

EIRO - Direct Air Carbon Capture & Storage (DACCS)

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Abbreviations

ASHP	Air source heat pump
ATR	Autothermal (methane) reformer
BECCS	Bioenergy with carbon capture & storage
CCC	Climate Change Committee
CCGT	Combined cycle gas turbine
CCS	Carbon capture & storage
DACCS	Direct air carbon capture & storage
DHN	District heat network
ESC	Energy Systems Catapult
ESME	Energy Systems Modelling Environment
GHG	Greenhouse gas
GPU	Gas permeance unit
GSHP	Ground source heat pump
HT	High temperature
ICE	Internal combustion engine
IGCC	Integrated gasification and combined cycle
LNG	Liquified natural gas
LT	Low temperature
MCA	Monte Carlo analysis
MOF	Metal organic framework
MPa	Mega Pascal
NCS	Norwegian continental shelf
PC	Pulverised coal
PV	Photovoltaic
SMR	Small modular reactor / steam methane reformer
SNG	Synthetic natural gas
TRL	Technology readiness level
TTF	Title Transfer Facility
UKCS	UK continental shelf
UKTM	UK TIMES Model
WP	Work package
Zeb	Zeebrugge

1. Executive Summary

The UK is committed to achieving net zero by 2050. Various models and projections have been produced by independent groups (including Energy Systems Catapult) as to how this commitment can be achieved. Consistent across those produced to date is that greenhouse gas removal (GGR) or negative emissions technologies are essential to achieve net zero in the UK by offsetting residual, or hard to abate, emissions in certain sectors of the UK economy.

Several negative emissions technologies exist in various stages of development. Two of the most well-known technological approaches are bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Each has seen significant development over the last decade, with many start-up technology developers emerging in the space and looking to deploy their technologies at scale in the coming years.

The purpose of this study was to assess the status of DACCS technologies and their potential role in achieving net zero emissions by 2050. It examines the current technological characteristics of DACCS, assessed energy and network needs, and brought these together in a modelling exercise to interpret their role in the energy transition.

Several companies and manufacturers are developing and promoting different types of DAC technology, each with their own nuances. All have the same core characteristic of passing air over a “medium” which captures CO₂. This medium can be liquid sorbents, solid sorbents, membranes, or metal organic frameworks. Once captured, CO₂ is separated for onward use or storage by a regeneration process, separating the CO₂ from the storage medium. Regeneration requires the largest amount of energy and is where DAC technologies can be differentiated by energy used. Typically, an 80/20 rule can be applied to DAC energy use with 80% applied to heat for the regeneration process and 20% for the electricity requirement (e.g., running fans). The DAC regeneration process can be placed in three categories based on the process and temperature required (Figure 1.1); high temperature (>600°C), medium temperature (300°C – 600°C), low temperature (<300°C). Current innovations require in the region of 1700-2500kWh of energy per tonne of CO₂ captured. Long-term development is directed towards processes that use either only electricity, including for heat, or a combination of electricity and low-grade waste heat.

Commercial scale deployment of DACCS has not yet been achieved but there are several projects in the pipeline. Globally some of these are of significant scale¹. A notable benefit of DACCS is its modularity which enables scale to be built over time. Many of the proposed projects are scheduled to scale incrementally. Small module sizes mean DAC plants are deployable anywhere with a relatively modest footprint and energy requirement where carbon use is desired. Storage of CO₂ from DAC necessitates siting close to CO₂ storage access (shipping or piped infrastructure). Projects which utilise DAC for carbon use are also in the work, however this is not the focus of this work. Where projects in proposal exist,

¹ <https://www.carboncapture.com/project-bison>
es.catapult.org.uk

they typically converge around 0.5-1 MtCO₂/yr facility. Once these “first generation” DACCS sites are operational, it may emerge that a different size of facility is desirable.

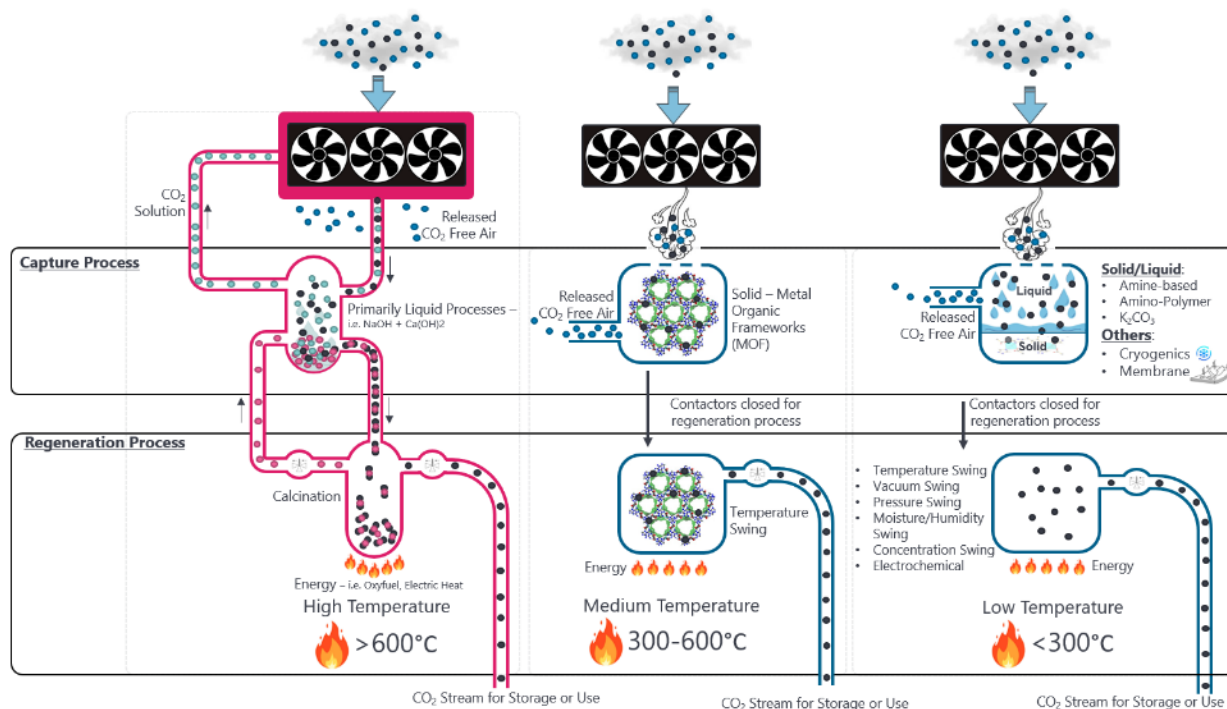


Figure 1.1: DAC plant types characterised by regeneration process temperature.

Sites for a 1 MtCO₂/yr DACCS facility would require around 80-100 acres, but this would be highly dependent on DAC configurations. Developers of low temperature DAC with a regeneration temperature in the 80-130°C range have identified waste heat from industry or power generation as a suitable source which could satisfy some or all their heat demand. Industrial clusters represent an attractive option for DACCS deployment, particularly in early years, due to waste heat availability and proposed CCS infrastructure.

Assessment of the infrastructure requirements and costs of DACCS required new methodologies. These methodologies were based on proximity to waste heat sources, electrical sub-stations, and indicative CO₂ pipelines routings around the industrial clusters.

Modelling was performed using ESC's in-house, whole energy system model, Energy Systems Modelling Environment (ESME) and the ESME Infrastructure Toolkit. To evaluate the role DACCS could play in the UK's transition to net zero.

ESME is a multi-regional model, allowing the broad features of transmission and distribution of energy across the UK to be assessed. However, only limited information at finer granularity is integrated. ESME Infrastructure Toolkit was used to overcome some of ESME's limitations related to spatial resolution and provide insights related to energy network infrastructure. The ESME Infrastructure Toolkit contains a series of modules, each of which has several processes that represent different types of infrastructure within each network type. ESME Infrastructure Toolkit disaggregates ESME outputs, which address national outcomes, to a local level (MSOA or LA). The new siting methodology employed, enabled the propagation of results from ESME through to ESME Infrastructure.

A deterministic reference case scenario was developed and agreed with DESNZ. The reference case, although not a “true net zero scenario” in that it fails to meet the 2050 target by approximately 2Mt, acted as a starting point for the Monte Carlo simulations that followed.

To evaluate the role of DACCS, subject to uncertainty, six batches of 100 simulations were performed, drawing upon ESME’s built in Monte Carlo functionality. Batches differ in that each one assumes different constraints on deployment of DACCS, general CCS infrastructure and recoverable waste heat from nuclear gen III plants. The Monte Carlo runs are summarised below in Table 1.1.

Table 1.1 - Description of Monte Carlo batches used in the whole system modelling.

Batch	DACCS	CCS	Waste heat from nuclear
1	No delay	No delay	Yes
2	5-year delay	No delay	Yes
3	10-year delay	No delay	Yes
4	No delay	5-year delay	Yes
5	No delay	10-year delay	Yes
6	No delay	No delay	No

1.1. Conclusions

1. Net zero is dependent on the capacity for the system to create negative emissions. Negative emissions from biomass and DACCS in the order of **75MtCO₂** are needed from a combination of these sources to make net zero possible. This is in addition to approximately 45Mt of negative emissions from other sources such as forestry and energy from waste with CCS. Therefore, total negative emissions in the order of 120MtCO₂ are needed to make net zero possible.
2. **In all system solutions DACCS plants are deployed to the maximum deployable capacity.** There is a clear priority order:
 - DACCS plants that utilise waste heat are deployed first
 - Natural Gas fuelled DACCS plants are next to be deployed
 - Net Zero systems then deploy hydrogen fuelled DACCS plants whilst non-compliant systems deploy high temperature DACCS
3. DACCS is an important source of negative emissions much needed to counteract emissions from difficult to decarbonise sectors such as agriculture, aviation and industry.
4. DACCS could be a useful option to hedge against slow adoption of low carbon behaviours across society (e.g., reduction in flights abroad) or in the event that innovative technologies in key sectors do not emerge (e.g., zero carbon aircraft).
5. **Biomass remains critical in achieving net zero but high capacities of DACCS influence where it gets used.** Net zero compliant systems with high capacities of DACCS

prefer to divert biomass away from hydrogen production (via gasification with CCS) to BECCS power. DACCS then takes advantage of additional waste heat from these BECCS plants. Gas price also affects the decision to produce hydrogen from biomass in net zero systems with higher gas prices prompting BECCS hydrogen production and lower gas prices seeing more hydrogen production through reformation (with CCS) and biomass diverted into power production.

6. Large waste heat sources are favoured as the primary source of waste heat for DACCS plants. Nuclear generation III plants and other large power producers are good options, especially where consistent grid baseload is delivered to maximise uptime and CO₂ stored.
7. To reduce new build infrastructure and grid reinforcement costs, larger and fewer DACCS sites are favoured. Leading to very large DACCS sites co-located with waste heat sources. The optimal solution for the reference case, was to build 3 large DACCS plants by 2050. ~9MtCO₂ /yr site coupled with Sizewell, ~8MtCO₂ /yr site at Hinkley and a ~4MtCO₂ /yr site at Hartlepool. Sourcing all energy requirements, heat and electricity on site.
8. Land requirements could become a constraint for large sites, especially in the UK, although they are not unrealistic elsewhere. Facilities in the 9MtCO₂/yr range would require 720-900 acres of land. Plants of this size may be feasible. Project Bison² in Wyoming is planned to capture 5MtCO₂/yr by 2030. Land areas of this amount being repurposed for future energy infrastructure in the UK are also possible. The proposed solar farm at Botley West is around 1400 hectares³. However, there are nuances to each low carbon project that must be considered i.e. land used for solar panels could still be used for other purposes.
9. Waste heat availability from sources other than nuclear is uncertain. As industry decarbonises and implements new process solutions waste heat could reduce. Efficiency could improve or waste heat streams could be redirected to other on-site needs such as carbon capture plants.
10. In system solutions without waste heat offtake availability from nuclear, waste heat DACCS remains the priority DACCS technology deployed. However, the amount of waste heat available to the system is significantly reduced. This impacts the overall amount of waste heat DACCS that can be deployed.
11. If DACCS is not able to utilise nuclear waste heat, waste heat from Power BECCS and Energy from Waste with CCS plants provides a good alternative.
12. In net zero compliant systems, with high availability of DACCS and biomass, biomass is diverted from hydrogen production into power generation, which becomes another key source of waste heat and enables maximum deployment of waste heat DACCS.
13. Delaying DACCS or CCS infrastructure rollout has the following impacts:
 - If delays to DACCS rollout lead to a reduction in the total amount of DACCS that can be deployed in 2050, then compliance with net zero is at risk.

² <https://www.carboncapture.com/project-bison>

³ <https://www.carboncommentary.com/blog/2023/1/12/c1d9rhg8s4j3t88vdkqi5d26epwpfd>
es.catapult.org.uk

- Delays to CCS infrastructure do not necessarily put net zero at risk provided that DACCS deployment rates are quick enough to deliver sufficient negative emissions in 2050.
- Delays to CCS do affect the wider energy system, particularly the amount and method of hydrogen production. This has knock-on effects on the DACCS technology choices made, with high temperature electric systems being preferred to hydrogen fuelled plants.
- Increases in electricity consumption by DACCS plants are offset by savings made in other sectors as a result of emissions headroom created by DACCS reducing pressure to maximise decarbonisation of aviation, residential & commercial heating, hydrogen production and road transport.

1.2. Recommendations for further work

1. Data Collection:

- a. Energy Systems Catapult will publish and make the input data publicly available from this project. Keeping this data up to date with revised technical data and cost projections should remain a focus. This is an important step as the first large-scale plants become operational over the next 5 years.
- b. Large industry energy users are a viable option for DACCS co-location. Limited data exists on industrial waste heat availability and how this will evolve over time as sites implement new processes and decarbonise.

2. National Strategy

- a. This study hasn't considered the need for constant CO₂ store injection rates. DACCS will have a role to play and could be used as "flex" option within the CO₂ injection stream.
- b. Assess DACCS use with Small Modular Reactors (SMR) and other distributed nuclear options.
- c. Investigate the siting and sizing required for distributed DACCS/DACCU (CO₂ use). What if much smaller DAC plants are deployed? What impact might this have on a CCS network requiring multiple small connections? How feasible is it to provide the network connections (electricity, CO₂ and/or waste heat) for a distributed DACCS system? Deeper consideration of waste heat integration at industrial clusters, e.g. infrastructure needs and costs when recovering waste heat from multiple sources and sites for DACCS facilities, as well as the cost-saving potential when connecting a smaller than 1 MtCO₂ /yr DACCS facility directly to a distribution network.
- d. A more detailed analysis of land and infrastructure needs for DACCS, factoring in, for example, detailed pipeline and grid connection routings and considerations, current land use and other locational factors that may impact the viability of deployment, etc.

3. DAC Integration

- a. DACCS/DACCU could provide electricity grid flexibility options. Making use of potentially curtailed renewables. DAC could compete with other grid flexibility options for the same resources to create useful zero carbon products (CU) or

store CO₂ (CS). This is an area of interest that was also noted by some technology developers.

- b. Further investigation into DACCS co-location options with power plants. What are the practicalities for integrating with nuclear sites, BECCS sites, Energy from Waste? Some of these “ideal” sites exist today and could be used to develop roadmaps for integration.
- c. The focus of this project was on DAC technologies for CO₂ capture and permanent storage. However, many technology developers are also considered utilisation options for CO₂, for example in the food and beverage sector or in eFuels together with hydrogen. These areas would reduce the need for fossil CO₂ emissions but would at most be net carbon neutral. There may be interest on the impact of these technologies versus their current fossil fuel equivalents.

2. Introduction

The Climate Change Act commits the UK government to achieve net zero greenhouse gas emissions by 2050. Various models and projections have been produced by independent groups as to how this commitment can be achieved, and the technologies required to do so. Consistent across the scenarios and projections produced to date is that greenhouse gas removal or negative emissions technologies are likely to be essential for achieving net zero, to offset residual emissions or hard to abate emissions in certain sectors of the UK economy.

Several negative emissions technologies exist in various stages of development. Perhaps the two most well-known technological approaches are bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). With BECCS, energy crops or forestry materials are used in bioenergy conversion technologies (e.g., for electricity, hydrogen, or biofuel production) with the CO₂ emissions arising from the respective processes captured. As this CO₂ is from biogenic sources, captured from the atmosphere by the feedstock during growth, the capture and storage of this CO₂ thus leads to net negative emissions. There are trade-offs and concerns around this approach, largely around the land needs to grow sustainable feedstock. DACCS technologies on the other hand capture CO₂ directly from ambient air. They have seen significant development progress over the last decade, with many start-up technology developers emerging in the space and looking to deploy their technologies at scale in the coming years.

Energy Systems Catapult (ESC) was commissioned by DESNZ to study the status of DACCS technologies and their potential role in achieving net zero emissions by 2050. This study looked at the current technological characteristics of DACCS, an assessment of energy and network needs, and modelling activities to elucidate their role in the energy transition at the whole systems level, and infrastructure and siting considerations for their deployment.

2.1. Project Overview & Work Packages

The project was divided up into the following work packages (WPs):

- WP1: Technology & Resource Assessment
- WP2: Energy & network Assessment
- WP3: ESME Modelling
- WP4: ESME Infrastructure Toolkit

WP1 focused on the fundamental characteristics and resource needs of the technologies. WP2 considered these needs in the context of the national needs for DACCS (heat, electricity, land, etc) and the potential co-location opportunities that may exist (e.g., with industrial clusters). WP3 uses ESCs proprietary model ESME (Energy Systems Modelling Environment)⁴ to perform a Monte Carlo analysis of DACCS technologies and their potential role in meeting the UK's net zero target by 2050. WP4 uses a further proprietary

⁴ <https://es.catapult.org.uk/tools-and-labs/our-national-net-zero-toolkit/energy-system-modelling-environment/>
es.catapult.org.uk

model ESME Infrastructure Toolkit⁵, to consider in greater detail the infrastructure needs and costs of DACCS if deployed at large scale. Each of these models require technology and resource data to create representative DACCS pathways for the whole UK energy system, with this data being gathered under WP1 and WP2. This report discusses the methods and outputs of each work package and considers them as a whole.

⁵ <https://es.catapult.org.uk/tools-and-labs/our-national-net-zero-toolkit/esme-networks-model/es.catapult.org.uk>

3. WP1: DACCS Technology Assessment

3.1. Background

Negative emission technologies have been widely recommended as an important solution for global GHG emissions reduction. A variety of negative emission technologies have been proposed which can be natural, engineered or hybrid based on the capture method used. Figure 3.1 shows a list of seven negative emission technologies classified by implementation, interaction with the environment and CO₂ storage. The afforestation and reforestation, soil carbon sequestration, biochar, bioenergy with carbon capture and storage, and ocean fertilisation options use photosynthesis to capture CO₂ from air.

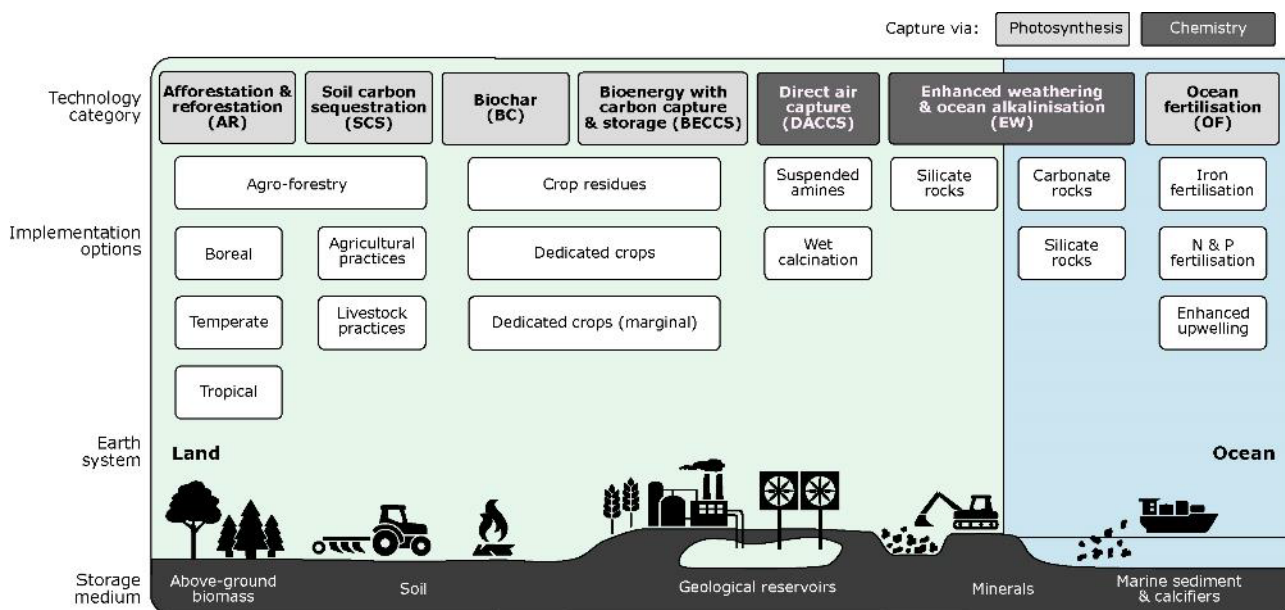


Figure 3.1: Types of negative emission technologies. Image from (Minx, et al, 2018).

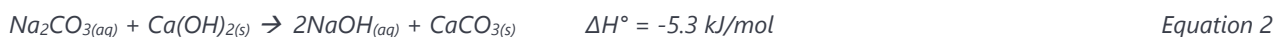
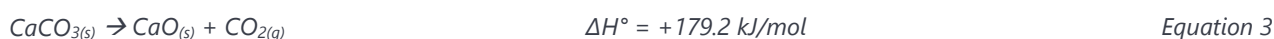
DACCS is a fully engineered solution for carbon removal and storage. CO₂ removal from air was first studied by Spector and Dodge (1946) in 1940s using alkaline sorbents. DAC was commercialised in the 1950s as a form of pre-treatment for cryogenic air separation and in the 1960s the captured CO₂ was used as feedstock for synthetic hydrocarbon fuel production. In 1999, Lackner et al. (1999), first suggested CO₂ capture from ambient air as means of reducing ambient CO₂ concentration. Since then, numerous DAC technologies have been proposed, or are in varying stages of development and deployment. Across sections 3.2.1-3.2.4, the main types of DAC technologies are summarised, followed by a categorisation approach for DAC technologies in section 3.2.5, which have been adopted for the subsequent modelling and analysis in this work.

3.2. DACCS technology characterisation

3.2.1. Liquid sorbents

Zeman and Lackner (2004) presented the thermodynamic feasibility of liquid DAC technology using aqueous alkaline hydroxide solution. In their process, CO₂ from air is absorbed by sodium hydroxide (NaOH) forming sodium carbonate (Na₂CO₃). The

carbonate ion is later removed from the solution by calcium hydroxide (CaOH), forming precipitates of calcium carbonate (CaCO₃), which is then filtered from the solution and thermally disintegrated in a calciner at around 900°C to release CO₂ as gas. The remaining lime (CaO) is hydrated to form Calcium Hydroxide. The chemical reactions for this whole process are shown in Equations 1-4.



In 2005, David Keith demonstrated liquid DAC technology at pilot scale. Keith founded Carbon Engineering in 2009 to develop and commercialise DAC mainly based on an aqueous alkaline solution. An article published by Carbon Engineering in 2018 (Keith, Holmes, St. Angelo, & Heidel, 2018) describes their DAC process using potassium hydroxide solution (KOH) at pilot scale and provides its performance based on energy consumption and costs. Carbon Engineering's DAC process is designed to use either both renewable electricity and natural gas (with carbon captured) or just renewable electricity to meet the energy requirements. The designs require either 1458 kWh_{th} of natural and 366 kWh_{el}, or 2447 kWh_{th} of natural gas per ton of CO₂ captured at a levelized cost of 94-232 \$/tCO₂.

