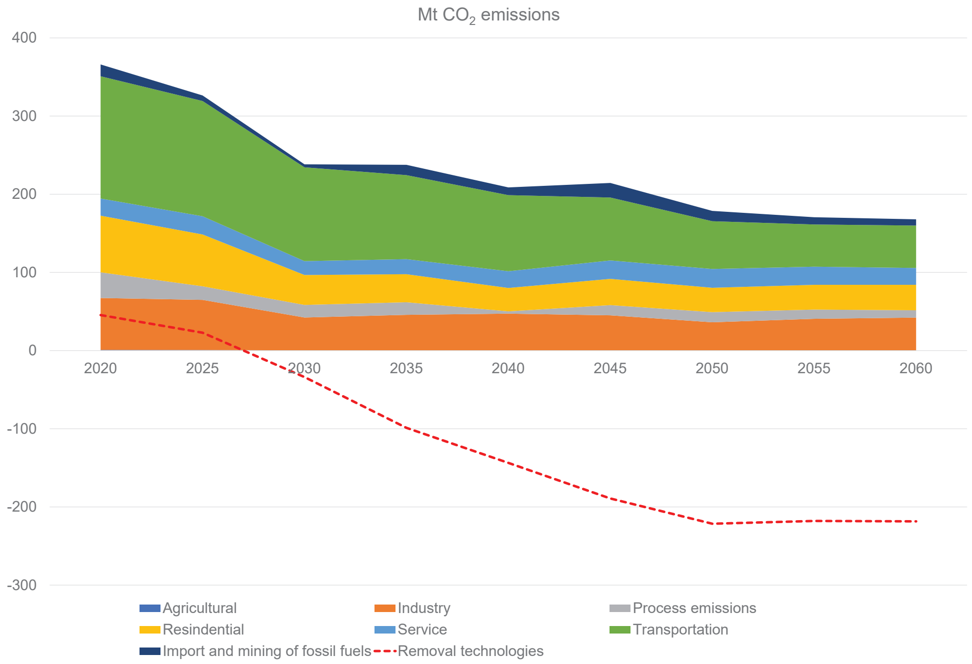

Figure A1. *Total positive CO_2 emissions when DACCS is integrated into industrial clusters.*

7. Nomenclatures

BECCS: Bioenergy carbon capture and storage
BEIS: Department of Business, Energy and Industrial Strategy
CAPEX: Capital investment cost
CCC: Climate Change Committe
CCS: Carbon capture and storage
DACCS: Direct air carbon cpture and storage
ETSAP: Energy Technology Systems Analysis Programme

GHG: Greenhouse gas
IEA: International Energy Agency
IND: Industry
MARKAL-EFOM: MARKet Allocation - Energy Flow Optimization Model
NETs: Negative Emission Technologies
OPEX: Operational and maintenance cost
RES: Reference energy system
TIMES: The Integrated MARKAL-EFOM System
UK: United Kingdom
VAR: variable

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