The sorbent regeneration is the most energy intensive step in liquid DAC technologies. To overcome this issue, electrochemical regeneration routes were proposed where alkali carbonate is supplied to a bipolar membrane electrodialysis stack with acidic and basic compartments separated by anion-exchange membrane (Sabatino, et al., 2020). Alkali hydroxide is regenerated in the basic compartment and CO₂ is released in the acidic compartment as gas. This process can work entirely on renewable electricity, thus eliminate additional CO₂ emissions related to heat use. One of the biggest challenges here is the high membrane material cost which makes Carbon Engineering's technology economically more attractive. Another evolving technology involves an electrochemical cell with H₂ recycling and a cation-exchange membrane and is believed to have even lower energy consumption than the prior two discussed (Shu, Legrand, Kuntke, Tedesco, & Hamelers, 2020). However, this technology is yet to be demonstrated experimentally.

3.2.2. Solid sorbents

Solid sorbent DAC is the second major type of DAC technology currently under development. In this approach, air at atmospheric conditions is forced across a solid sorbent where CO₂ is adsorbed (McQueen, et al., 2021), at the exothermic stage. Once saturated, CO₂ is released by sealing the sorbent chamber, removing air under a vacuum, and then heating the sorbent to desorb and release the CO₂, during an endothermic stage. This heating typically occurs at temperatures of 80-120°C, dependent on the sorbent. Technology developers frequently propose the use of low-grade waste heat or low-grade steam as the heat source, and more broadly that the energy requirements of the process

should be supplied fully via renewable energy sources. The solid sorbent varies per technology developer, but a common option is amine sorbents such as those used by Climeworks and Global Thermostat, albeit with different sorbent support materials (Sanz-Pérez, Murdock, Didas, & Jones, 2016). A variety of support materials may be used for the amine sorbent, e.g. silica, nanocellulose or metal organic frameworks (MOFs; see also section 3.2.4) (Elfving, Bajamundi, & Kauppinen, 2017), though the specific formulation of the sorbent and support typically remains proprietary to the developer.

The most widely known developers of solid sorbent technologies are Climeworks and GlobalThermostat, both of which have been developing their respective technologies since around 2010 (McQueen, et al., 2021).

3.2.3. Membranes

Due to the very low concentration and partial pressure of CO₂ in the air, membrane-based technologies were considered unsuitable for DAC. However, recently membranes have gained attention as DAC technology with development of polymeric materials with high CO₂ permeance. Teflon-based defect-free membranes and free-standing Siloxane nanomembranes showed a high CO₂ permeance of ~31,500 GPU (gas permeance unit) and over 40,000 GPU, respectively (Yoo, et al., 2018; Fujikawa, Ariyoshi, Selyanchyn, & Kunitake, 2019), making it easier to capture CO₂ from air efficiently. Membrane-based DAC or m-DAC has comparatively lower energy consumption and easier construction and operations. Fujikawa et al. (2021) studied the performance of organic polymer membranes through process simulation and found the energy requirement for vacuuming to be between 17.29 to 12.29 kWh/kgCO₂/day for a CO₂ selectivity of 30-50 and a pressure ratio of 50. m-DAC technologies work more efficiently indoors, such as in lecture theatres and concert halls, where CO₂ concentrations are higher than ambient. With new technologies capable of using low-purity CO₂ in electrochemical conversion processes to produce CO, the CO₂ purity from m-DAC can be kept low at ~40%. Thus, reducing the overall energy requirement for m-DAC.

The Dutch research institute TNO founded a spin-off called Carbyon in 2019 to develop m-DAC technologies. Carbyon's technology applies a fast-swing process by using rotating drum containing amine-based thin film adsorbing fibre membrane for CO₂ capture (Carbyon, 2022). This setup requires 1000 kWh to capture per ton of CO₂, which is a significant energy saving compared to other DAC technologies. The system has a capex of circa £21/tCO₂ captured and is expected to reduce the overall capture cost below £42/tCO₂ with future developments.

A California based firm called Carbon Capture is developing molecular sieves using Zeolite for DAC (CarbonCapture Inc., 2022). In their process, ambient air after dehumidification enters a reactor containing zeolites which adsorbs CO₂. Once saturated, the reactor is depressurised to create a vacuum along with simultaneous heating. This releases the captured CO₂ from the zeolite.

3.2.4. Metal-organic frameworks (MOFs)

Metal–organic frameworks (MOFs) are considered attractive for gas separation due to their large pore volumes, high surface area and tuneable pore size. From DAC technology perspective, they can offer lower heats of adsorption of around 45-70 kJ/mol compared to over 200 kJ/mol for heat of reaction of liquid sorbents and calcination. There have been several findings that underlined the possible merits of adsorption route for DAC using MOFs. Kulkarni et al. tested TRI-PE-MCM-41 adsorbent for CO₂ capture and found that depending on the sources of electricity used, an operating cost up to \$100/tCO₂ captured can be obtained (Kulkarni & Sholl, 2012).

MOFs like MIL-101-(Cr) (Darunte, Oetomo, Walton, Sholl, & Jones, 2016) and Mg₂(dobpdc) (McDonald, et al., 2012) (dobpdc⁴⁻ = 4,4-dioxido-3,3-biphenyldicarboxylate) have high pore volume, fast kinetics, high selectivity and capacity which makes them exceptionally suitable for DAC. MOF-based DAC technologies are still at an early stage of development with TRLs around 2-4.

3.2.5. **Technology characterisation summary**

There are a variety of ways by which DAC technologies could be classified or grouped, with several different approaches presented in prior literature, such as:

- The physical state (solid or liquid) of the sorbent material used.
- Sorbent regeneration method.
- Process temperature.
- Number of process cycles etc.

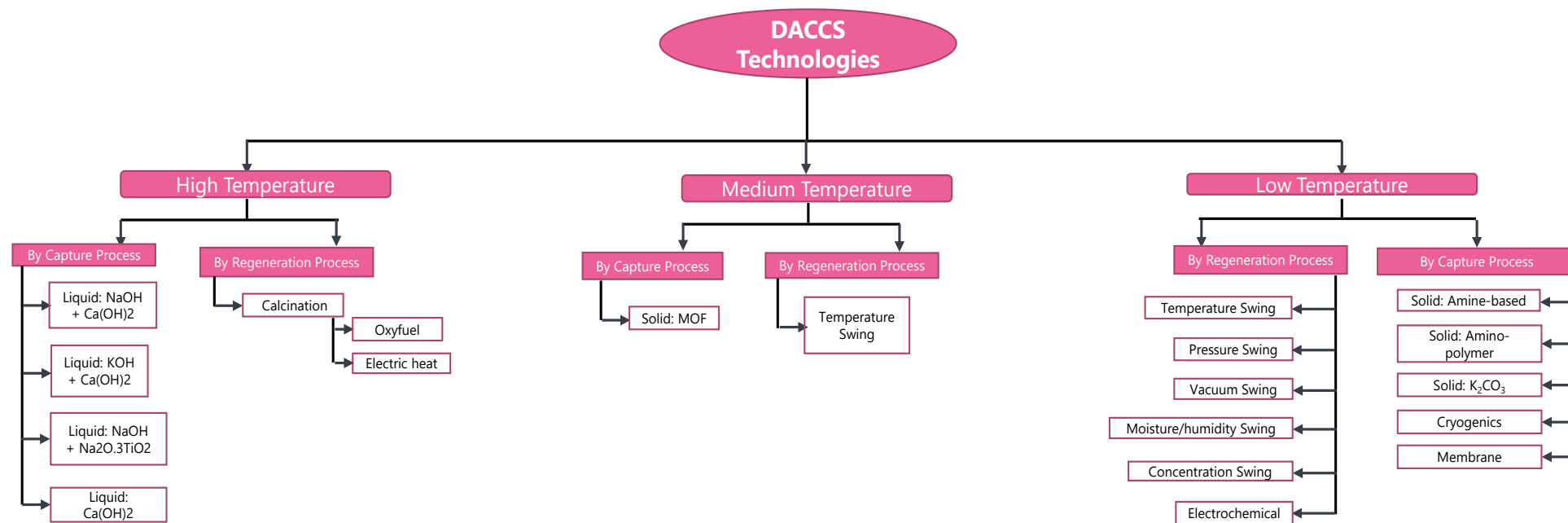


Figure 3.2: Characterisation of DAC technologies.

In this project, ESC has used process temperature as the main characterisation criteria, as shown in Figure 3.2. Further sub-categories as shown in Figure 3.2, e.g., sorbent state, regeneration method etc. The temperature ranges for high, medium, and low temperature categories are as follows:

- High Temperature: >600°C
- Medium Temperature: 300 – 600°C
- Low Temperature: <300°C

It is noted that most of the liquid DAC technologies found in our review operate at temperatures around 850-900°C. This is the temperature of the calciner in the secondary cycle, where CO₂ is obtained as gas for storage or utilisation. Hence, the high temperature classification only consists of liquid DAC technologies. The solid DAC technologies operate at temperatures around 100°C and therefore fits into low temperature category. The vast majority of DAC technologies in development fall under either the high or low temperature category, with some exceptions like MOF-based DAC, where maximum process temperatures are in the medium temperature range.

3.3. DACCS technology data

Alongside the characterisation and categorisation of DAC technologies, state-of-the-art technical and economic data was gathered to be used in WP2, 3 and 4. This data was gathered from publicly available sources: industrial reports, articles, and peer reviewed academic literature. Table 3.1 shows the type of data collected along with its source, notes of the process and challenges, and the confidence in the data.

Table 3.1: Type of data collected and their sources.

Type of Data	Source	Data Collection Summary	Confidence in Data
Technology descriptions, process operating conditions, and any other key engineering criteria not listed below	Industrial reports, academic literature, company news articles/websites, stakeholder engagement	A large number of technologies and developers were identified through our thorough literature review. However, DACCS is a very active area of development with new technologies and technology developers emerging regularly. Therefore, there is a chance that some very early-stage technologies or developers were not captured due to lack of literature.	High
Costs	Industrial reports, academic literature,	Various cost projections for DAC technologies, when scaled up, are available in	Medium

Type of Data	Source	Data Collection Summary	Confidence in Data
	company news articles/websites	academic and industrial literature. Developers typically quote future targets for levelized cost of capture of around \$100 per tonne CO ₂ , with the cost reductions in the projections driven by the modularity of their solution and/or economies of scale. However, at present there are no large-scale facilities (e.g. 1MtCO ₂ /yr) in operation with firm costing data. Therefore, whilst a wide range of costing data has been gathered, there is still the open question as to whether these projections can be achieved when large-scale deployment begins.	
Energy consumption	Industrial reports, academic literature, company news articles/websites	A good range of energy data (heat, electricity) was acquired for the different DAC technologies. This encompasses both current consumption and projected future consumption.	High
Other resources	Industrial reports, academic literature, company news articles/websites	Data of water usage was available for a variety of technologies and to a high quality. For land, estimates for large scale deployment are more limited, and a representative value from Carbon Engineering was used as they appear to be the developer closest to a large scale deployment of their technology (1MtCO ₂ /yr capture).	High
TRL	Industrial reports, academic literature, ESC evaluation	TRL data for the different solutions offered by technology developers was	High

Type of Data	Source	Data Collection Summary	Confidence in Data
		determined through academic and industrial literature, as well as ESC's internal judgement when comparing the commercial status of the different offerings.	

3.4. DAC resource requirements

A summary of the low and high estimates for electricity, heat, water and land requirements for low temperature (LT), high temperature (HT), HT Electrified and Electrochemical DA is presented in Table 3.2 as a point of reference. The bounds are based on the collated DA technology data. These ranges were then applied in the energy and network assessment (WP2; section 4).

As can be seen from Table 3.2, DAC technologies require substantial resources per tonne of CO₂ captured, largely in the form of energy as heat. As McQueen et al. (McQueen, et al., 2021) summarise, there is an "80/20" rule of thumb for liquid and solid sorbent DAC, which is 80% of the energy input as heat for temperature swing regeneration and the remaining 20% as electricity for fans and supporting equipment. Current DAC technologies require in the region of 1700-2500kWh of energy per tonne of CO₂ captured.

Energy requirements can be met with renewable electricity generation and waste heat sources. Both of these energy sources were highlighted in literature and in conversations with technology developers. It has been noted in our review that the long-term development of DAC technologies is directed towards processes that use either only electricity, including for heat, or a combination of electricity and low-grade waste heat. A summary of energy sources for DAC is given in Table 3.3.

Table 3.2: High and low resource bounds for different DAC technologies, used in the energy and network assessment (WP2).

DAC Type	Criteria	Units	Low	High
LT DAC	Electricity Demand	kWh/tCO ₂	200	300
LT DAC	Heat Demand	kWh/tCO ₂	1500	2000
LT DAC	Water Demand	t/tCO ₂	-0.8	-2
HT DAC	Electricity Demand	kWh/tCO ₂	77	366
HT DAC	Heat Demand	kWh/tCO ₂	1458	2447
HT DAC	Water Demand	t/tCO ₂	4.7	4.7
HT Electrified DAC	Electricity Demand	kWh/tCO ₂	1500	1500
HT Electrified DAC	Heat Demand	kWh/tCO ₂	0	0
HT Electrified DAC	Water Demand	t/tCO ₂	4.7	4.7
Electrochemical	Electricity Demand	kWh/tCO ₂	631	2209

DAC Type	Criteria	Units	Low	High
Electrochemical	Heat Demand	kWh/tCO ₂	0	0
Electrochemical	Water Demand	t/tCO ₂	0	0
All (assumed)	Land for a 1 MtCO ₂ /yr DAC Facility	Acres	80	100

Table 3.3: Summary of the suitability of energy sources for DACCS.

Source	Comments
Renewable Electricity	<ul style="list-style-type: none"> Can satisfy process electricity & heating requirements. Can be used in off-grid or off-shore scenarios. Assets can be developed specifically for DACCS facilities. Will substantially increase overall land/area requirements for DACCS.
Renewable Heat	<ul style="list-style-type: none"> Geothermal heat sources can supply heat needs for low temperature DACCS facilities; an approach currently used in the Climeworks ORCA project in Iceland. Solar heaters or concentrators can generate temperatures of up to 300°C, suitable for low temperature and some medium temperature DACCS technologies
Waste Heat	<ul style="list-style-type: none"> Industrial sectors such as iron and steel, chemicals, cement, and food & drink have large sources of low-grade waste heat for which they currently have no use. Low grade heat would be suitable, in some cases with upgrading, for low temperature DACCS technologies. Effective and economical use of waste heat would be the main challenge, e.g., source(s) of the heat, routing and distance to DACCS facility, etc.
Nuclear Energy	<ul style="list-style-type: none"> Small modular reactors can be tuned to produce the desired quantity and quality of heat for low to high temperature DAC technologies. Rolls Royce have been actively exploring SMRs for DAC.
Fossil Fuels with CCS	<ul style="list-style-type: none"> Fossil fuel systems with CCS are an option for DACCS where renewables may not be suitable, e.g., land area need, cost. Carbon Engineering has studied the feasibility and performance of oxyfuel combustion of natural gas with CCS for their solvent-based high temperature DAC system.
Hydrogen	<ul style="list-style-type: none"> Blue or green hydrogen can be used as an energy source or as a raw material for producing synthetic fuels utilising the captured CO₂. Hydrogen burns with a very high flame temperature and therefore, is technically feasible for all ranges of DAC systems from low to high temperature.

3.5. Support schemes for DAC development and deployment

During our literature review, and discussions with technology developers, we also considered government support schemes available for DAC development and deployment. The UK government, principally via DESNZ (BEIS at the time), currently runs innovation support schemes for DAC technologies such as the DAC and other greenhouse gas removal technologies competition (Department for Business, Energy and Industrial Strategy, 2022). The UK government is also developing support mechanisms for greenhouse gas removals⁶.

In recent months, the USA has begun offering large scale support for DAC deployment. The Bipartisan Infrastructure Law will enable \$3.5bn of funding to support four large scale direct air capture hubs (US Department of Energy, 2022). This level of funding would likely enable large scale demonstration, e.g., potentially millions of tonnes of capture capacity across the hubs, and would appear to enable multiple technology developers to demonstrate and deploy their solutions at each hub. In conversations with one technology developer, they stated that the USA appeared to be a leader in wanting to enable large scale demonstration and deployment of DAC technology. Moreover, the Inflation Reduction Act (ArentFox Schiff, 2022), another recently passed piece of legislation by the USA, provides amongst other things up to a \$180/tonne tax credit for CO₂ captured and geologically stored via DAC, or up to \$130/tonne for CO₂ capture via DAC and used in a "qualified manner". This is a revision to the pre-existing "45Q" tax credit for carbon sequestration. With regards to usage, a second technology developer focused on utilisation applications stated that in some cases, the financials for DAC were close to being viable versus other CO₂ sources, however, some form of smaller operational subsidy would be needed to push the deals over the line. It would appear likely that some DAC plus CO₂ utilisation use cases may become more viable in the USA with the increased 45Q credit under the Inflation Reduction Act.

⁶ <https://www.gov.uk/government/consultations/greenhouse-gas-removals-ggr-business-models>

4. WP2: Energy and Network Assessment

4.1. Methodology and data sources

4.1.1. Site requirements for DACCS

To assess energy and network requirements for DAC, the “per tonne CO₂” resource needs were to be scaled to reflect large-scale facility needs and create an indicative initial analysis. The low and high resource requirements (Table 3.2) for DAC were scaled to a 1MtCO₂/yr DACCS facility size, as this is the size to which current DAC technology developers are looking to scale their technology. For example, Carbon Engineering is currently developing a 1MtCO₂/yr DACCS facility in the Permian Basin (USA) and are looking to develop a 0.5-1MtCO₂/yr facility in Scotland (ACORN project) as noted in the appendix (section 9.1)9.1. Once these “first generation” DACCS sites are operational, it may emerge that a different size of facility is more preferable as a benchmark, though for now a 1MtCO₂/yr facility appears a reasonable benchmark.

As additional high-level assessment of national scale requirements was made using projections of DACCS needs (i.e. MtCO₂ DACCS capacity) from Element Energy (2021) (2050 DACCS scenarios) and CCC 6th Carbon Budget (2050 DACCS scenarios) (Climate Change Committee, 2020). This national analysis is shown in the Appendix (section 9.2). Note that this is largely superseded by the results of WP3, as this initial assessment was based upon current resource needs at a national level, rather than future projections.

4.1.2. Waste heat availability at industrial clusters

DAC technology developers, especially those developing LT solutions with regeneration temperatures in the 80-130°C range, have identified that waste heat sources may be suitable to satisfy some (with upgrading) or all their heat demand. HT DAC solutions have regeneration temperatures (~900°C) that are typically too high for there to be any viable matching waste heat source that isn't already recovered and reused by the source industrial process.

Industrial clusters have previously been identified as potential sites for CCS infrastructure. “Track-1” clusters will see active development over the forthcoming years; these being projects in the East Coast Cluster and the HyNet Cluster (BEIS, 2021; DESNZ, 2023). Moreover, clusters all have some availability of waste heat due to the variety of industrial processes present at each. Therefore, they were identified as a good option for the co-location of DACCS facilities, particularly for deployment in earlier years.

Data on UK industrial waste heat availability only went down to sector level availability, e.g., iron & steel, chemicals, etc. Four studies had looked at UK wide industrial waste heat, and their overall estimates are tabulated in Table 4.1. These studies all had slightly different approaches, assumptions, and sector coverages.

Table 4.1: Estimates of UK industrial waste heat from different studies.

Study	Waste Heat Estimate (GWh/yr)
Albert et al (2022)	47,300
Element Energy (2014)	48,000
McKenna & Norman (2010)	10,000-20,000
Papapetrou et al (2018)	25,000

Of these studies in Table 4.1, the estimates of McKenna & Norman (2010) and Element Energy (2014) were taken forward as these were viewed as the better quality studies. It should be noted that even though these were considered better quality, there are still significant differences in the sector level estimates made by each. The detailed data is shown in Table 4.2. There are significant differences to iron and steel estimates, and a lack of oil refining estimates by McKenna & Norman (2010). Therefore, these differences will naturally impact the estimated availability of waste heat for DACCS.

Table 4.2: Estimates of waste heat by sector made by Element Energy (2014) and McKenna & Norman (2010). The Element Energy (2014) value here is the technical potential for recovery, whereas the value shown in Table 4.1 was the overall waste heat potential.

Industrial Sector	Element Energy (2014) (TWh/year)	McKenna & Norman (2010) High Recovery (TWh/year)	McKenna & Norman (2010) Low Recovery (TWh/year)
Iron & Steel	0.35	10.28	5.14
Chemicals	2.79	2.77	1.40
Cement	0.39	1.93	0.99
Ceramics	0.03	0.27	0.16
Glass	0.53	1.40	0.69
Food & Drinks	1.04	0.83	0.43
Paper & Pulp	0.24	0.56	0.28
Oil Refining	3.6	N/A	N/A
Total	8.98	18.04	9.07

As waste heat estimates were only available to sector level, these values had to be adjusted to estimate cluster level waste heat availability. To do this, it was assumed that CO₂ emissions scale with waste heat availability. This is a rough, high-level assumption. The basis was that higher CO₂ emissions are likely to result from higher energy inputs and/or higher levels of product output (e.g., cement), therefore would have higher levels of waste heat availability. Of course, this is not strictly true, as differences in emissions data time periods, processes, current decarbonisation technologies, and/or levels of waste heat recovery will break this relationship. However, given the lack of more granular data, this was identified as the best possible approach. Sector level emissions data from various sources 2012-2019 was combined with cluster level emissions from Annex 3 of the

Industrial Decarbonisation Strategy (2021) to calculate the percentage of each sectors emissions at each cluster. These percentages were then multiplied by the national sector level waste heat estimates in Table 4.2, to find the TWh of waste heat by sector at each cluster. These values were then summed for each cluster to produce a single cluster estimate of waste heat availability. The results of this, in the context of a 1MtCO₂/yr DACCS facility, are discussed in results section 4.2.2.

4.1.3. Power generation waste heat

Power generation was also considered as a waste heat source for LT DAC. Similar to industrial waste, various estimates exist for power generation waste heat availability. Element Energy (2014) estimated 58TWh of waste heat from power generation from cooling water sources. Albert et al (2022) estimated 346TWh from all possible sources, including those currently widely recovered and reused (e.g. flue gas heat used for preheating air and water) and sources that are unlikely to be recoverable (e.g. solar). Albert et al (2022) provided a detailed breakdown of their estimate by sector, and this is further discussed in results section 4.2.3.

4.1.4. Waste heat quality and future availability

A key criterion when assessing waste heat usage is the quality/grade of heat, and whether it would be suitable for the purpose. LT DAC applications were the focus when assessing suitability for waste heat. These have regeneration temperatures in the 80-130°C range depending on the specific technology. Therefore, many low-grade sources of waste heat would be suitable, in some cases with upgrading. This was confirmed by reviewing a list of waste heat sources and temperatures previously prepared by Element Energy (2014).

A further consideration is the future availability of waste heat sources. Different sectors and processes will have different decarbonisation pathways, and the implementation of these may change the availability of waste heat. The potential impact of this, at a sector level, is discussed in section 4.2.4.

A final point of note is the heterogeneity of waste heat sources in industrial processes. They may arise at different parts of processes in spatially different areas. Therefore, confirming the realistic viability of recovering the various waste heat sources for DACCS would require detailed study of sites.

4.2. Energy and network assessment results

4.2.1. Example 1MtCO₂/yr DACCS facility

Resource requirements for a 1MtCO₂/yr DACCS facility are shown across Figure 4.1 (electricity), Figure 4.2 (heat), Figure 4.3 (water), and Figure 4.4 (size/land). Looking first at Figure 4.1 and Figure 4.2, it should be noted that fully electric solutions (HT Electrified, Electrochemical) have no heat requirements. In the case of the former, heat is supplied electrically, whilst electrochemical DAC has no heat requirement at all. Electrified HT DAC is at present a speculated future development. Heat requirements for LT DAC could of course, in theory also be supplied electrically, though as noted many technology

developers suggest waste heat as a promising vector to fulfil some or all of the heat demand.

A further point to highlight is that there is an 80/20 “rule of thumb” for DAC, which is that 80% of the energy demand is for heat (e.g., regeneration) and the remaining 20% for electricity (e.g., fans) (McQueen, et al., 2021). Therefore when viewing Figure 4.1 and Figure 4.2 together, it is evident that for a 1MtCO₂/yr DACCS facility, a total energy consumption of around 2TWh/yr would be a reasonable estimate in all except the highest cases. On a similar note, the large range associated with electrochemical DACCS electricity demand shows promise if this technology can achieve the “low” electricity consumption in the future. At present, the low TRL pilot-scale solutions if scaled to 1MtCO₂/yr would be close to the high case of ~2.2TWh/yr (Mission Zero Technologies, 2022), which is similar to the combined heat and power consumption of the other solutions.

Figure 4.3 shows water requirements. HT DAC have the highest demand, though in discussions with one HT DAC technology developer it was noted that this water could be brackish water – it does not need to be potable water. The LT DAC water consumption value is negative. This is based on the Climeworks process which is a net water producer. Therefore, there may be potential to balance water demand at a site if a mixture of DACCS technologies is used. More broadly, other LT DAC and Electrochemical DAC technologies quote negligible or evaporative water losses only, which would of course be significantly lower than HT DAC demands. To put water demands into perspective, Thames Water supplies 2.6bn litres of water a day (~2.6 million tonnes) (Thames Water, 2022). Therefore, demands of close to 5Mt (billion litres per year) for HT DAC are feasible amounts, and again do not have to be potable water quality. There may be future co-benefits to locating DACCS facilities with coastal nuclear sites, to tie together energy and water needs, though these do not seem to have been considered by developers at present.

Figure 4.4 provides a visual representation of the land requirements for a DAC facility, with an area of ~100 acres marked at a cluster which is the upper end of requirements for current generation DAC facilities. In discussions with technology developers, requirements may vary from 80-100 acres at present though should reduce in the future. Some site variation will always be apparent due to altitude and climate affecting contactor design.

One final point of note is that these resource estimates – electricity, heat, water and land – do not factor in needs for electricity generation, heat supply, or CO₂ compression, transport and storage. Requirements for these could be quite significant in some cases, e.g., land requirements if a wind farm is built primarily to supply a DAC facility. An additional point of note is that these resource estimates are based on current data, and resource needs are projected to decrease into the future with further DAC technology development.

Electricity Requirements - Reference 1MtCO₂/yr DAC site

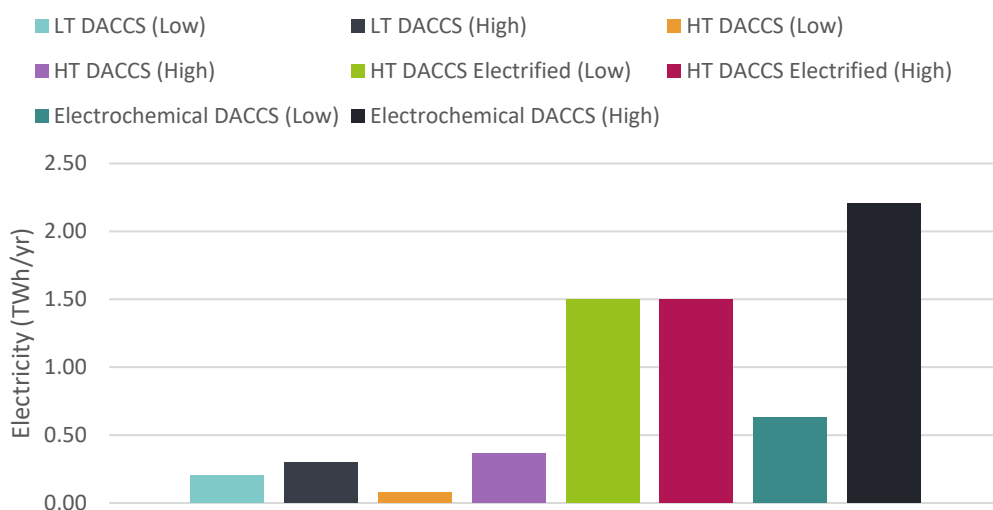


Figure 4.1: Electricity requirements for a 1MtCO₂/yr DACCS facility for various DAC technologies.

Heat Requirements - Reference 1MtCO₂/yr DAC site

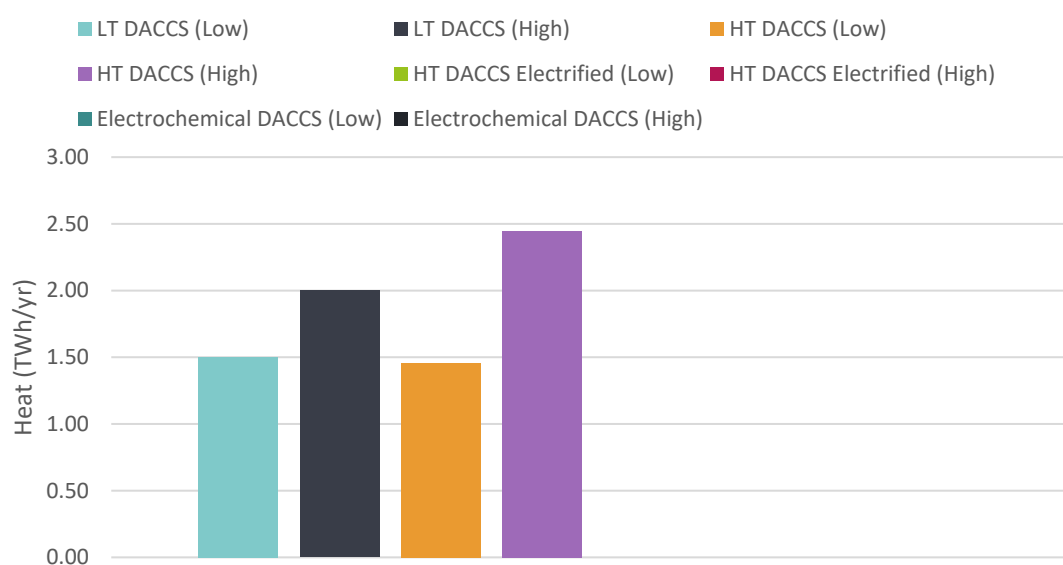


Figure 4.2: Heat requirements for a 1MtCO₂/yr DACCS facility for various DAC technologies.

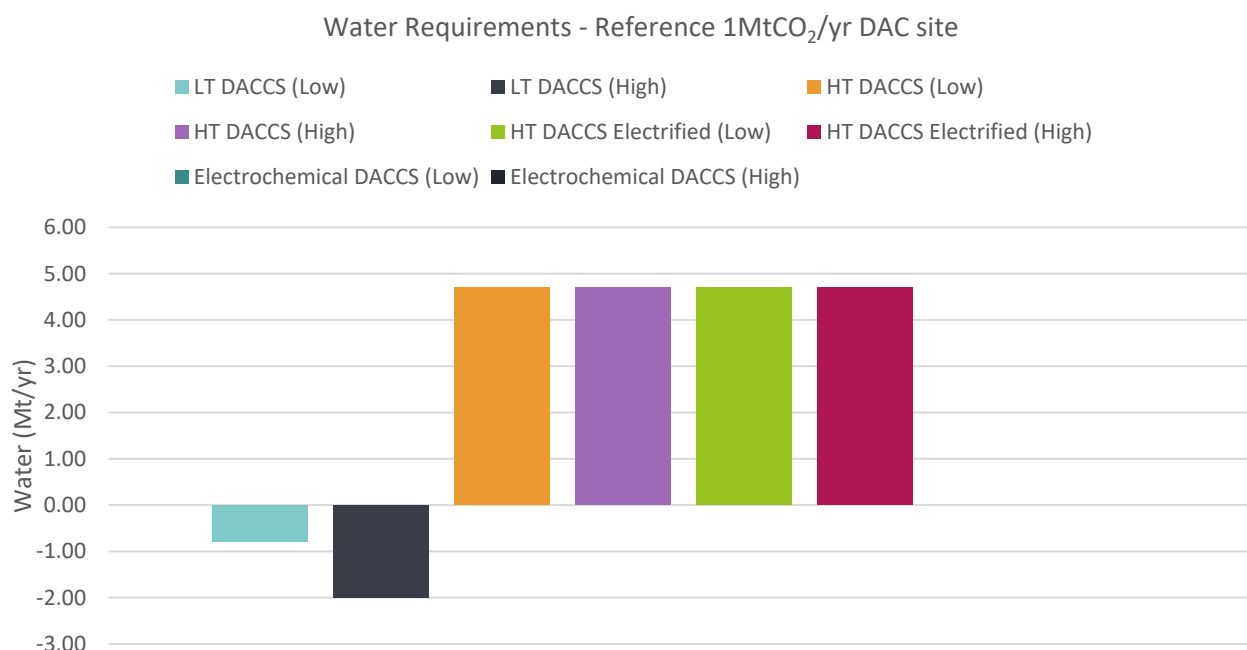


Figure 4.3: Water requirements for a 1MtCO₂/yr DACCS facility for various DAC technologies.



Figure 4.4: Example of size and land requirements for 1MtCO₂/yr DACCS facility. Top left & bottom left: renders of Carbon Engineering DACCS facility. Renders produced by Carbon Engineering (Carbon Engineering, 2021; Leah Burrows, 2018). Right: Example ~100 acre plot marked out in red at the Wilton International site in the Teesside cluster). Image from Wilton International (Wilton International, 2023).

4.2.2. Industrial cluster waste heat availability

The estimates for waste heat availability at each cluster, together with the low and high heat requirements for a 1MtCO₂/yr LT DACCS facility, are shown in Figure 4.5. Waste heat estimates at each cluster are also shown in Table 4.3.

As is evident, the original differences in waste heat estimation by Element Energy (2014) and McKenna & Norman (2010) have propagated through. McKenna and Norman (2010) have far higher estimates at Humberside and South Wales, due to the large iron and steel industries in these areas and their higher estimates for this sector as shown in Table 4.2. Similarly, McKenna & Norman (2010) have very low estimates at Southampton, which is primarily a refining cluster; a sector not covered in their study. This does naturally have a major impact on the suitability of clusters for a DACCS facility. Broadly however, all clusters

currently show potential to satisfy a major proportion of the heat requirements for a 1MtCO₂/yr LT DACCS facility.

It should also be mentioned that the values for Element Energy (2014) in Figure 4.5 are scaled from the quantity of waste heat that they deemed to be technically feasible to recover. In the same report, Element Energy (2014) also state that up to 28TWh of waste heat may be suitable for district heating though was not technically feasible to recover. This additional heat may be suitable for LT DAC applications as the DACCS facility could be located closer to the heat source in cases where distance to a population centre was an issue. It may, in some cases require some upgrading of this heat to meet LT DACCS regeneration temperatures. More broadly, it suggests that additional waste heat potential may be identified if waste heat surveys consider DACCS applications and technical feasibility for this purpose.

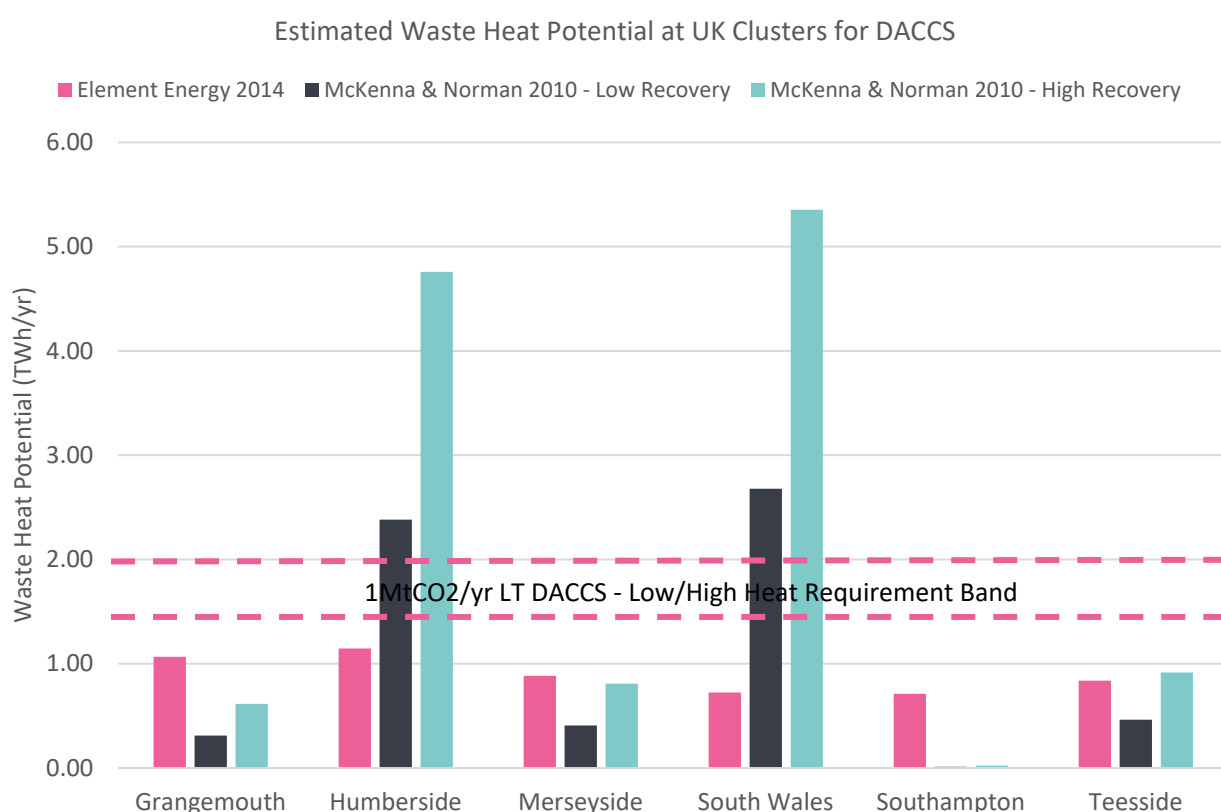


Figure 4.5: Estimated waste heat potential at each industrial cluster, benchmarked against the low & high heat requirements for an example 1MtCO₂/yr LT DACCS facility.

Table 4.3: Estimates of waste heat availability at each industrial cluster, scaled by CO₂ emissions.

Industrial Cluster	Element Energy (2014) (TWh/year)	McKenna & Norman (2010) High Recovery (TWh/year)	McKenna & Norman (2010) Low Recovery (TWh/year)
Grangemouth	1.07	0.62	0.31
Humberside	1.15	4.76	2.38
Merseyside	0.88	0.81	0.41

South Wales	0.72	5.35	2.68
Southampton	0.71	0.02	0.01
Teesside	0.84	0.92	0.46
Total	5.37	12.48	6.25

4.2.3. Power generation waste heat availability

Similar to industrial waste, various estimates exist for power generation waste heat availability. Element Energy (2014) estimated 58TWh of waste heat from power generation from cooling water sources. Albert et al (2022) estimated 346TWh from all possible sources, including those currently widely recovered and reused (e.g., flue gas heat used for preheating air and water) and sources that are unlikely to be recoverable (e.g., solar).

Table 4.4 shows the breakdown of the estimate by Albert et al (2022). In addition to the aforementioned overestimation issues, it is also evident that some of these sources may disappear (e.g., unabated coal phaseout in 2024), whilst others (natural gas, energy from waste, biomass) may require CCS technologies. Amine CCS plants may have some use for waste heat, such as preheating water for steam in an amine CCS plant. One technology developer we spoke with said they had discussed the potential of nuclear waste heat or using steam from nuclear power plants with the National Nuclear Laboratory for example.

More generally, thermal and nuclear power stations are located in a variety of areas around the country rather than clustered as is the case for many industrial processes. Therefore, use of waste heat from these sources would have additional considerations, such as access to CO₂ transport and storage infrastructure.

Table 4.4: Estimated waste heat by power generation technology in the UK from the study of Albert et al (2022). Note this includes all possible sources of waste heat, including those already recovered and reused (e.g. flue gas heat used for air or water preheating) and those that are not likely feasible to recover (e.g. solar).

Power Station Type	Number	Average installed capacity (MW)	Efficiency (%)	Load factor (%)	Estimated Waste Heat (GWh/yr)
Coal	6	1932	34.1	14.2	30,000
Coal/Oil	1	56	34.1	14.2	
Gas	8	102	48.9	21.8	
Gas Oil	14	73	48.9	21.8	
Gas Oil/Kerosene	11	140	48.9	21.8	
CCGT	38	793	48.9	42.7	20
OCGT	1	32	48.9	21.8	
Diesel	8	17.5	48.9	21.8	
Biomass	11	211	36	21.8	29,000
Waste	11	36	25	21.8	

Nuclear	8	1170	39.8	72.3	91,000
Solar	17	36	15	11.3	76,000
Total	-	-	-	-	346,020

4.2.4. Future waste heat availability

As noted in section 4.1.4, a further aspect to consider is the availability of industrial waste heat in the future as industry decarbonises. There are published studies into the sources and quality of waste heat in industry (Element Energy, 2014). From this assessment, it is clear that many waste heat sources are largely unavoidable functions of the core production process in question, for example: drying processes, boilers (for steam/hot water provision), recovery of heat from flue gases, and high temperature furnaces or kilns (cement, iron and steel). In the future, the production processes will largely remain, but fuels and heating methods will change. The major options would be either fuel switching (e.g., natural gas to hydrogen) or process electrification, as identified in the Industrial Decarbonisation Strategy (HM Government, 2021). Switching to hydrogen would be a very close parallel to natural gas, with waste heat likely to be equally as available. Electrification would necessitate larger changes to equipment and processes, and thus changes to the availability of waste heat would likely be more significant. Assessing in detail the future availability of waste heat would be best done when also assessing waste heat availability at clusters or large industrial sites. A parallel study could be performed on the processes present, the preferred decarbonisation options, and the net effect on waste heat availability for DACCS over a 20-30 year time horizon.

5. WP3: ESME Modelling of DACCS

This section reports on the modelling work that was carried out to evaluate the role direct air carbon capture and storage (DACCS) plants play in the UK's transition to net zero. Modelling was conducted using ESC's in-house, whole energy system model, ESME (Energy Systems Modelling Environment). A description of ESME, the methodology employed, and a discussion of the results are presented below.

5.1. Energy Systems Modelling Environment (ESME)

ESME was originally developed to evaluate the role of innovation in UK energy system decarbonisation, from energy resources and conversion through to end use in buildings, transport and industry. It is used by ESC, Government, industry, the Climate Change Committee (CCC) and academia.

ESME is an optimisation model and finds the least-cost combination of energy resources and technologies that satisfy UK energy service demands along the pathway to 2050. Constraints include emissions targets, resource availability and technology deployment rates, as well as operational factors that ensure adequate system capacity and flexibility. It is focussed on the physical components of such a system – infrastructure, energy flows and associated costs – and does not look at other layers of the system such as commercial aspects or communications between actors.

Importantly, ESME includes a multi-regional UK representation and can assess the infrastructure needed to join up resources, technologies and demands across the country. This includes transmission and distribution networks for electricity and gas, and pipelines and storage for CO₂.

The philosophy within ESME is of modelling the UK as an energy island. This means that ESME designs do not rely on international cross-border electricity infrastructure to absorb excess generation or import electricity when indigenous sources are not available. Policy-neutrality is a fundamental principle when using scenarios built in ESME, wherein minimal second-guessing of how policy could de-risk investment in the future takes place.

5.2. Limitations of the model

It should be appreciated that models such as ESME attempt to represent very complex systems that operate on a continuous scale of space and time. Given the complexity of such systems, and the limitations to today's computing power, certain simplifications have to be made in order to have models that produce useful outputs in reasonable timeframes. These simplifications, along with other considerations such as data availability, introduce practical limitations to the modelling. Recognition of these limitations is crucial when selecting the most appropriate model for the questions being answered. Some key limitations to be aware of include the following:

Data: ESME is a data-driven model, with projections for demands, technologies and resource being central to its decision-making. These projections are, by their nature,

uncertain, and results should be assessed carefully in this context. Notably, decisions made in one sector can radically affect the timing or extent of decarbonisation in others.

Linearity: Like many similar models (e.g., UK TIMES), ESME adopts a linear representation for technology and resource costs, and for constraints affecting the energy system. Such a representation precludes “lumpy investment”, where technologies are deployed in blocks of minimum size, and neglects any cost scaling of technologies. This has particular impacts on key sectors, as outlined below.

Spatial resolution: ESME is a multi-regional model, allowing the broad features of transmission and distribution of energy across the UK to be assessed. However, only limited information at finer granularity is integrated. Demand centres are not spatially positioned, and local challenges of transmitting energy within a region are not substantively modelled. Where physical limitations are key (for example, where there are permitted locations for particular power stations), these are implemented as regional constraints within the model⁷.

Sector representations: Within ESME each current and future emission point is not modelled independently. Instead, a set of coarse archetypes is used to characterise users of energy and sources of emissions across the whole system. In each case, sector representations are chosen to retain as much operational flexibility as possible, ensuring that innovations in technology properties and control do not impose overly constraining routes. Key examples of these representations are:

- **Heating in buildings:** A small set of building archetypes is used to represent the UK’s complex building stock. Within this framework, a simplified methodology is employed where heating supply and demand are pooled and subsequently balanced. This weakens the link between specific building types and heating systems; at single building level not all possible system combinations can be distinguished. The retained flexibility within ESME permits multiple plausible operational interpretations for heating systems – in particular, the operation of gas/hydrogen-fired and heat pump systems across different times of day and seasons regularly hints at hybrid heat pumps as a solution likely to be valuable to the energy system. It should be noted that the heating system costs remain subject to the linearity requirement described above, meaning that there are no additionality effects or cost savings implied for installation of hybrid systems of any type.
- **Industry:** Archotyping of industry in ESME is informed by fuel consumption data provided regularly by DESNZ. These data provide a natural disaggregation of industrial fuel use into sectors and end-uses. Within ESME, a set of industrial interventions is available that allows these sectors to transition to low or zero-carbon. As noted above, ESME does not attempt to spatially locate industrial sites within a region and to consider the local infrastructure needs consistent with

⁷ In this project, ESME Infrastructure has been used in an effort to overcome some of ESME’s limitations related to spatial resolution and provide insights related to energy network infrastructure.

decarbonisation⁸. Crucially, any retained energy flows within industry must be reconciled with the infrastructure available in the future.

- **Energy network infrastructure⁴:** All of the key networked energy carriers – notably electricity, gas and hydrogen – are subject to archotyping within ESME, representing energy at particular voltage or pressure levels. At the transmission level, it is assumed that all barriers to network reinforcement can be overcome with sufficient network investment. For future distribution of low-pressure hydrogen, ESME assumes that local networks can be generated only through repurposing of existing gas distribution networks at a fixed, linear repurposing cost. Network operation and maintenance costs are also assumed to be linear, meaning that additional costs associated with more infrequent flows of gas through the networks are not captured fully.
- **Non-energy system sectors:** ESME is first and foremost an energy systems model. This means it constructs energy systems by making choices about technologies that satisfy energy demands (power, heating, transport, industry and infrastructure). The major greenhouse gas (GHG) emitted by the energy system is CO₂. However, the UK's net zero GHG target mean that it is insufficient to consider only the energy system and only CO₂. Non-energy system sectors (land use, agriculture, waste management) need to be accounted for in the modelling. These sectors are associated more with non-CO₂ GHG emissions (methane (CH₄), and nitrous oxide (N₂O)). However, ESME does not currently have the functionality to make in-model decisions about strategies/methods to reduce such emissions from these sectors. Therefore, in order to account for them, emissions trajectories for these sectors are determined off-model and introduced as exogenous assumptions in ESME. Emissions trajectories for these sectors are generally taken from work conducted by other organisations (e.g., CCC). These trajectories represent hard-coded emissions that ESME must allow for but is unable to directly influence (through suitable technology choices). Instead, ESME must make decisions in the energy system to ensure that non-energy system emissions are accounted for.

5.3. Methodology

The modelling approach taken in this project drew on ESME's in-built Monte Carlo functionality to allow uncertainty in input assumptions to be propagated through the model. Before Monte Carlo modelling could take place, a reference case scenario was developed in accordance with DESNZ. The reference case serves as an agreed deterministic scenario to which uncertainty is applied. A description of the reference case and Monte Carlo approach is given below.

5.3.1. Reference case scenario

The reference case scenario (Ref Case) is a single deterministic pathway to net zero. Input assumptions were discussed and agreed with DESNZ policy teams to ensure key policies

⁸ Recent completion of a project has provided the data to be able to represent all industrial sites within each cluster and their decarbonisation options. However, the data was not available in time for use in this project.

were included and to maximise the usefulness to DESNZ. Seven different DACCS technologies were added to the option set in ESME. These are:

- Electrified High Temperature Direct Air Capture (HT DAC) – consumes electricity
- Electrochemical Direct Air Capture – consumes electricity
- High Temperature Direct Air Capture (HT DAC) – consumes electricity and natural gas
- Low Temperature Direct Air Capture (LT DAC) (electricity) – consumes electricity
- Low Temperature Direct Air Capture (LT DAC) (gas) – consumes electricity and natural gas
- Low Temperature Direct Air Capture (LT DAC) (hydrogen) – consumes electricity and hydrogen
- Low Temperature Direct Air Capture (LT DAC) (waste heat) – consumes electricity and waste heat

The aim of the reference case was not to provide insight into the role of DACCS in the UK's net zero transition. Rather it was the starting point for the Monte Carlo analysis (MCA), laying out the boundaries and fixing elements of the pathway before subjecting it to uncertainty in the MCA. It was therefore important that input assumptions and the resulting energy system design were broadly accepted by DESNZ. However, it was not the aim to produce a scenario that exactly mirrored each and every assumption or element of policy expected by policy teams across DESNZ. To do so would be counterproductive as: 1) it could take a long time to agree such a scenario with all policy teams in DESNZ; and 2) fixing too many elements in the scenario would limit the flexibility and optionality in the model. Instead, high level assumptions were agreed and implemented; these are presented below.

5.3.2. Reference case assumptions

High level input assumptions agreed with DESNZ are given in Table 5.1.

Table 5.1: High level input assumptions used in the reference case scenario

Input	Assumption
Emissions target	<ul style="list-style-type: none"> • 6th Carbon budget included • AR5 without feedback global warming potential used
Biomass	<ul style="list-style-type: none"> • Domestic and imported biomass availability (TWh/yr) aligned with UKTM assumptions (2050: 127TWh domestic and 41TWh imported)
Hydrogen production	<ul style="list-style-type: none"> • Coal gasification (with and without CCS) is excluded from the options • BECCS hydrogen production aligned with amount seen in DESNZ High Electrification scenario: first deployment in 2035, max. production 64TWh H₂ in 2050. • Minimum 5GW electrolyzers in 2030 • No hydrogen production from nuclear cogeneration
Nuclear power	<ul style="list-style-type: none"> • Maximum 24GW nuclear in 2050 • Nuclear small modular reactors supply electricity only (no cogeneration of heat)

	<ul style="list-style-type: none"> • First deployment of SMRs in 2035 • Waste heat can be extracted from generation III plants • No hydrogen cogeneration plants
Offshore wind	<ul style="list-style-type: none"> • Minimum 40GW by 2030
DACCS	<ul style="list-style-type: none"> • Maximum 25Mt DACCS in 2050 (note that this constraint is removed from the Monte Carlo analysis so that the effect of different DACCS quantities can be evaluated) • Maximum 3Mt DACCS in 2030 • Minimum 1Mt DACCS located in Scotland in 2030
Transport	<ul style="list-style-type: none"> • No new sales of ICE/hybrid cars & vans post-2030 • HGVs <26t zero emission from 2035 • HGVs >26t zero emission from 2040

5.3.3. Reference case pathway

Some high-level outputs from the reference case are presented in Table 5.2.

Table 5.2: High level outputs from the reference case scenario

	High level output
Emissions target	<ul style="list-style-type: none"> • Meets interim emissions targets but misses the 2050 net zero target by 2.1mt.
Biomass	<ul style="list-style-type: none"> • Pre-CCS (pre-2030), biomass resource not fully utilised. Biomass mainly consumed in industry, power and heating at this time. • From 2030 onwards (CCS available at commercial scale), all available biomass is consumed. • Biomass is an important source of negative emissions when combined with CCS from the 2030s onwards. BECCS seen in power, hydrogen and industry. • Biomass used in BECCS power plant when CCS first available at large scale in 2030. First deployment of hydrogen BECCS plant occurs in 2035 (as per constraints, see above). This leads to a gradual shift from BECCS power to BECCS hydrogen in the mid-2030s to 2050, when hydrogen production becomes main use of biomass.
Hydrogen	<ul style="list-style-type: none"> • Main source of hydrogen is blue. BECCS hydrogen deployed from 2035 and reaches maximum permitted in 2050 (64TWh). Electrolysed hydrogen produced from 2030 (minimum 5GW electrolyser capacity in 2030). • Production ramps up from approx. 60TWh in 2030 to 140TWh by mid-2030s. Around 180TWh.yr produced from mid-2040s. • Industry is the single largest consumer of hydrogen in all time periods from 2020s. Hydrogen used to supply domestic heat from 2030 and to decarbonise road transport (HGVs) from mid-2030s. Hydrogen used in shipping from 2045 when ammonia ships become available. Finally, hydrogen also important form of zero carbon dispatchable power.

Power generation	<ul style="list-style-type: none"> • Unabated gas plant leaves the system by 2030. 2GW CCGT with CCS built in 2030 and operational until mid-2040s, providing dispatchable power. • 15GW nuclear gen. III plant built by 2050 supply electricity and heat offtake to DACCS plants. First small modular reactor built in 2035. 9GW SMR capacity by 2050 – these are assumed to only supply electricity (i.e., no heat offtake). • Offshore wind supplies most of the electricity needed from 2025 onwards. This is supported by firm generation from nuclear plant and dispatchable power from hydrogen turbines and abated CCGTs. Pumped storage plays a key role throughout the pathway. Battery and thermomechanical storage also help balance the system in 2050. • Solar PV (mainly as farms but also some roof top systems) present from the 2020s. • Wave & tidal systems along with geothermal feature in the system in mid-2040s/2050.
DACCS	<ul style="list-style-type: none"> • Max. DACCS capacity limited to 25Mt in 2050. ESME deploys 19.5Mt of waste heat DACCS, utilising the heat taken from gen. III nuclear plant. The remaining 5.5Mt is gas fuelled DACCS. • First deployment of DACCS is 2030 limited to 3Mt (1Mt being in Scotland). This is entirely waste heat DACCS (assumed no new nuclear plant in Scotland, so the waste heat source will have to come from some other form of thermal power generation e.g., BECCS or waste plants). • For each time period, DACCS deployed to maximum capacity described by build constraints (build rates and max. build quantities).
Transport	<ul style="list-style-type: none"> • Constraints (bans on new sales of internal combustion engines) are the main driver for decarbonisation of the transport sector. • Natural gas vehicles are an important transition technology for road freight. However, electrification becomes the dominant method of decarbonising road freight by 2040. • By 2040, most vans on the road are electric. However, there is a role for hydrogen in this vehicle type. The car fleet is entirely electric by 2045 as old ICE and hybrid cars are gone after 2040. • There are no alternative aviation technologies included in this scenario. However, aviation does reduce emissions by retiring older aircraft early and replacing with more fuel-efficient planes. • Ammonia ships decarbonise the shipping sector from 2045.
Buildings & heat	<ul style="list-style-type: none"> • Residential and commercial heat (excluding industry) is zero carbon in 2050 as combustion of natural gas ceases. • Electricity (predominantly in air source heat pumps (ASHP)), hydrogen and district heat are three key zero carbon energy vectors used in heating. • The role of hydrogen for heat sees a changing role throughout the pathway: When first rolled out in 2030, hydrogen boilers supply residential heat in a small number of homes. As hydrogen is rolled out to more homes, hydrogen boilers are paired with heat pumps in a hybrid system. In these systems, electricity supplies the majority of the heat

	<p>throughout the year with hydrogen helping to meet peak demand during peak times and cold winters. In this way, the volume of hydrogen needed to supply heat is minimised (only being consumed during peak periods). The size of the heat pump is also minimised (does not need to be sized for peak demand) and the supporting infrastructure (generation and grid reinforcement) is also kept to a minimum. All of this keeps the total system cost to a minimum.</p>
Industry	<ul style="list-style-type: none"> • Industry makes a series of fuel switches away from fossil fuels to electricity, hydrogen and biomass. • Crucially in ESME, industry is unable to fully switch away from fossil fuels and there remains some residual use in 2050. However, industry is able to apply CCS to reduce emissions – this also helps to capture process CO₂, which is emitted from industrial processes (i.e., not associated with the combustion of fossil fuels). • Net emissions from industry reach 5.5Mt by 2050.

5.3.4. Monte Carlo analysis (MCA) in ESME

Monte Carlo is a method of uncertainty analysis used in ESME by which uncertainty associated with input variables is propagated through the model to produce outputs that vary in response to this uncertainty.

Uncertainty in the input variables is captured in the form of a probability distribution. This probability distribution is sampled N times so that for each uncertain variable, N values are held in the model database.

The model then uses these N sampled values to solve N times, creating N unique energy system designs or pathways. Figure 5.1 illustrates how the Monte Carlo approach works in ESME with input variables being sampled, values being passed to the optimiser and multiple energy systems/pathways being created.

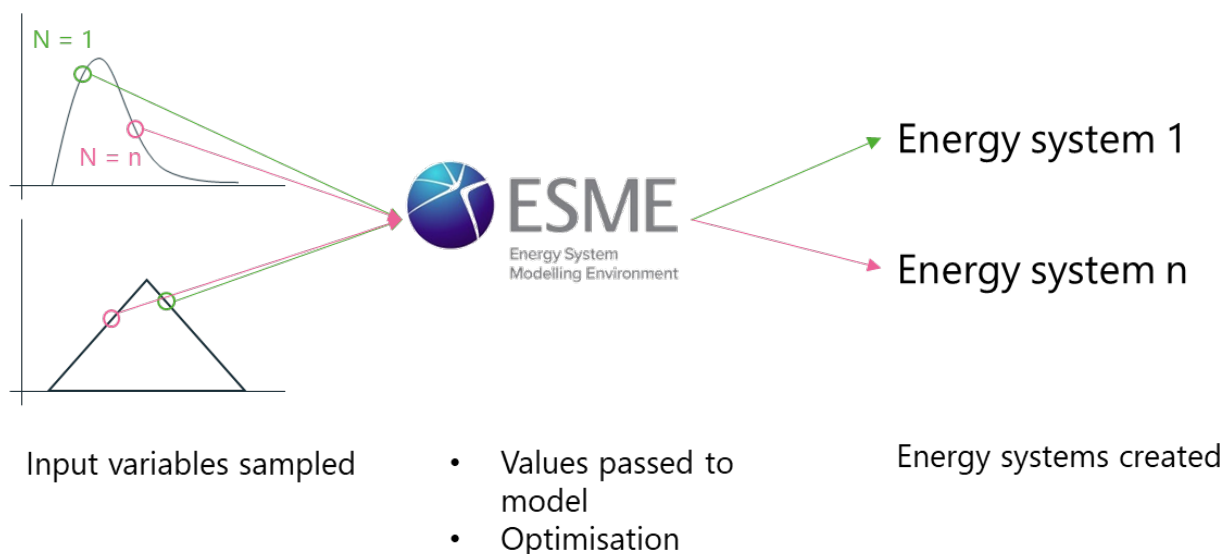


Figure 5.1: Monte Carlo analysis in ESME: sampling input distributions N times to create N energy systems

5.3.4.1. MCA set up

To evaluate the role of DACCS subject to uncertainty, six batches of 100 simulations were performed. The batches differ in that each one assumes different constraints on deployment of DACCS, general CCS infrastructure and recoverable waste heat from nuclear gen III plants. The batch descriptions are summarised in Table 5.3.

Table 5.4 shows the variables that were sampled 100 times in each of the batches. The values sampled from these particular variables were the same across all batches of runs i.e., simulation 1 in all six batches will have the same values for each of the variables.

All the uncertain variables sampled are described by triangular distributions with minimum, mode and maximum values used to characterise the distribution. This distribution type is suitable in cases where a lack of data makes full statistical analysis impossible. Given the nascent nature of DACCS (and other technologies) and the fact that pathways are being modelled to 2050, this is an appropriate distribution to use in this analysis.

Table 5.3: Description of Monte Carlo batches

Batch	DACCS	CCS	Waste heat from nuclear
1	No delay	No delay	Yes
2	5-year delay	No delay	Yes
3	10-year delay	No delay	Yes
4	No delay	5-year delay	Yes
5	No delay	10-year delay	Yes
6	No delay	No delay	No

Table 5.4: Input parameters sampled as part of the MCA

Technology costs (2050), £/kW	Energy resource costs (2050), p/kWh	Resource availability (2050), TWh/yr.	DACCS quantity (2050), Mt/yr.
Anaerobic Digestion CHP Plant	Biofuel Imports	Biomass Importing	DACCS
Anaerobic Digestion Gas Plant	Biomass Imports	UK Biomass	
Biomass Fired Generation	Coal		
Biomass Fired Generation with CCS	Dry Waste Resource		
Biomass Macro CHP	Gas_LNG_Import		
CCGT	Gas NCS Import		

Technology costs (2050), £/kW	Energy resource costs (2050), p/kWh	Resource availability (2050), TWh/yr.	DACCS quantity (2050), Mt/yr.
CCGT with CCS	Gas_TTF_Import		
Gas Macro CHP	Gas_UKCS_Import		
Geothermal Plant (EGS) Electricity & Heat	Gas_Zeb_Import		
Geothermal Plant (HSA) Electricity & Heat	Liquid Fuel		
Geothermal Plant (HSA) Heat Only	Nuclear		
H2 Plant (Biomass Gasification with CCS)	UK Biomass		
H2 Plant (Biomass Gasification)	Wet Waste		
H2 Plant (Coal Gasification with CCS)			
H2 Plant (Electrolysis)			
H2 Plant (SMR with CCS)			
H2 Turbine			
IGCC Biomass			
IGCC Biomass with CCS			
IGCC Coal			
IGCC Coal with CCS			
Incineration of Waste			
Nuclear (Gen III)			
Nuclear (SMR Elec Only)			
Nuclear Gen IV Cogen Power and H2			
Nuclear SMR Cogen Power and Heat (DH)			
Offshore Wind (fixed)			
Offshore Wind (floating)			
Onshore Wind			
PC Coal			
PC Coal with CCS			
Severn Barrage			
SNG Plant (Biomass Gasification with CCS)			

Technology costs (2050), £/kW	Energy resource costs (2050), p/kWh	Resource availability (2050), TWh/yr.	DACCS quantity (2050), Mt/yr.
SNG Plant (Biomass Gasification)			
Solar PV (Domestic)			
Solar PV (Farm)			
Tidal Range			
Tidal Stream			
Waste Gasification			
Waste Gasification with CCS			
Wave Power			

5.4. Results

Six batches of 100 simulations were modelled using ESME's Monte Carlo functionality. This section presents the results of those simulations.

5.4.1. Introducing uncertainty to the reference case scenario

In the first batch of 100 simulations, the distributed variables listed in Table 5.4 were sampled and the sampled values applied to the reference case scenario. The quantity of DACCS deployed was also included in the sampling and ranged from 9Mt-50Mt in 2050 with a mode of 25Mt (as per the reference case assumption); Figure 5.2 shows the distribution of the sampled DACCS deployment quantities in 2050.

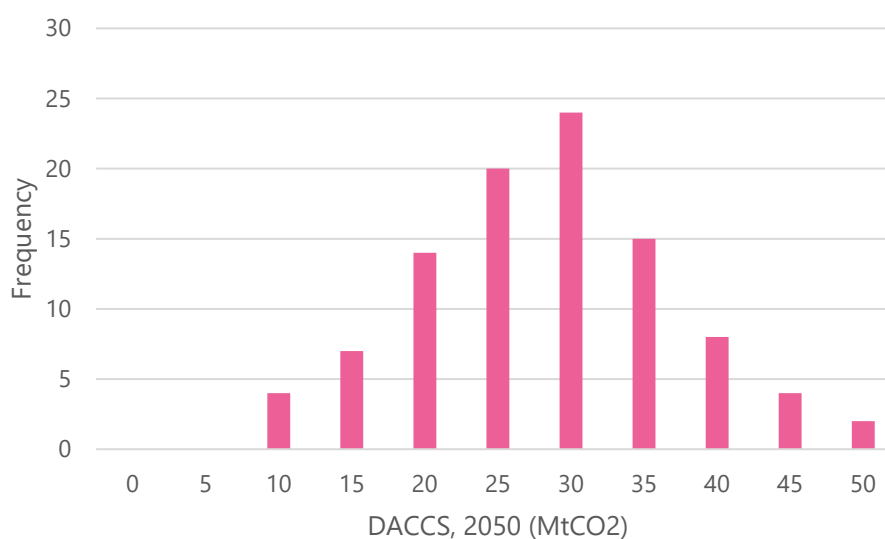


Figure 5.2: Distribution of DACCS deployment in 2050 (min. = 9Mt, mode = 25Mt, max. = 50Mt)

Figure 5.3 plots the actual amount of DACCS deployed in 2050 in each simulation versus the maximum amount of DACCS that could have been deployed in that simulation.

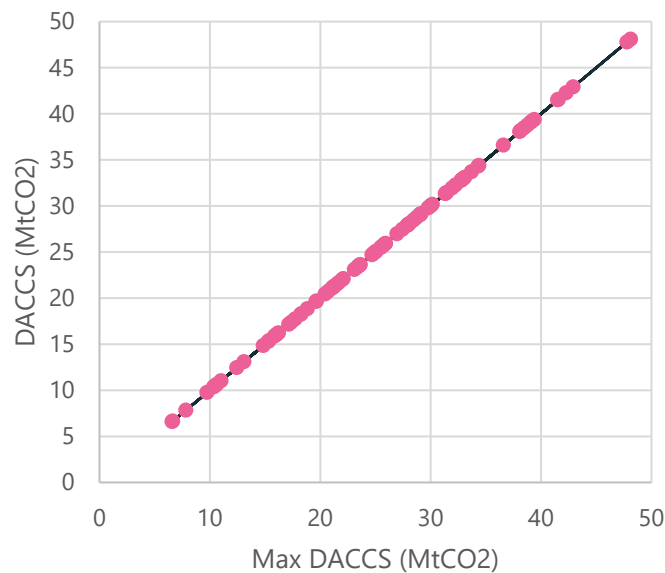


Figure 5.3: Actual DACCS deployment in 2050 vs. maximum possible deployment

The figure shows that in all simulations, the maximum amount of DACCS that could possibly deployed is being deployed. This is an expected result given the ability of DACCS to remove CO₂ from the system for relatively low cost. Had there been any simulations in which DACCS was not fully deployed, these would have been interesting systems to delve into to understand what would drive such behaviour.

5.4.1.1. DACCS availability and meeting net zero

If any of the simulated energy systems are unable to meet emission targets, these would be deemed infeasible by ESME and results not provided. However, it is useful to understand how the presence, or absence, of DACCS might impact the ability of the UK to meet net zero. To ensure that any simulations that are unable to meet net zero are still solvable by ESME a backstop CO₂ removal technology (known simply as the Backstop) is included in the technology options. The Backstop is a so-called dummy technology that removes CO₂ from the system for a very high cost. The high cost is to ensure that it is the last technology option to be deployed.

The amount of Backstop deployed corresponds to the amount of CO₂ each simulation misses the net zero target by (emissions reduction deficit). Figure 5.4 shows how many of the systems simulated were able to meet net zero; 18 simulations were able to meet net zero (i.e., did not deploy any Backstop).

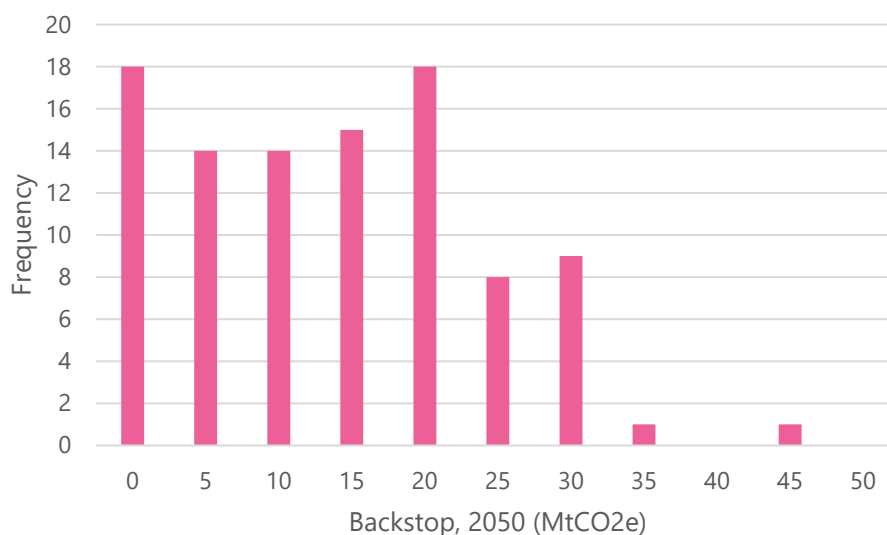


Figure 5.4: Distribution of Backstop deployment (emissions reduction deficit) in 2050 for batch 1 simulations

There is a strong negative correlation between Backstop and DACCS deployment (Figure 5.5). No simulations with <25Mt DACCS were able to meet net zero whereas all simulation with >40Mt DACCS were able to meet net zero. Between 25Mt and 40Mt DACCS, other factors come into play that affect the likelihood of a simulation being able to meet net zero. A strong influencing variable is the amount of biomass available to the system.

A point to note here is that there are potentially some abatement options that might exist by 2050 in various sectors that are currently not captured in ESME. It might be feasible to assume that 5Mt CO₂ captured by the Backstop could be abated by other means. If so, one might assume that 25Mt DACCS would be sufficient to meet net zero.

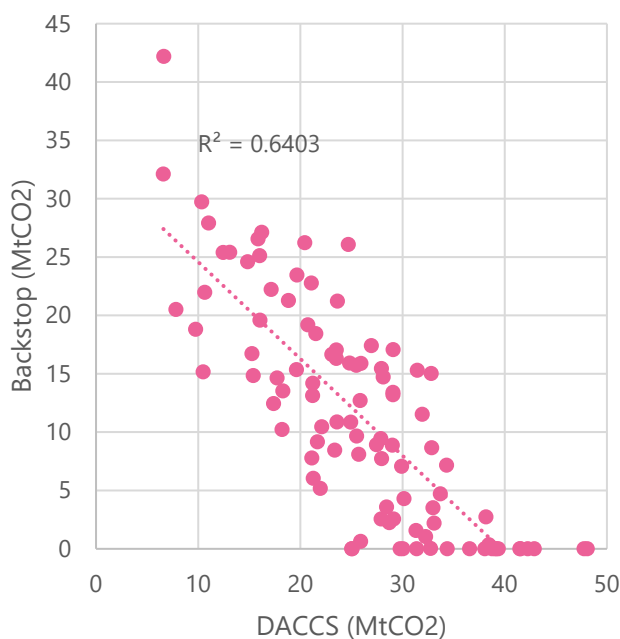


Figure 5.5: Backstop deployment vs. DACCS deployment in 2050 for batch 1 simulations

5.4.1.2. The influence of biomass availability

The amount of biomass available to the system is known to have an influence on the energy system design and whether the pathway reaches net zero. When combined with CCS, biomass is able to deliver negative emissions creating “emissions headroom” which is useful in removing residual emissions from difficult to decarbonise sectors such as aviation, agriculture and industry. If there are insufficient removals to cover any residual emissions, the system will not meet the net zero target. If negative emissions are available in large quantities, this can prompt different technology choices in some sectors. For example, negative emissions might permit some sectors to slow down their rate of decarbonisation or avoid investment in more costly, low carbon technologies (such as a continuation of gas boiler use in homes in 2050). It should be noted that this is how least cost optimisation models like ESME operate; in reality, things such as policy, legislation and consumer preference can lead to different decisions being made.

Due to the value ESME sees in biomass and the negative emissions it can provide, it is a general expectation that all available biomass resource is consumed (at least in the later time periods when it can be combined with CCS – bioenergy with carbon capture and storage (BECCS)). Figure 5.6 plots the amount of biomass (domestic and imported sources) consumed in 2050 in each simulation versus the maximum amount of biomass that could have been consumed in that simulation. Imported and domestic biomass quantities were sampled from triangular distributions. Figure 5.6 shows that in all simulations, the maximum amount of biomass that could possibly be consumed was consumed. It confirms that in all simulations, biomass is a crucial source of negative emissions regardless of the amount of DACCS that is available.

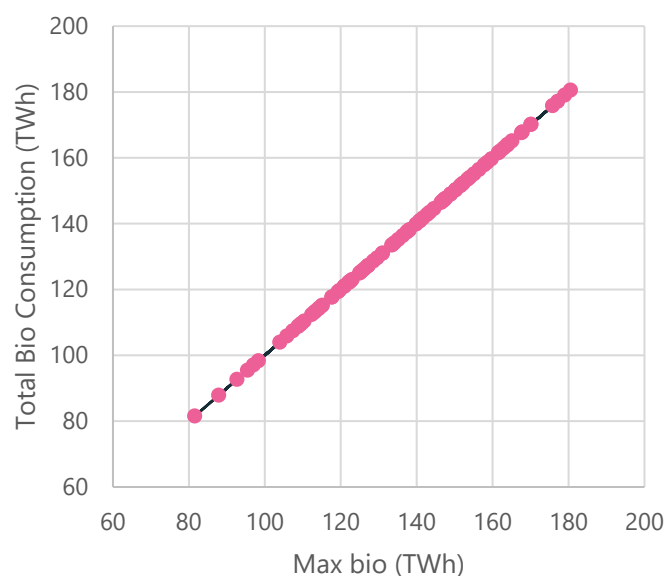


Figure 5.6: Actual biomass consumption in 2050 vs. maximum possible consumption

Figure 5.7 shows the correlation between biomass availability and net zero compliance (indicated by Backstop deployment). As with DACCS, there is a relationship between the amount of biomass available to a system and whether it can meet net zero, but this

relationship is weaker or more variable. In the simulations modelled, there is no obvious amount of biomass required to meet net zero.

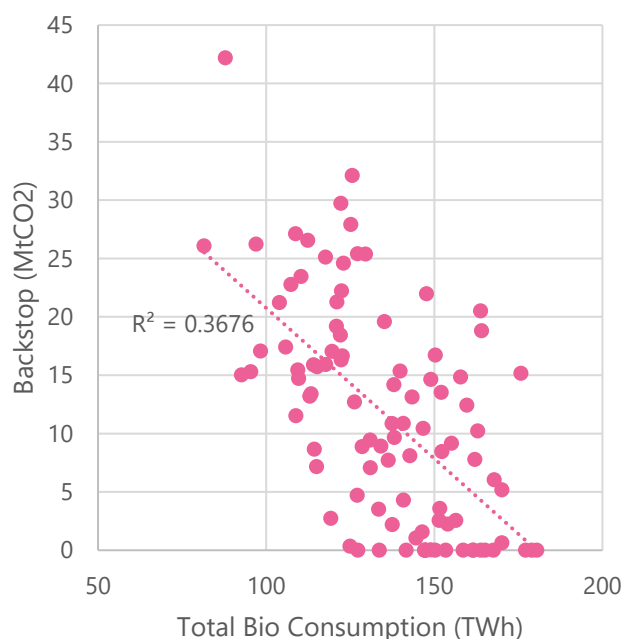


Figure 5.7: Backstop deployment vs. biomass consumption in 2050 for batch 1 simulations

5.4.1.3. The interplay between biomass and daccs

DACCS and biomass (used in BECCS processes) are two important sources of negative emissions deployed at their maximum quantities in all simulations. In 18 of the 100 simulations, this combination of DACCS and BECCS (along with other sources of negative emissions⁹) is able to deliver on net zero. Figure 5.8 shows the relationship between net zero compliance and the total amount of negative emissions provided by BECCS and DACCS. The black dots indicate the net zero compliant systems. All systems with >75MtCO₂ negative emissions from biomass and DACCS were net zero. The chart illustrates the strong dependence of these simulations meeting net zero on negative emissions technologies, especially BECCS and DACCS.

⁹ There are other sources of negative emissions in the model such as energy from waste (EfW) with CCS (on account of the biogenic content of waste) and forestry. These have not been included in the total negative emissions summation because they do not vary across simulations. Non-energy/non-CO₂ related emissions sources (e.g. negative emissions from forestry) are hard-coded values included in ESME to ensure they are accounted for in the energy system design. EfW plants are the only technology that can consume a dry waste resource. Given this, and the importance of negative emissions delivered by these plants (when combined with CCS), deployment of these plants and the negative emissions created are consistent across all simulations. Negative emissions from these other sources are approx. 45Mt in 2050. Therefore the total amount of negative emissions needed for these simulations to meet Net Zero in 2050 is in the order of 120Mt (75Mt from biomass and DACCS plus 45Mt from other sources).

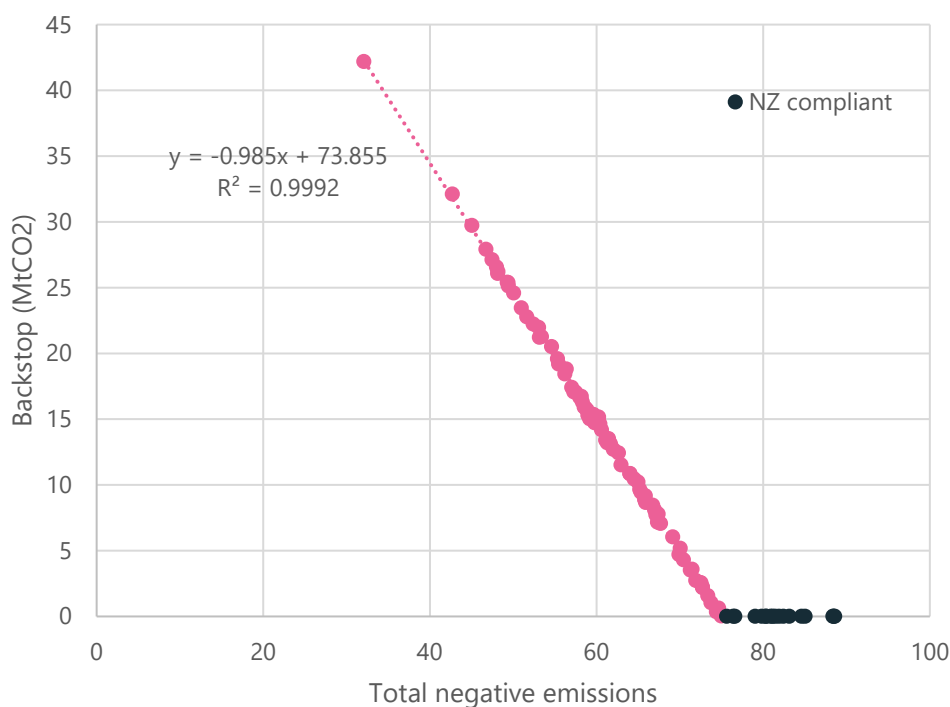


Figure 5.8: Backstop deployment vs. total negative emissions from DACCS and BECCS in 2050 for batch 1 simulations

Figure 5.9 shows the combination of total biomass consumed and DACCS deployment in 2050 for all simulations in batch 1. The pink dots represent the net zero compliant systems. The blue dots fail to meet net zero. The dashed line shows the mean combination of DACCS and biomass needed to deliver 75MtCO₂ negative emissions. It is the dividing line between the net zero compliant systems and those that fail to meet targets.

Given that the average emission factor associated with biomass can change in ESME depending on the mix of domestic and imported biomass that is consumed, there are upper and lower amounts of biomass that when combined with DACCS can also deliver the 75MtCO₂ negative emissions. These are represented by the solid lines either side of the dashed line.

The reference case assumes the UK has 168TWh of biomass (127TWh domestic and 41TWh imported) in 2050. Figure 5.9 suggests that it is possible to meet net zero with biomass resource total less than 168TWh, but this would depend on having sufficient removals from DACCS (>30Mt by 2050).

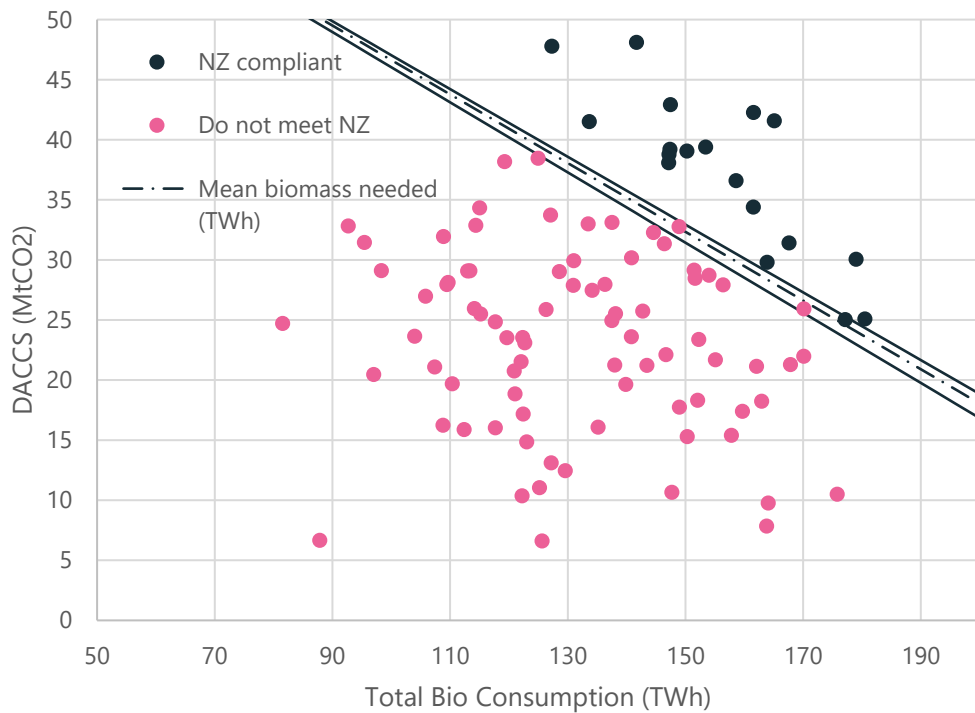


Figure 5.9: Combination of DACCS deployment and biomass consumption for batch 1 simulations. Pink dots are net zero compliant systems; blue dots fail to meet net zero.

5.4.1.4. DACCS priority order

Results presented thus far have focused on the total amount of DACCS deployed (in MtCO₂) and how this impacts meeting net zero. Seven different DACCS technologies were included in the model each consuming different energy vectors and having different costs. Models like ESME are well-suited to making trade-offs between cost, efficiency and emissions/removals of different technology options whilst considering wider system impacts such as the type of energy resource required (such as whether that is a primary or secondary resource i.e., a natural resource or requiring some kind of conversion process e.g., into electricity or hydrogen). This section draws out the different DACCS technology choices made by ESME in the batch 1 simulations.

Figure 5.10 shows the breakdown of the DACCS technologies deployed in each simulation in batch 1. The chart has been ordered by the total amount of DACCS deployed. The dots above the stacked bars indicate the 18 simulations that were net zero compliant. Net zero systems tend to be those with the highest amount of DACCS available (towards the left end of the chart).

A clear observation is the priority order for deploying DACCS technologies. First and foremost, ESME deploys DACCS that utilises waste heat from thermal power generation. The next type of DACCS to be deployed is low temperature gas powered plants. Emissions from the consumption of gas by the plant are assumed to be captured on top of the CO₂ removed directly from the air, so there is no emissions penalty for deploying such a technology in ESME.

The majority of the net zero systems (14/18) then deploy hydrogen fuelled DACCS plants. It is not clear from this chart what the driver behind this is, but it is likely related to the amount of hydrogen that can be produced, by which means, and which sectors it is being used in. The quantity and production method of hydrogen is influenced by the amount of emissions headroom that is possible. Emissions headroom is created by negative emission technologies like DACCS as well as the amount of biomass available to the system and used in BECCS processes (such as hydrogen production).

In those simulations where hydrogen fuelled low temperature DACCS is not deployed, high temperature DACCS plants are chosen. However, these simulations do not meet net zero.

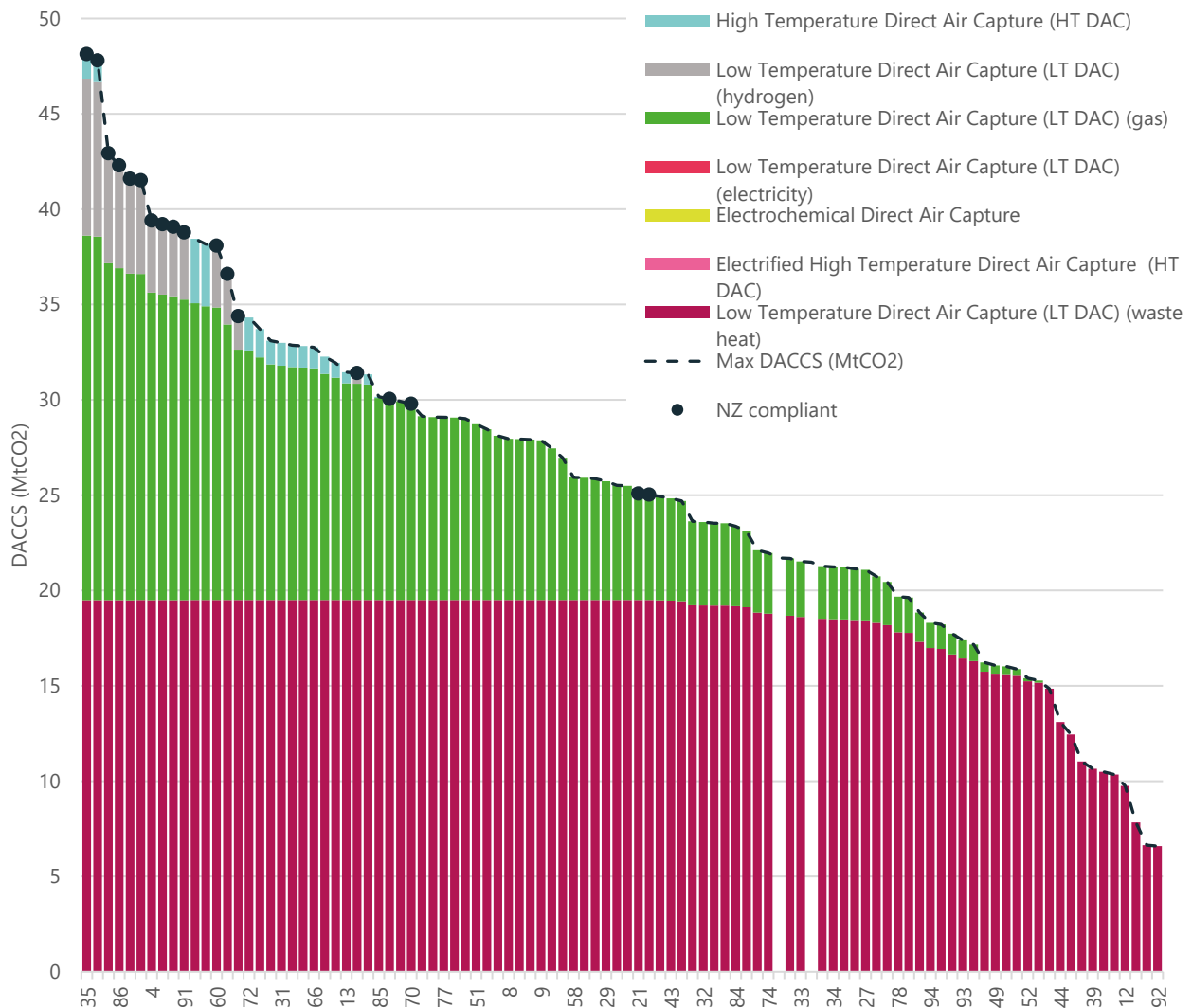


Figure 5.10: DACCS technology deployment for each batch 1 simulation (no results available for simulations 56 and 63 indicated by blank column – this was due to modelling infeasibilities)

5.4.1.5. Sources of waste heat for DACCS

As shown in Figure 5.10, waste heat is an important energy source for DACCS plants deployed in ESME. Waste heat DACCS plants are the first choice DACCS plants to be deployed in all simulations in batch 1 and are deployed to the maximum quantities permitted by build constraints (maximum build quantities and maximum build rates). The source of waste heat is therefore an important factor in their deployment. Figure 5.11

shows the amount of waste heat produced in the batch 1 simulations and where that waste heat originates.

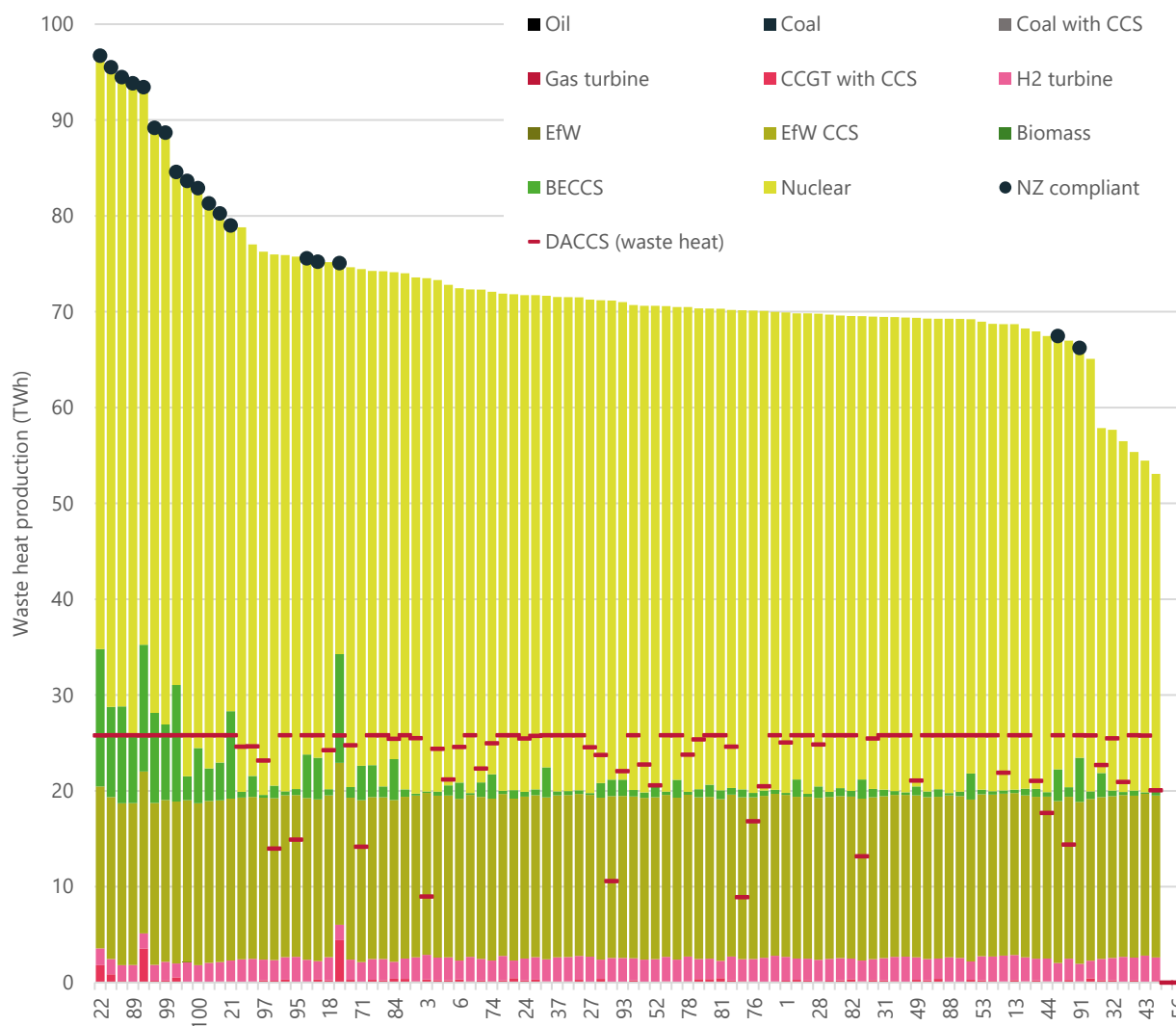


Figure 5.11: Sources of waste heat in batch 1 simulations (red dashes indicate the amount of waste heat consumed by DACCS plants)

The primary source of waste heat is large scale generation III nuclear plant.

Energy from waste (EfW) plants (equipped with CCS) also supply a consistent amount of waste heat across simulations. EfW with CCS plants in ESME are the only plant that can consume a dry waste resource. Dry waste is assumed to have a 50% biogenic content meaning that when combined with CCS, it is able to deliver negative emissions – this is what drives EfW with CCS deployment.

By 2050, hydrogen turbines are also deployed to provide zero carbon dispatchable power. These plants are also able to supply waste heat. Waste heat is also extracted from dispatchable plant in the form of combined cycle gas turbines (CCGT) with CCS. These plants are deployed in several of the net zero systems in 2050 which is indicative of emissions headroom created by DACCS and biomass permitting the operation of CCGTs (with CCS) in 2050.

BECCS power plants are another source of waste heat, but this varies considerably across simulations. Typically, biomass is combined with CCS in biomass gasification plants to produce hydrogen. The drivers behind this are: the value of hydrogen as a flexible, storable, zero carbon energy vector which can be used to decarbonise industry and heavy transport modes; and the negative emissions created by BECCS hydrogen plants. As a result, it is usual to see the majority of biomass being used in BECCS hydrogen plants, with some biomass being used in BECCS industry – very little is seen in BECCS power processes because there are a number of other zero carbon electricity generation technologies available to the model.

To see BECCS power being deployed in the high-DACCS, net zero systems does provide a clue as to what else might be happening in these simulations. Either biomass availability is so high that there is more than enough to meet hydrogen demand, or biomass is being diverted from hydrogen production into the power sector. In all of the simulations, hydrogen BECCS capacity is limited as per the agreed assumptions with DESNZ, so it is possible that in the net zero systems (with high biomass) there is more biomass than the limited hydrogen BECCS capacity can make use of. However, inspection of the results shows that in the net zero simulations, the installed hydrogen BECCS plant capacity is consistently below the limits set by the agreed assumption. This means that biomass is being deliberately diverted from hydrogen production to power generation. Diversion of biomass into power production might be driven either by a need for waste heat to power DACCS plants (hydrogen production facilities do not supply waste heat in ESME), or as a result of BECCS power plant costs being lower (BECCS power plant cost is a sampled variable in the Monte Carlo Analysis).

5.4.1.6. Hydrogen production

Appearance of BECCS power production in the net zero systems might suggest a diversion of biomass from hydrogen production. Figure 5.12 shows the volume and method of hydrogen production in each simulation. The figure shows that the net zero systems are able to produce more hydrogen than non-compliant systems. This increased volume of production may enable (or be driven by) the deployment of hydrogen fuelled DACCS plants. This additional hydrogen is also consumed in agriculture (vehicles and fuel-switching) and residential/commercial heating.

Across all simulations, the main source of hydrogen is blue hydrogen (autothermal methane reforming (ATR) with CCS). There are a number of reasons for this primarily related to cost (capex of reformers vs. other production methods and system-wide impacts) and include:

1. Capex of gas reformers is lower than that of electrolyzers
2. Gas price is relatively low compared to the endogenous electricity price
3. Blue hydrogen production does not require additional electricity generating capacity/transmission infrastructure to be built

BECCS is another important source of hydrogen. Biomass combined with CCS delivers negative emissions, which are crucial for meeting net zero. The value of hydrogen is its

storability and flexibility. It is a critical zero carbon energy vector used in industry, heating and transport. It is also used to provide zero carbon dispatchable electricity.

Figure 5.12 shows that net zero systems produce less hydrogen from BECCS in favour of blue hydrogen production. This confirms that biomass in these systems is being diverted into the power sector where negative emissions are still produced but waste heat can also be supplied to DACCS plants and/or district heat networks.

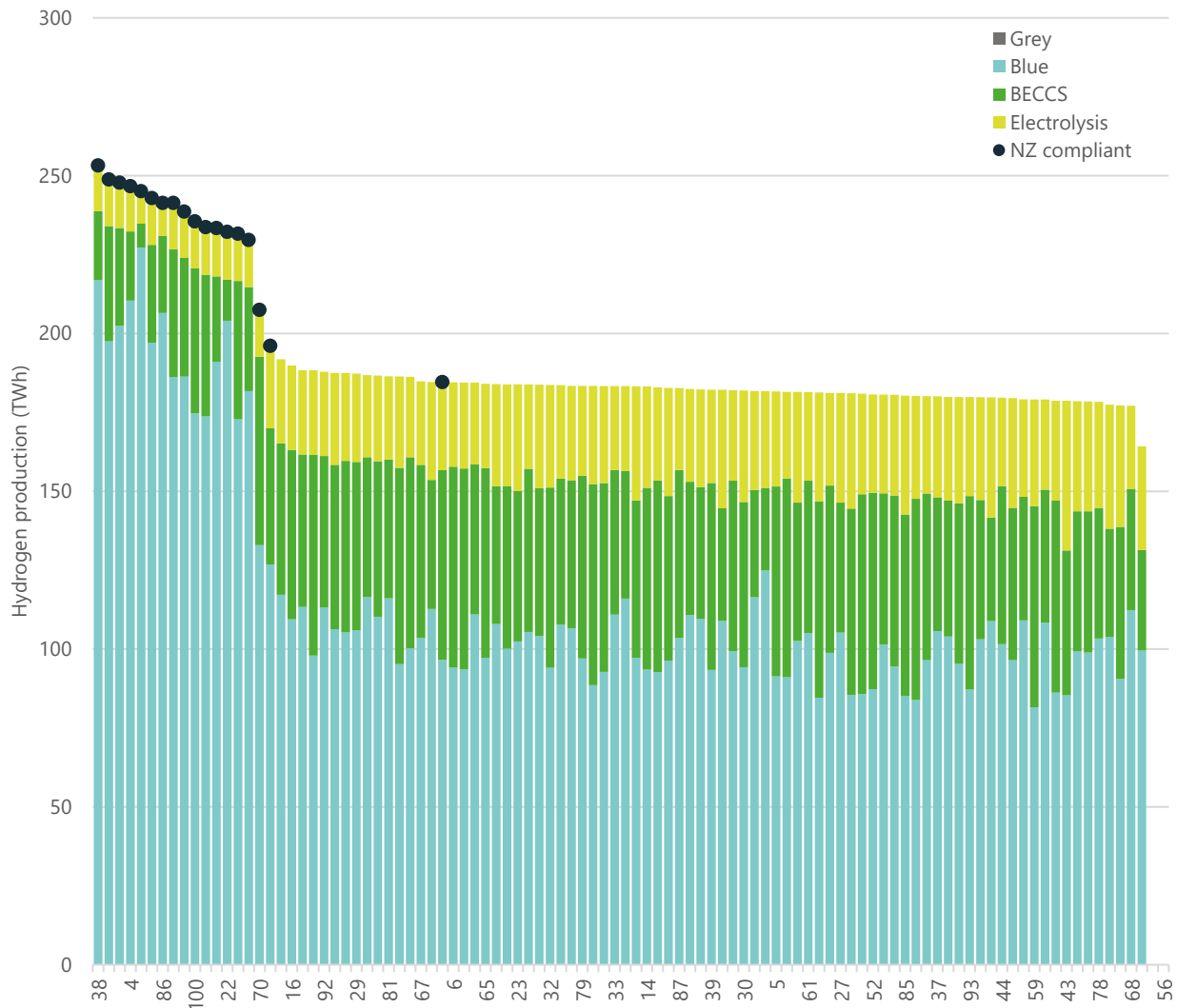


Figure 5.12: Hydrogen production volume broken down by source for batch 1 simulations

There are other drivers behind hydrogen production choices made in ESME. In the net zero systems, high quantities of DACCS and biomass mean that the model has enough flexibility to respond to changes in gas price across the simulations. Figure 5.13 shows that for net zero compliant systems, lower gas prices at least partially drive lower production of hydrogen from BECCS.

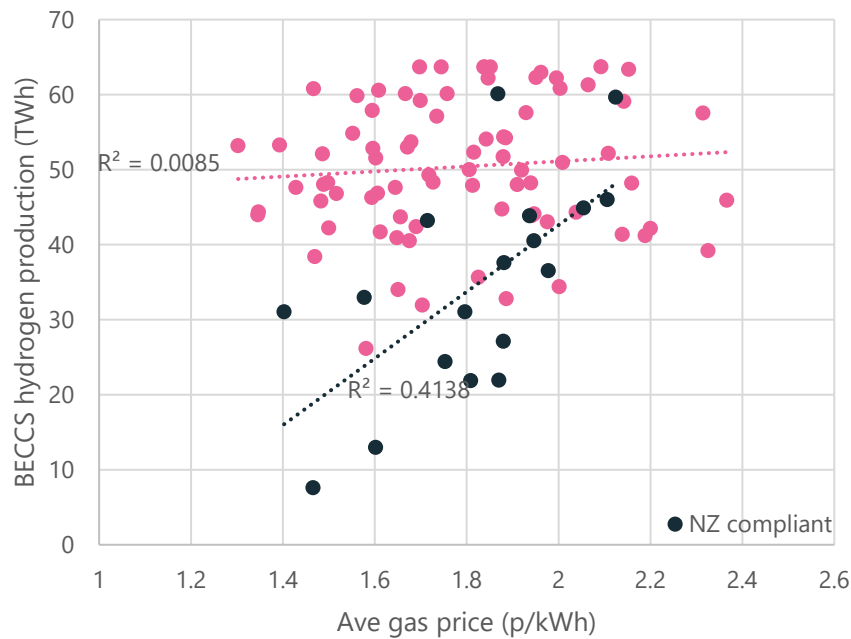


Figure 5.13: BECCS hydrogen production volume vs. average gas price in 2050.

For systems unable to meet targets (either a result of insufficient DACCS or biomass), the amount of hydrogen produced by BECCS does not respond to average gas price – the need to reduce, avoid and remove emissions is the primary driver for BECCS over blue hydrogen. Instead, hydrogen from BECCS in these systems is strongly related to the amount of biomass available (Figure 5.14).

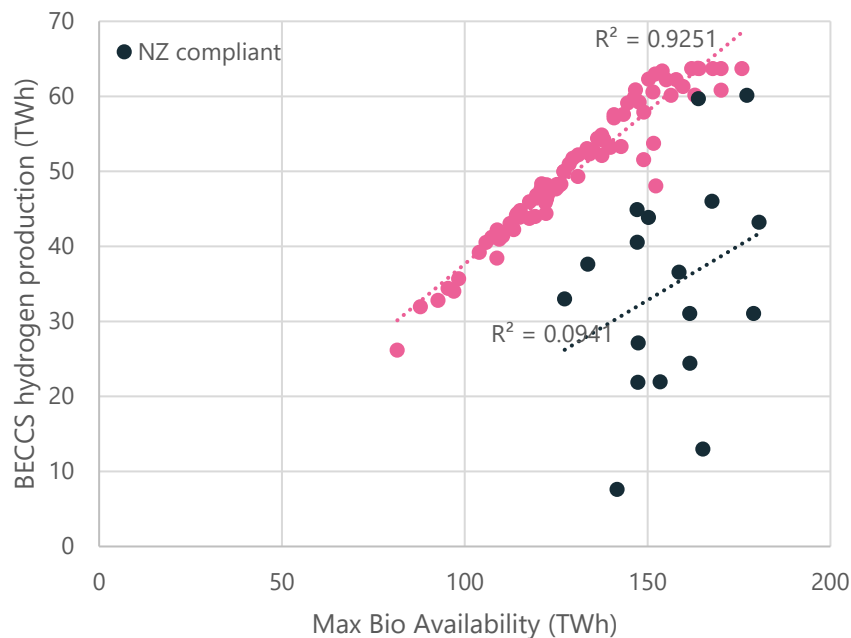


Figure 5.14: BECCS hydrogen production volume vs. biomass availability in 2050

Figure 5.15 shows the biomass consumption in power and hydrogen production vs. maximum biomass availability for four bands of DACCS deployment in 2050. The figure shows that generally, the amount of biomass consumed in hydrogen production increases

with availability. It also shows that biomass consumption in power generation tends to be much lower than in hydrogen production.

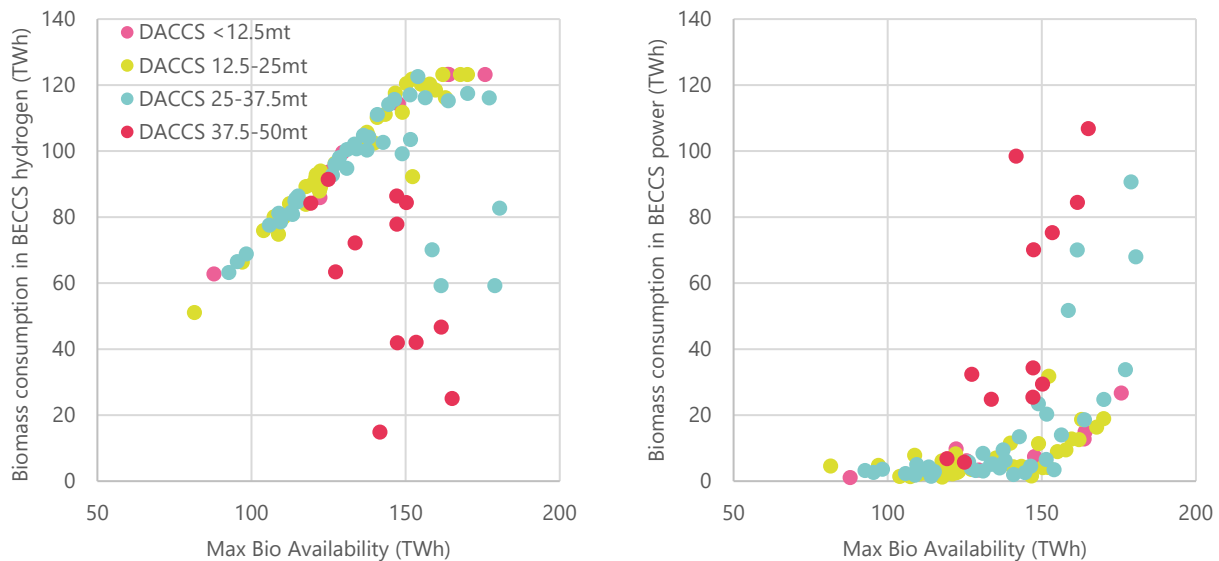


Figure 5.15: Biomass consumption in BECCS hydrogen production (left) and BECCS power production (right) vs. maximum biomass available in 2050 for four levels of DACCS deployment in batch 1 simulations

As the amount of DACCS available to the system increases, there is a shift in where biomass gets used. With DACCS deployment >25Mt in 2050, biomass starts to be diverted into power generation away from hydrogen production. When this happens, the amount of biomass being used in power generation increases with biomass availability. For DACCS amounts >37.5Mt, this diversion into power generation occurs at lower levels of biomass availability.

5.4.2. Absence of waste heat from nuclear generation III plants

An important observation from batch 1 simulations was the amount of waste heat being supplied by nuclear generation III (gen. III) plants and how this enables the deployment of waste heat DACCS plants. Batch 6 simulations were setup to explore what effect an absence of waste heat from gen. III plants might have on DACCS deployment. Batch 6 is essentially a duplication of batch 1 simulations but with waste heat extraction from gen. III plants prohibited.

5.4.2.1. The impact on meeting Net Zero

Prohibition of waste heat extraction from gen. III plants has had a small effect on the ability of modelled systems to meet net zero. However, this effect is relatively small as shown in Figure 5.16, which shows a similar distribution of Backstop deployment to that seen in batch 1.

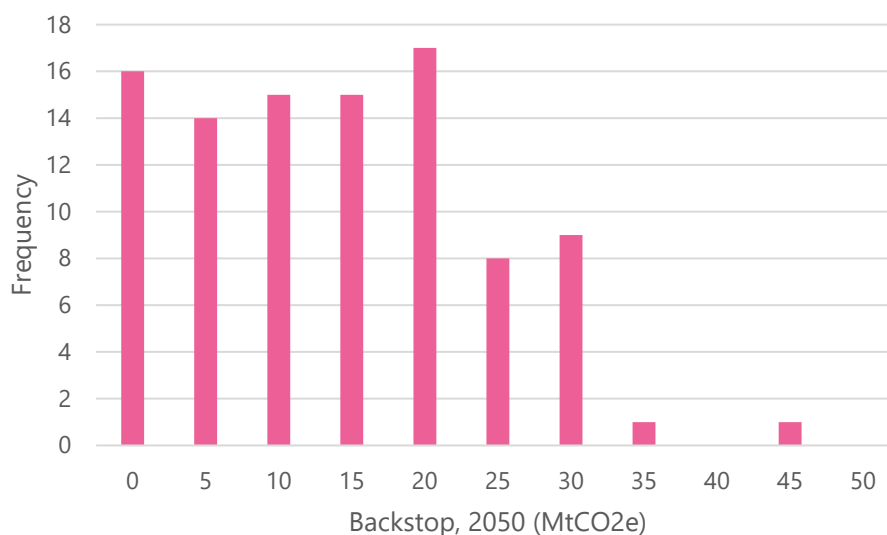


Figure 5.16: Distribution of Backstop deployment (emissions reduction deficit) in 2050 for batch 6 simulations

Of the 100 simulations modelled, 16 (vs. 18 in batch 1) were able to meet net zero. This suggests that sufficient negative emissions from biomass and DACCS were achievable. Indeed, inspection of the results confirms that DACCS deployment and biomass consumption in each of the simulations was maximised. Therefore, it appears that absence of waste heat from nuclear gen. III plants does not impact the amount of DACCS that can be deployed.

5.4.2.2. The impact on the type of DACCS plant deployed

Absence of waste heat from gen. III plants does not impact the total amount of DACCS that can be deployed. This is confirmed in Figure 5.17 which shows total DACCS deployment (stacked bars) equal to the maximum that could have been deployed (dashed line).

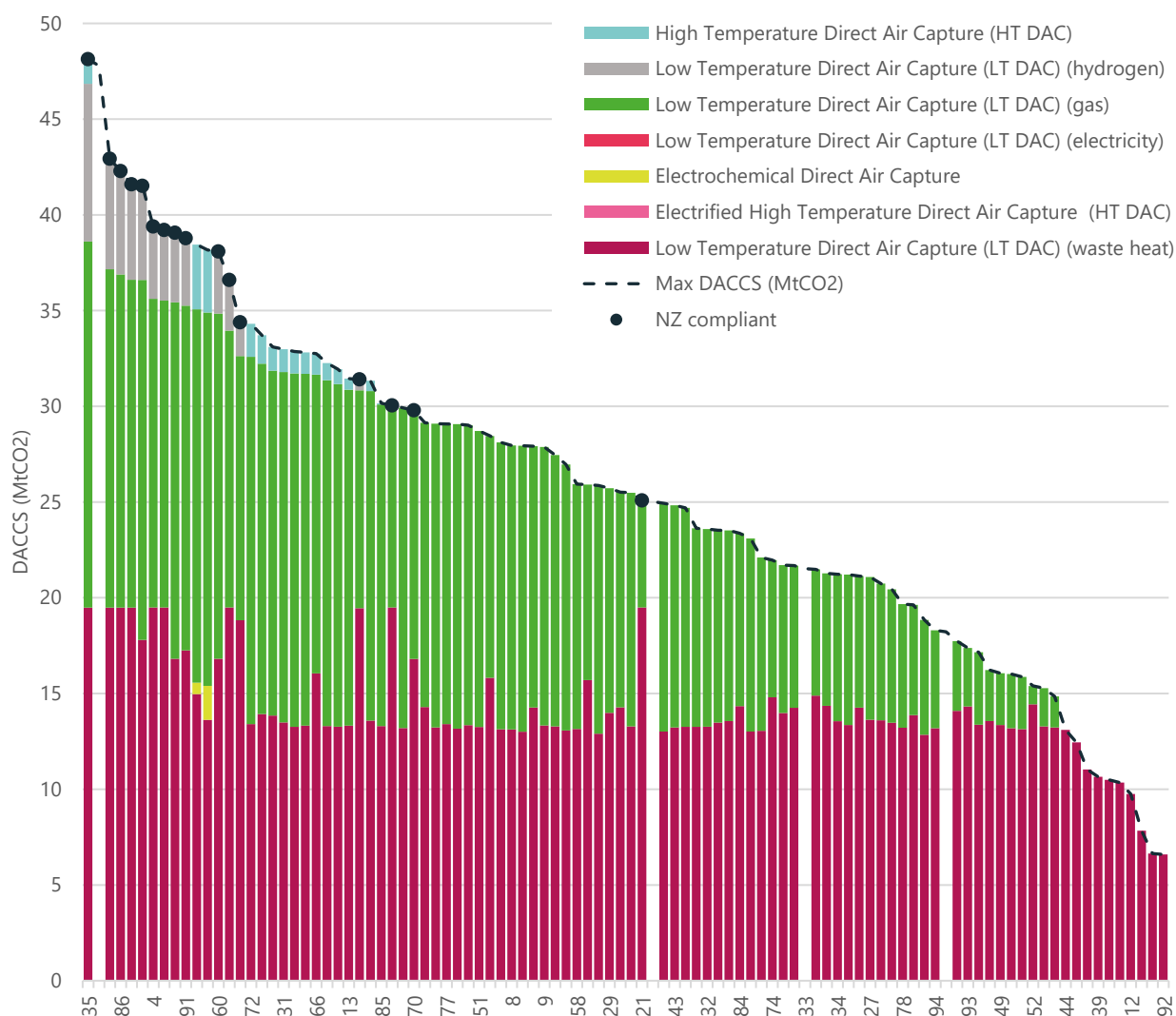


Figure 5.17: DACCS technology deployment for each batch 6 simulation (no results available for simulations 5, 11, 33 and 64 indicated by blank columns)

Figure 5.17 shows that waste heat DACCS plants are still the first priority DACCS option despite gen. III nuclear plants no longer supplying waste heat. However, the absence of waste heat from gen. III plants has affected the amount of waste heat DACCS that is deployed. In batch 1, an abundance of waste heat caused the waste heat DACCS plants to be deployed to the maximum amount (only limited by maximum DACCS quantity permitted in the simulation or waste heat DACCS build rates) – this was around 19.5Mt by 2050. In batch 6, many of the simulations are unable to deploy 19.5Mt waste heat DACCS as a result of a smaller overall supply of waste heat (see below).

The net zero compliant systems tend to deploy higher quantities of waste heat DACCS, often up to the 19.5Mt limit. This is a result of higher quantities of biomass enabling the diversion of biomass into BECCS power plants (from hydrogen production), and the subsequent extraction of waste heat for DACCS plants.

5.4.2.3. The impact on sources of waste heat

The exclusion of waste heat from nuclear gen. III plants leads to a massive reduction in the overall amount of waste heat available to the model (Figure 5.18). This has been shown to impact the amount of waste heat DACCS that is deployed (Figure 5.17).

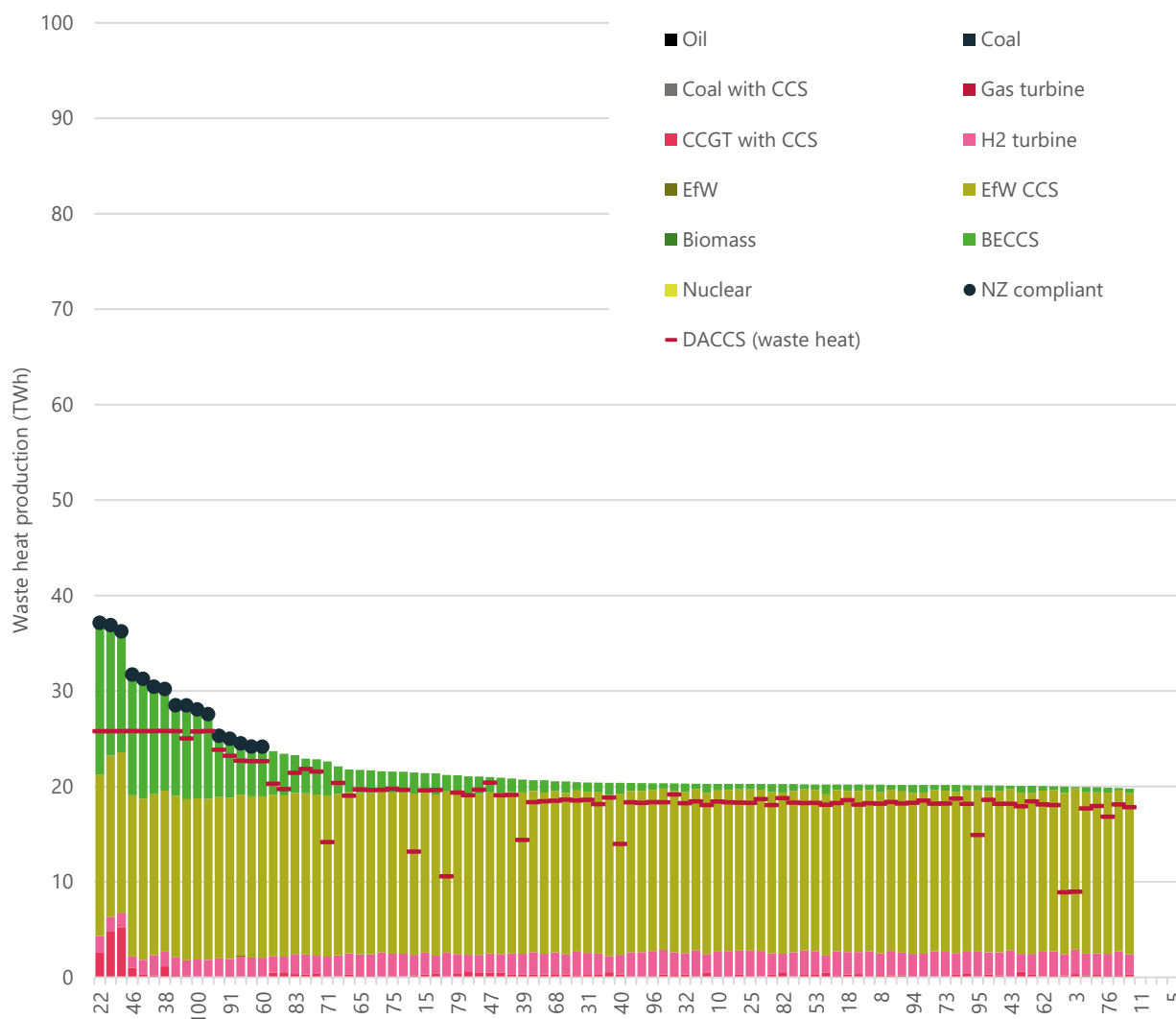


Figure 5.18: Sources of waste heat in batch 6 simulations (red dashes indicate the amount of waste heat consumed by DACCS plants)

The primary source of waste heat in batch 6 is from EfW with CCS plants. There is also a consistent supply from hydrogen turbines across the simulations. In simulations with high quantities of biomass, BECCS powerplants become an important source of waste heat for DACCS. In net zero compliant systems (indicated by black dots), biomass is diverted from hydrogen production into power generation in response to gas price as in batch 1. In addition, the waste heat extraction from BECCS powerplants enable waste heat DACCS deployment to approach maximum levels (19.5Mt in 2050 seen in Figure 5.19).

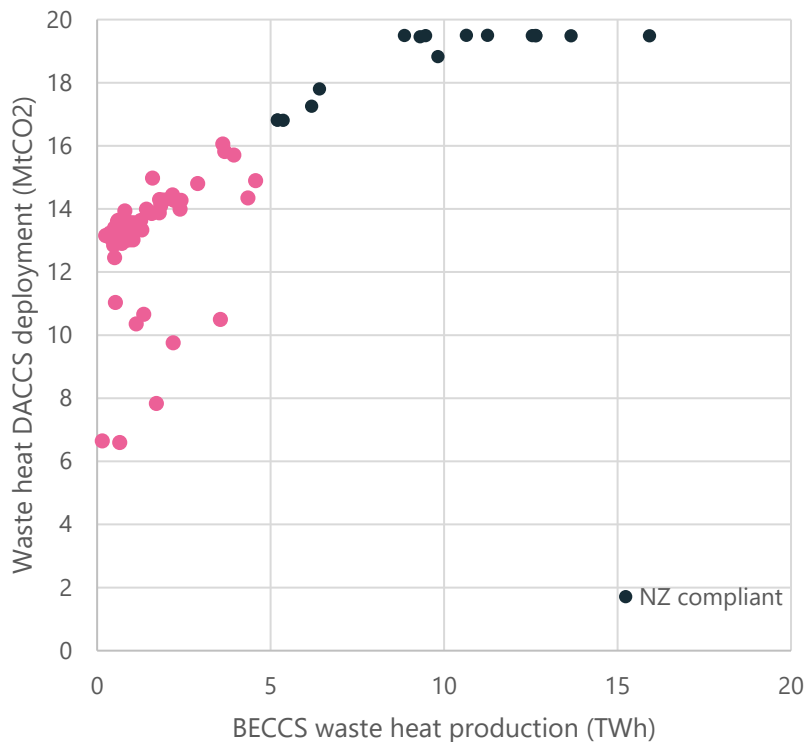


Figure 5.19: Waste heat DACCS deployment in 2050 vs. waste heat production from BECCS plants for batch 6 simulations

In summary, waste heat DACCS remains an important DACCS technology even when the amount of waste heat available to the system is reduced. There is a clear relationship between the amount of negative emissions available to the system in the form of BECCS and DACCS potential and the amount of waste heat DACCS that can be deployed:

1. High amounts of DACCS potential and biomass mean biomass can be diverted into BECCS power
2. More BECCS power means more of the DACCS can be waste heat DACCS
 - a. There are other uses of waste heat too such as district heat, which also benefits from BECCS in power

5.4.3. The effect of delayed CCS/DACCS rollout

The remaining four batches of simulations tested the impact of delaying the rollout of either DACCS (batches 2 and 3) or CCS infrastructure (batches 4 and 5).

5.4.3.1. Delaying DACCS rollout

Delays to DACCS rollout were modelled by shifting the DACCS build rate constraints used in batch 1 towards 2050 by 5 and 10 years (batch 2 and 3 respectively). This ultimately impacted the total amount of DACCS that could be deployed by 2050 because the shape of the curve (rate of deployment) remained unchanged (Figure 5.20).

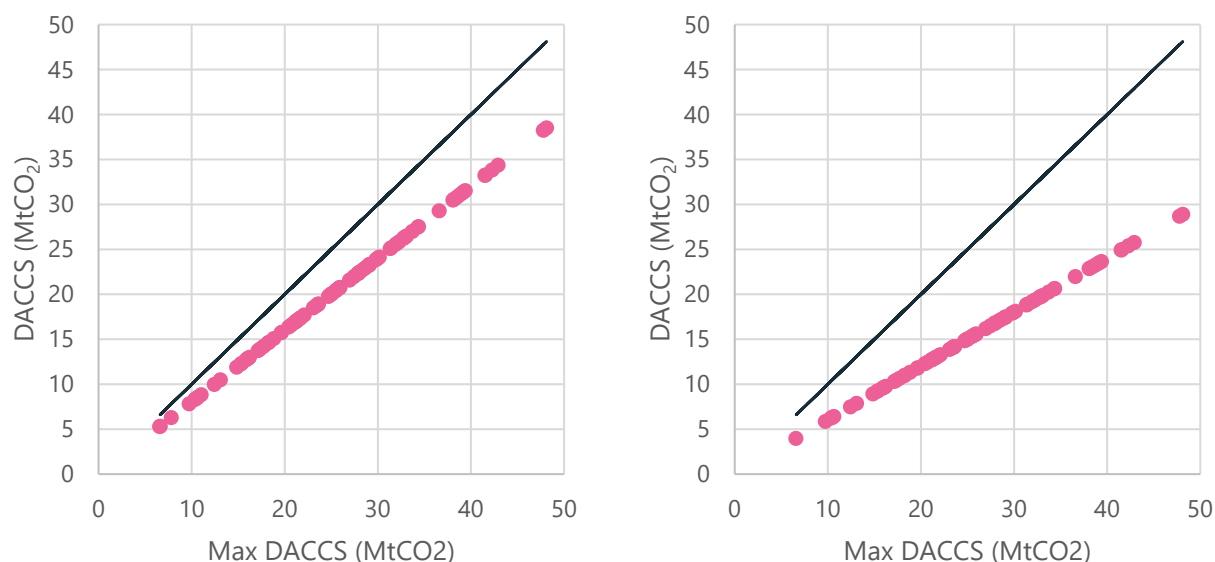


Figure 5.20: Actual 2050 DACCS deployment for DACCS delay of 5 years (left, batch 2) and 10 years (right, batch 3) vs. maximum possible deployment with no delay (black line)

Delaying DACCS deployment puts compliance with net zero at risk (Figure 5.21).

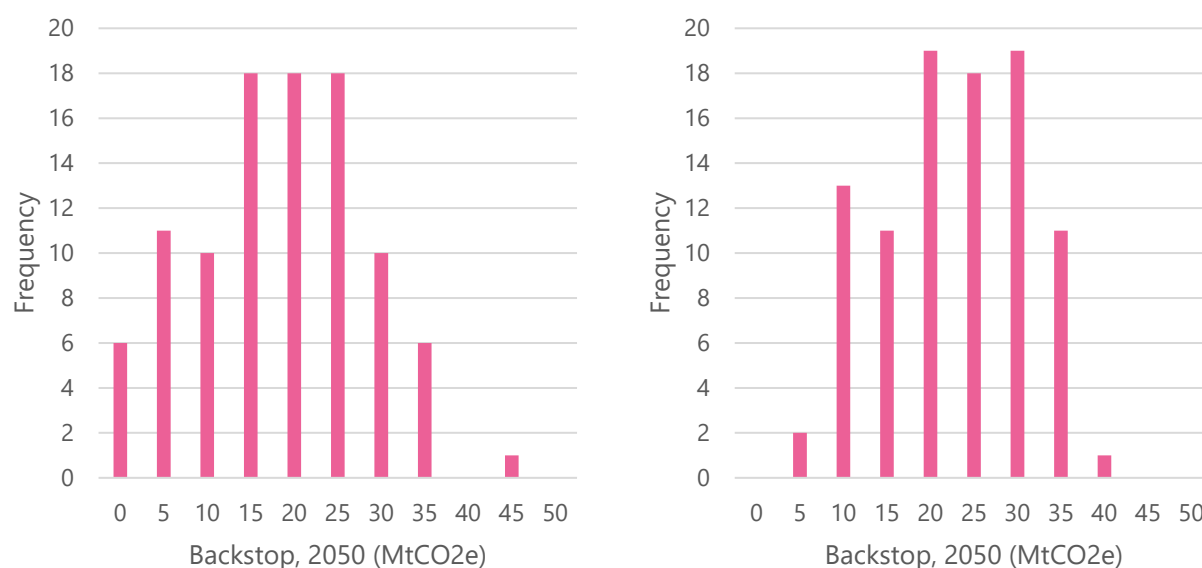


Figure 5.21: Distribution of Backstop deployment (emissions reduction deficit) in 2050 5-year delay to DACCS (left) and 10-year delay to DACCS (right)

Figure 5.21 shows that delaying DACCS, which reduces the amount that can be deployed in 2050, results in lower numbers of systems meeting net zero. A 10-year delay to DACCS results in no systems simulated meeting net zero. This assumes that the speed of DACCS rollout does not accelerate in response to the delay.

Quite simply, not having sufficient DACCS in 2050 means that there are not enough negative emissions in the system to offset residual emissions from sectors such as agriculture, industry and aviation.

5.4.3.2. Delaying CCS rollout

Delays to CCS infrastructure were modelled by shifting the availability of geological storage of CO₂ in batch 1 towards 2050 by 5 and 10 years (batch 4 and 5 respectively). A 5-year delay to CCS infrastructure rollout reduced the amount of CO₂ captured in 2030 but had negligible effect on the amount captured by 2050. A 10-year delay reduced the amount of CO₂ captured in 2030 and 2035 but also had a longer lasting impact, reducing the amount of CO₂ that could be captured from CCS processes in 2050 (Figure 5.22).

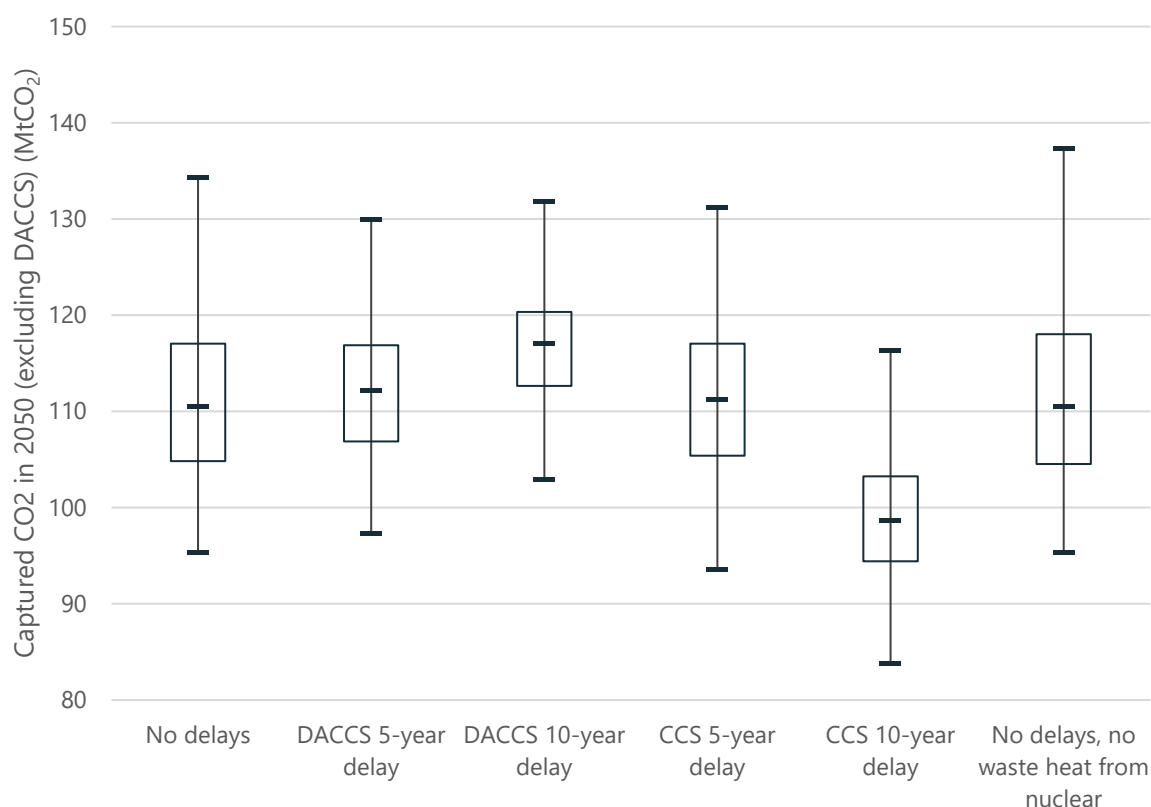


Figure 5.22: Range of captured CO₂ in 2050 (excluding that from DACCS) for each batch of simulations

In these simulations, delays to CCS also impacted the first year of deployment of DACCS plants because they are assumed to share some basic infrastructure in particular geological storage of CO₂ in offshore regions around the UK. However, because the DACCS build rate remained unaffected by delays to CCS infrastructure, it was able to be deployed to levels seen in the no CCS delay simulations (batches 1 and 6) once the CCS infrastructure was in place. The result of this was no difference to the likelihood of net zero being met compared to the no CCS delay simulations.

5.4.3.3. Wider system impacts

Whilst delaying CCS does not seem to impact the amount of DACCS that can be deployed by 2050 in these simulations, it does have other effects in the wider energy system, which also influence the choice of DACCS plant deployed. These effects are more pronounced with a 10-year delay to CCS rollout.

5.4.3.4. Hydrogen production

The first impact is noticed in the hydrogen production sector. Delaying CCS reduces the total amount of hydrogen that is produced because methane reforming with CCS tends to be the preferred option for bulk hydrogen production. In all simulations the amount of blue hydrogen produced is less when CCS is delayed. In response, the amount of electrolysed hydrogen increases – this is most apparent in non-Net Zero systems. In net zero systems (high biomass quantities and DACCS potential), biomass is no longer diverted into the power sector as occurred in batches 1 and 6 but it utilised almost entirely in hydrogen production.

Effects on the production volume are more pronounced in the net zero systems, which see a greater reduction in the amount of hydrogen produced vs. non-compliant systems. Non-compliant systems already see hydrogen production volumes limited by a lack of emissions headroom (from biomass and DACCS). These systems increase electrolysis to compensate for a reduction in blue hydrogen production to achieve nearly the same levels of production as in simulations without delayed CCS. Net zero systems are no longer able to increase blue hydrogen production to the levels seen in the no CCS delay simulations. Instead BECCS and a small increase in electrolysis makes up some of the shortfall but ultimately ESME is choosing to reduce overall production, which will impact consumption of hydrogen in the system.

5.4.3.5. Hydrogen consumption

A reduction in the amount of hydrogen produced by the system means the model makes choices about which sectors to supply. The main sectors to be supplied with hydrogen across all simulations are industry, power, residential & commercial heating and shipping.

For non-Net Zero compliant simulations, the reduction in hydrogen production is relatively modest as explained above. In response, small commercial vehicles (vans) are no longer switching to hydrogen. There are also small reductions in the consumption of hydrogen in industry and residential & commercial heating.

In net zero simulations, there are noticeable reductions in the amount of hydrogen being supplied to agriculture, residential & commercial heating and small commercial vehicles. Finally, these systems no longer deploy hydrogen fuelled DACCS plants, instead high temperature electric DACCS systems are rolled out after waste heat and gas fuelled build limits have been maximised.

5.4.3.6. Electricity consumption

High temperature DACCS systems have a greater electricity requirement than the hydrogen fuelled systems that are seen in the no CCS delay simulations. Figure 5.23 shows how electricity consumption by DACCS plants increases with increasing DACCS deployment. The figure shows that electricity consumption by DACCS plants increases approximately linearly with DACCS deployment in the no CCS delay simulations. In the 10-year delay simulations, there is an observable increase in the amount of electricity

consumed by DACCS vs. no delay simulations. This occurs at DACCS deployment of around 30Mt by 2050, when high temperature DACCS plants enter as part of the DACCS fleet.

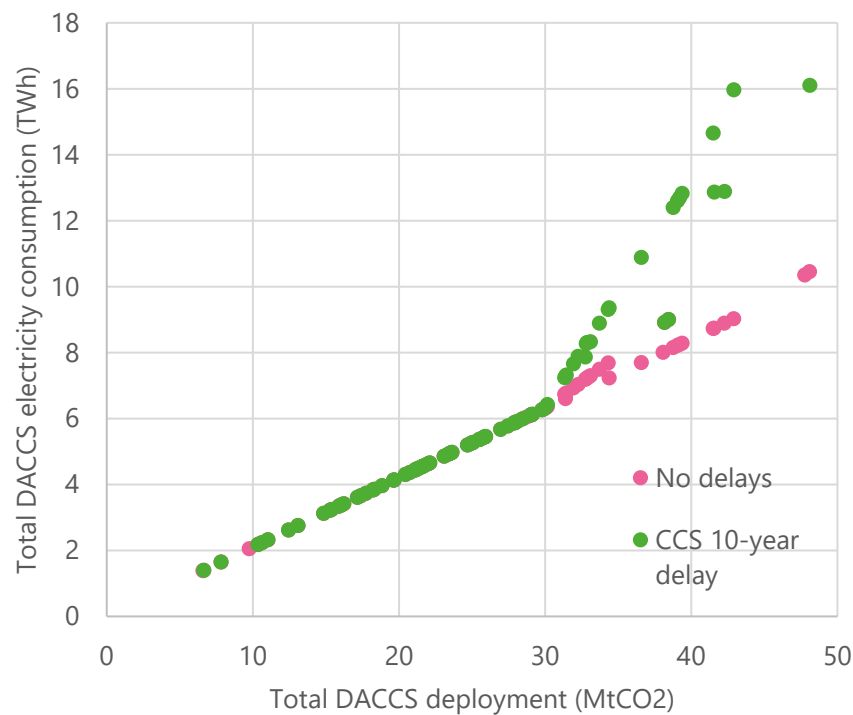


Figure 5.23: DACCS electricity consumption vs. DACCS deployment for no CCS delay simulations (batch 1) and 10-year CCS delay (batch 5)

Figure 5.23 shows a seemingly drastic increase in the amount of electricity consumed by DACCS when high temperature systems are deployed. However, this should be viewed in the context of the wider system. Figure 5.24 shows the total electricity consumption for the entire system vs. total DACCS deployment in 2050.

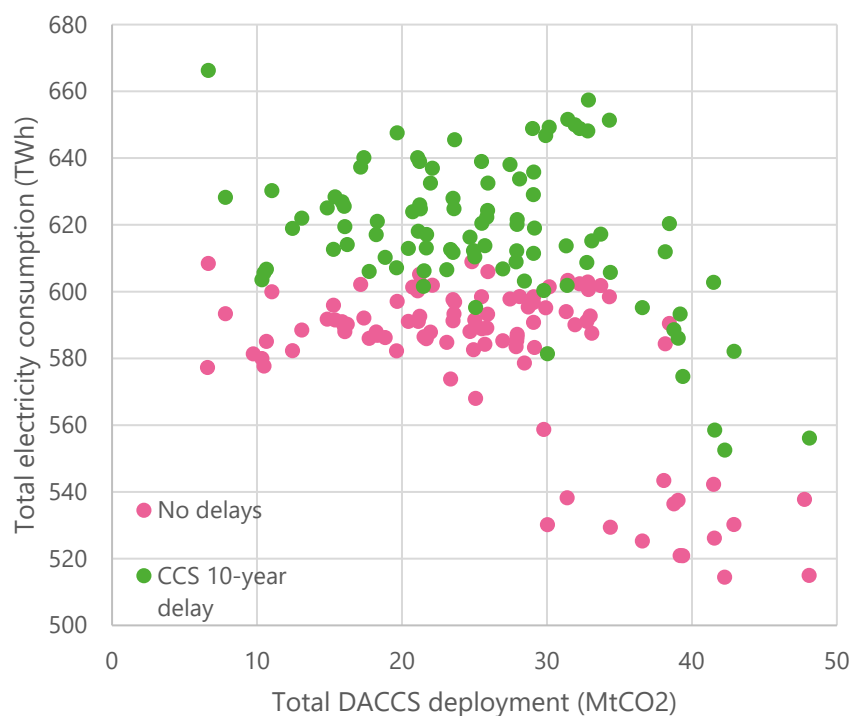


Figure 5.24: Total electricity consumption in 2050 vs. total DACCS deployment for no CCS delay simulations (batch 1) and 10-year CCS delay (batch 5)

The figure shows two main observations:

- Electricity consumption tends to be higher in systems with delays to CCS as a result of greater electrification necessary to decarbonise. In non-Net Zero simulations this is mainly to support hydrogen production. In net zero systems, this is a result of increase electrification across almost all sectors of the energy system including hydrogen production, agriculture, transport, residential & commercial heating and DACCS.
- As DACCS quantity increases beyond 30Mt in 2050, total electricity consumption decreases regardless of the type of DACCS plant being deployed. This is because DACCS (combined with other sources of negative emissions) creates emissions headroom, which alleviates pressure for some sectors (notably residential & commercial heating, road transport, aviation and hydrogen production) to maximise decarbonisation.

Figure 5.25 shows the distribution of electricity consumed by DACCS as a proportion of total electricity demand in 2050.

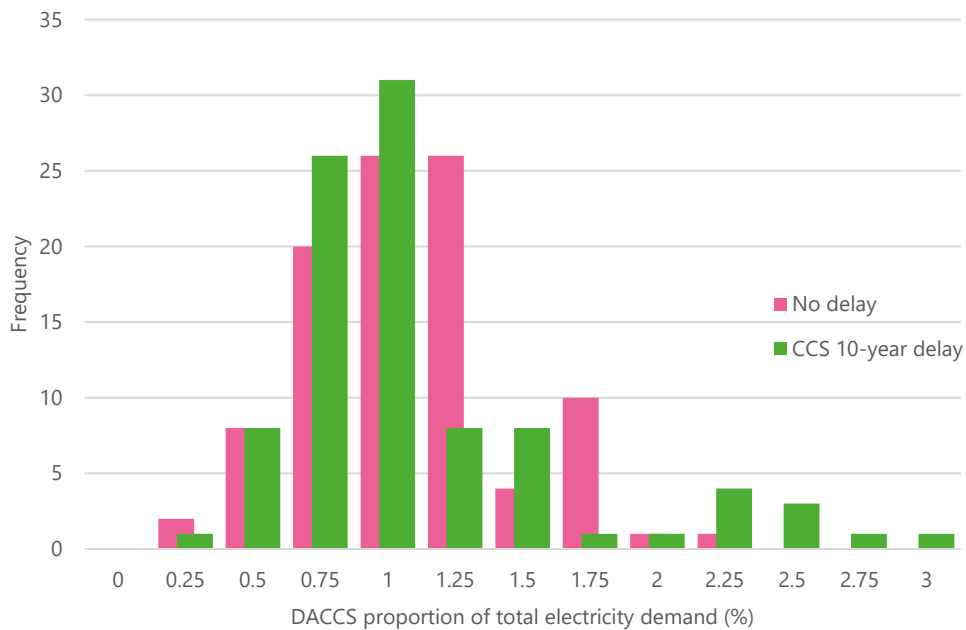


Figure 5.25: Distribution of DACCS electricity consumption as a percentage of total electricity demand in 2050 for no CCS delay simulations (batch 1) and 10-year CCS delay (batch 5)

On average, electricity consumption by DACCS plants is 1% of the total electricity consumption in 2050. This depends on the type of DACCS plant being deployed with simulations with high temperature DACCS plants seeing total consumption up to approximately 3% of total electricity demand. These plants are deployed in the simulations with a 10-year delay to DACCS as explained above.

5.4.4. Medium term results: implications for 2030-2040

The six batches of simulations can be characterised by three types of constraint applied to DACCS and CCS:

2. No delays to the deployment of DACCS or CCS: Maximum build rate for the group of DACCS technologies are sampled to deliver between 9-50Mt DACCS by 2050.
3. Delays to CCS deployment: DACCS maximum group build rates are still sampled between 9-50Mt, but the delay of CCS infrastructure also delays deployment of DACCS. However, since maximum build rates for DACCS technologies have not been altered, it is possible for DACCS deployment to “catch up” achieving up to 50Mt in 2050.
4. Delays to DACCS deployment: Individual DACCS maximum build rates are shifted back 5 and 10 years, delaying first deployment of DACCS. This impacts the final amount of DACCS that is deployed in 2050.

The maximum group build rate constraint is sampled to give the desired amount of DACCS in 2050. The shape of the build rate is not altered but rather scaled accordingly. For example, the build rate that gives 9Mt DACCS in 2050 is the same shape as the build rate that gives 50Mt in 2050 but the amount of DACCS that can be built per year is lower.

Delays to DACCS or CCS rollout will obviously have an impact on how much DACCS can be installed in the first year of deployment but also by 2050. This has been shown to have

implications on 2050 and whether the energy system is able to meet net zero targets or not. Figure 5.26 – Figure 5.28 show the distribution of total DACCS installed in the first year of deployment for each of the batches of simulations.

The charts show that in the first year of deployment between 2-10Mt DACCS is installed in simulations with no delays to CCS. Delaying CCS results in a delayed first year of deployment for DACCS but DACCS build rates are assumed to recover (i.e. are not affected by the delay to CCS) and between 4-20Mt DACCS is deployed in these runs in the first year (2035, batch 4 and 2040, batch 5 right hand charts of Figure 5.27 and Figure 5.28 respectively).

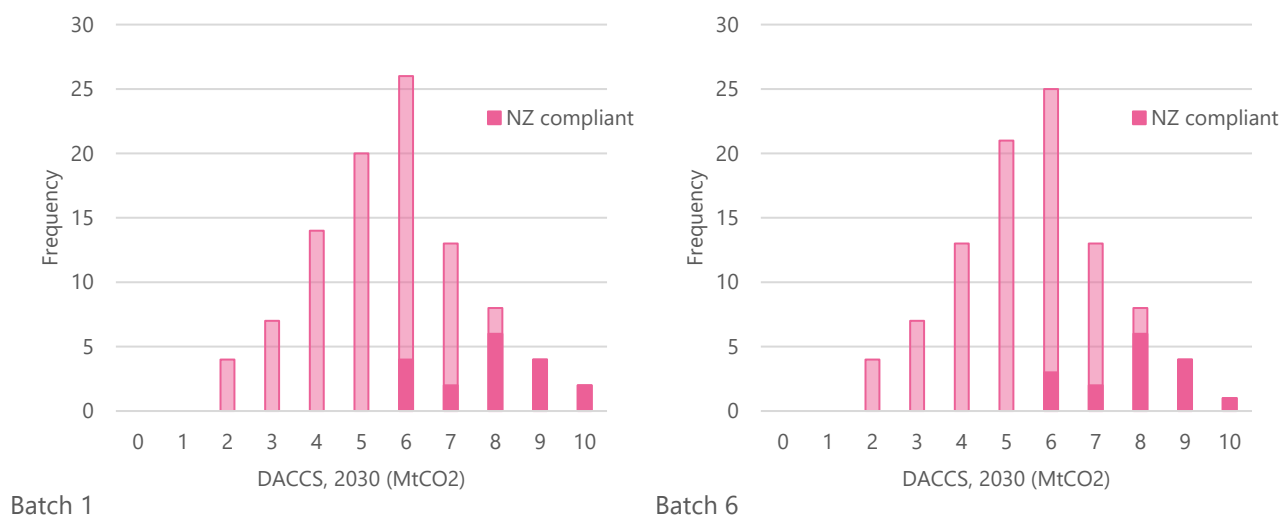


Figure 5.26: Distribution of DACCS quantity in first year of deployment for no delay to DACCS/CCS (batch 1, left) and no delay to DACCS/CCS with no waste heat from nuclear gen. III plant (batch 6, right)

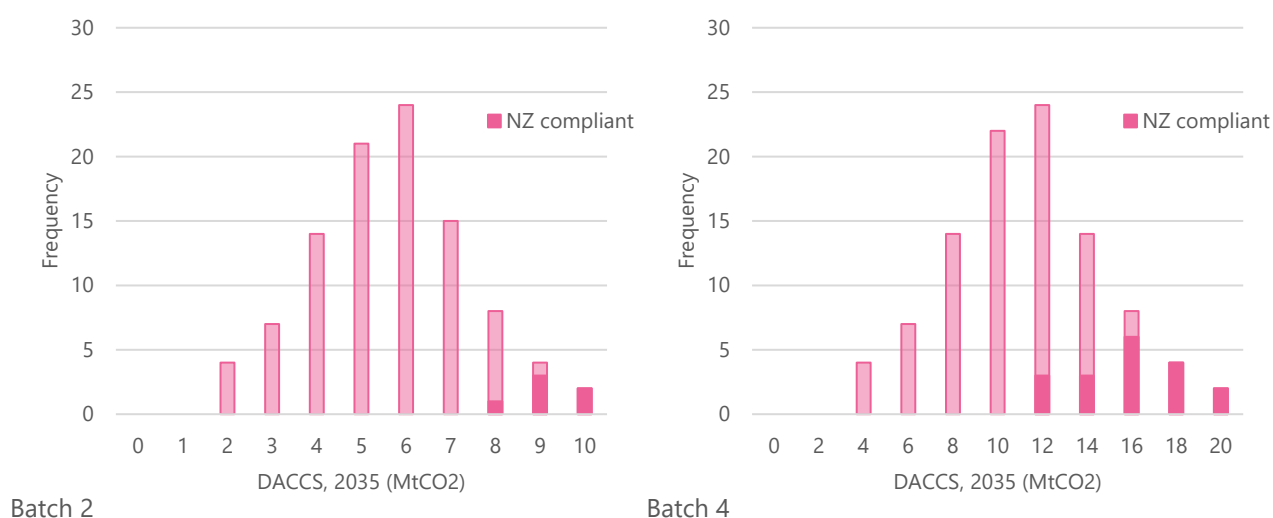


Figure 5.27: Distribution of DACCS quantity in first year of deployment for 5-year delay to DACCS (batch 2, left) and 5-year delay to CCS (batch 4, right)

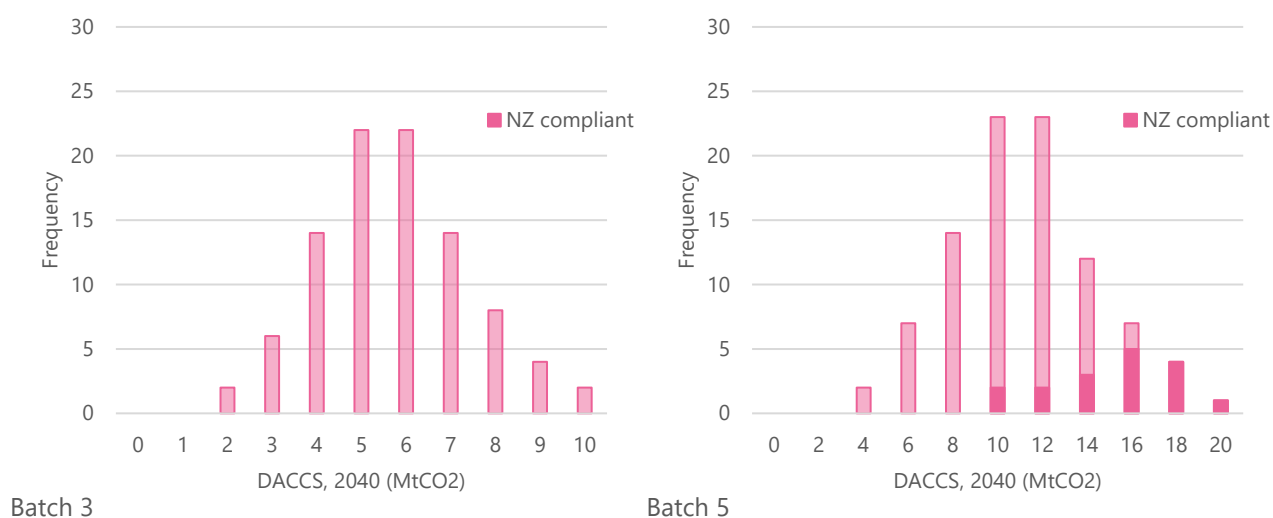


Figure 5.28: Distribution of DACCS quantity in first year of deployment for 10-year delay to DACCS (batch 3, left) and 10-year delay to CCS (batch 5, right)

In all batches, near term GHG targets are almost always met even with DACCS and CCS delays. The exception is for a single simulation in each of the batches which fails to meet targets in 2045. This simulation has the lowest amount of biomass and DACCS and is therefore unable to generate enough negative emissions in 2045 to offset emissions in other sectors (especially aviation, industry and agriculture).

DACCS (and CCS) is not necessary in 2030/35 to meet targets in those years. Instead DACCS/CCS should be deployed in these years to allow sufficient capacity to be built by 2050.

5.4.5. Costs

In least cost optimisation problems such as this, constraining the system or removing options leads to an increase in the total system cost. Figure 5.29 shows the impact on cost for two batches of simulations: no waste heat from nuclear gen. III plants (batch 6) and a 10-year delay to CCS deployment (batch 5). The chart shows the additional cost incurred for each of these batches relative to the batch 1 simulations (waste heat offtake from gen. III plant permitted and no delay to CCS deployment). Only cost differences for net zero systems were calculated. Total system costs have been discounted to 2020. A 2020 value of GBP is used.

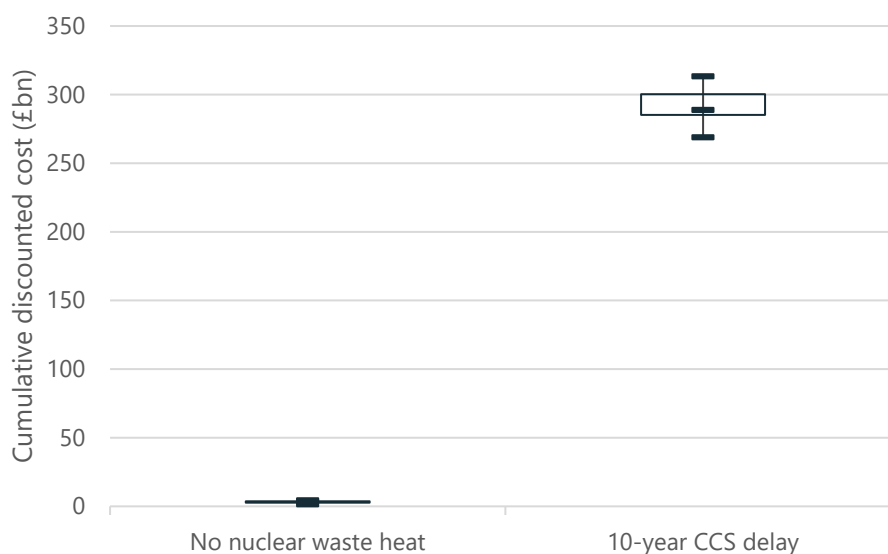


Figure 5.29: Additional whole system cost of meeting net zero for simulations without nuclear waste heat (batch 6) and 10-year CCS delay (batch 5) relative to the batch 1 simulations.

An absence of waste heat from nuclear gen. III plant has a relatively small implication on total system cost ranging from £1.5-4.4bn between 2020 and 2050. A 10-year delay to CCS on the other hand has a much starker impact with additional cost ranging between £269-313bn incurred over the period 2020-2050.

5.5. Energy system modelling conclusions

In this analysis, a deterministic reference case scenario was developed in accordance with DESNZ. The reference case included seven different DACCS technologies each characterised by capital and operating costs, energy requirements and build constraints.

The primary function of the reference case was to act as a starting point for the Monte Carlo simulations that followed. The main point to note about the reference case is that it is not a true net zero scenario in that it fails to meet the 2050 target by approximately 2Mt.

The Monte Carlo analysis suggests that net zero is dependent on the capacity for the system to create negative emissions. Two important sources of negative emissions are DACCS and biomass. Negative emissions from biomass and DACCS in the order of 75MtCO₂ are needed from a combination of these sources to make net zero possible in these simulations.

In all simulations DACCS plants are deployed to the maximum deployable capacity. There is a clear priority order:

- DACCS plants that utilise waste heat are deployed first
- Natural Gas fuelled DACCS plants are next to be deployed
- Net Zero systems then deploy hydrogen fuelled DACCS plants whilst non-compliant systems deploy high temperature DACCS

Biomass is also deployed to the maximum amount but simulations with high capacities of DACCS influence where this biomass gets used. Net zero systems are able to divert biomass away from hydrogen production (with CCS) to BECCS power and take advantage of additional waste heat from these plants. Gas price also affects the decision to produce hydrogen from biomass in net zero systems with higher gas prices prompting BECCS hydrogen production and lower gas prices seeing more blue hydrogen produced and biomass diverted into power production.

Nuclear gen. III plants are the primary source of waste heat for DACCS plants. However, DACCS deployment is not linked to nuclear gen. III capacity. In the absence of waste heat from nuclear gen. III plants, DACCS deployment is still maximised.

In simulations without waste heat offtake from nuclear plant, waste heat DACCS remains the first, priority DACCS technology deployed. However, the amount of waste heat available to the system is significantly reduced, which ultimately impacts the overall amount of waste heat DACCS that can be deployed. In these instances, energy from waste plants (with CCS) become one of the key sources of waste heat for DACCS. In net zero compliant systems, with high availability of DACCS and biomass, biomass is diverted from hydrogen production into power generation, which becomes another key source of waste heat and enables maximum deployment of waste heat DACCS.

Delaying DACCS or CCS infrastructure rollout has the following impacts:

- If delays to DACCS rollout lead to a reduction in the total amount of DACCS that can be deployed in 2050, then compliance with net zero is at risk.
- Delays to CCS infrastructure do not necessarily put net zero at risk provided that DACCS deployment rates are quick enough to deliver sufficient negative emissions in 2050.
- Delays to CCS do affect the wider energy system, particularly the amount and method of hydrogen production. This has knock-on effects on the DACCS

technology choices made, with high temperature electric systems being preferred to hydrogen fuelled plants.

- Increase in electricity consumption by DACCS plants are offset by savings made in other sectors as a result of emissions headroom created by DACCS reducing pressure to maximise decarbonisation of aviation, residential & commercial heating, hydrogen production and road transport.

DACCS is an important source of negative emissions much needed to counteract emissions from difficult to decarbonise sectors such as agriculture, aviation and industry. It could be a useful option to hedge against slow adoption of low carbon behaviours across society (e.g., reduction in flights abroad) or in the event that innovative technologies in key sectors do not emerge (e.g., zero carbon aircraft).

6. WP4: ESME Infrastructure Toolkit Modelling

6.1. Background

Infrastructure is one of the five pillars of the Industrial Strategy and is recognised within the Clean Growth Strategy as key to meeting our carbon targets. Net zero energy systems will require new ways of heating homes, powering vehicles, producing power and fuelling industry. The transition to a net zero energy system in 2050 will need us to expand and repurpose existing energy infrastructure networks, build new ones and integrate them together into a single energy system to ensure that changing end user demands can be matched to new ways of delivering energy.

However, infrastructure takes a long time to build, has a typically long asset life and requires substantial investment. Given future energy system uncertainties, it is challenging to define what to build, and where and when to build it. Nevertheless, the implied scale and rate of required infrastructure transition is likely to be unprecedented within the UK regardless of the low carbon energy system that emerges. It is also difficult to develop a national infrastructure strategy without more detailed information on local characteristics.

6.2. The ESME Infrastructure Toolkit

The ESME Infrastructure Toolkit contains a series of modules, each of which has several processes that represent different types of infrastructure within each network type. It can work as one tool or its processes can be used as individual elements and tailored to derive insights. Allocation or disaggregation processes require outputs produced by ESME which address national outcomes. ESME Infrastructure Toolkit disaggregates these to a local level (MSOA or LA).

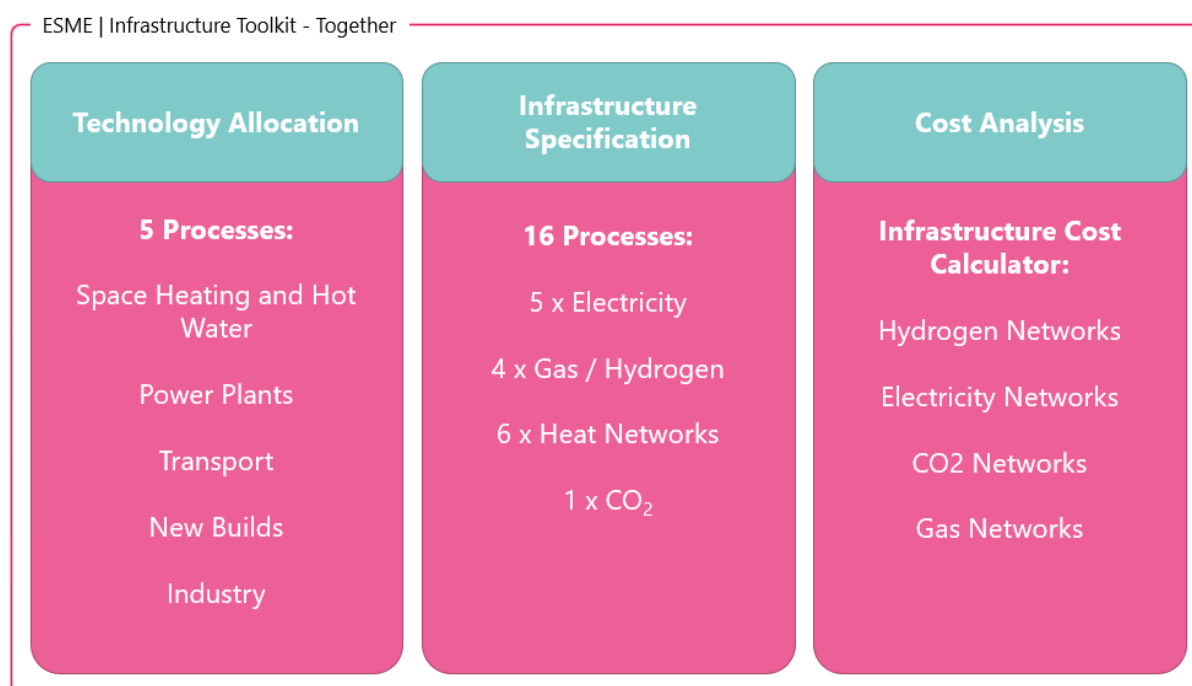


Figure 6.1 – ESME Infrastructure Toolkit and its Processes

6.3. Data inputs

6.3.1. National Grid substations

Locations of National Grid substations are used to determine the length of electrical connection required. Base costs of connecting to the sub-station were also required. It is assumed that all DAC plants in this work are directly connected to a National Grid substation with current (March 2023) locations represented in Figure 6.2.

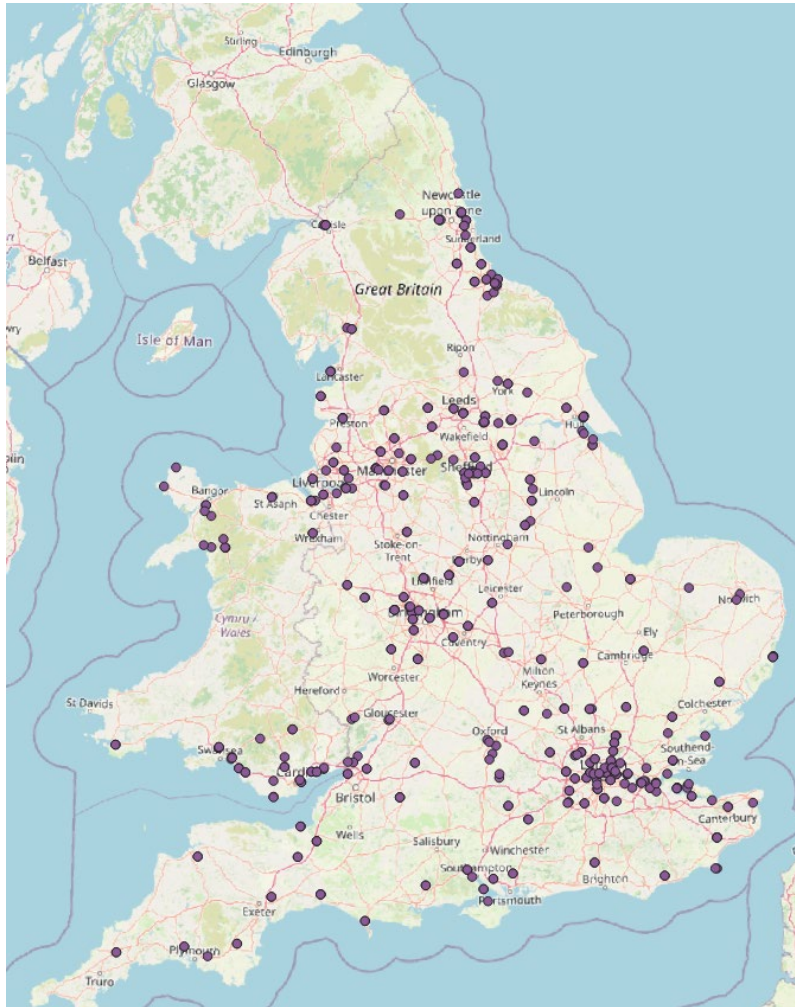


Figure 6.2 - Existing National Grid substations.

Section 5 presented ESME results which showed low-temperature waste heat DAC as the most readily deployed technology. Power generation (including Nuclear) and Industry are favourable sources of waste heat. Substation capacity (specifically for the power and nuclear examples) are expected not to be an issue. Most configurations of DAC plant would require less electricity than the power or nuclear sites would produce. This work assumes National Grid substation capacity is sufficient for the purposes of this analysis.

6.4. Indicative CO₂ pipelines

Indicative CO₂ pipelines corridors and port locations have been gathered from the sources shown in Table 6.1. Route locations are shown in Figure 6.3. For some industrial clusters (North West, North East, Teesside, Humber, Scotland), relatively detailed pipeline corridors

exist within the planning system. Reflecting the relatively advanced status of these clusters' plans for CO₂ pipelines. For others (e.g., South Wales, Bacton) terminals for CO₂ storage are known as either port options for South Wales or gas terminals for Bacton. Onshore pipeline corridors to these "potential" terminals do not exist, hence only the terminals were represented with the expectation that the model would then cost a dedicated CO₂ pipeline from a DACCS facility to these locations.

Table 6.1: References for Indicative CO₂ Pipeline Routes

Carrier	Area	Reference
Hydrogen	GB	Project Union ¹⁰
CO ₂	Scotland	Acorn ¹¹
CO ₂	Teesside	Aecom ¹²
CO ₂	Bacton	Hydrogen East ¹³
CO ₂	North West	Hynet ¹⁴
CO ₂	Humber	National Grid ¹⁵
CO ₂	South Wales	Welsh Government ¹⁶

¹⁰ <https://www.nationalgas.com/document/139641/download>

¹¹ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1057558/A01_KKD7_D08_Ops_and_Maintenance.pdf

¹² <https://www.netzeroteesside.co.uk/wp-content/uploads/2020/06/PEIR-Appendix-01A-Scoping-Report.pdf>

¹³ <https://hydrogeneast.uk/wp-content/uploads/2021/05/Hydrogen-East-Bacton-Stage-One-Report-Launch-Final.pdf>

¹⁴ <https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN070007/EN070007-000022-HYNE%20-%20Scoping%20Report.pdf>

¹⁵ <https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN070007/EN070007-000022-HYNE%20-%20Scoping%20Report.pdf>

¹⁶ <https://www.gov.wales/sites/default/files/publications/2021-10/a-carbon-capture-utilisation-and-storage-network-for-wales-report.pdf>



Figure 6.3: Indicative CO₂ pipeline corridor and terminal locations (with buffer).

6.4.1. Infrastructure costs

Three elements of infrastructure cost were considered in the siting methodology for DACCS facilities. The cost of the following is summarised in Table 6.2: Costs for CO₂ pipelines, waste heat pipelines and electrical grid connections as used in the DACCS siting formula.

- CO₂ pipeline cost
- Waste heat pipeline cost
- Grid connection cost.

For CO₂ pipelines, a cost was assumed on a “per kilometre” basis. Together with the distance from the planned CO₂ pipeline corridors a cost to run a CO₂ pipeline from the indicative corridor to a prospective DACCS site could then be calculated by distance of pipe needed. The cost per kilometre was taken from a combination of internal ESC data in our Infrastructure Cost Calculator, and a report by Element Energy for BEIS¹⁷. It is worth noting that the diameter of the pipeline is not being considered in this cost. In future work the diameter of the pipeline could be calculated based on the amount of CO₂ being transported and the pressure that needs to be maintained to calculate a required diameter and a more accurate cost.

Waste heat pipeline cost was equated on the basis of distance from the waste heat source (e.g., industry, power generation) to the prospective DACCS site. A per kilometre costing for a waste heat pipeline was taken from a 2015 report for the Department for Energy and Climate Change on UK heat networks¹⁸.

For electrical grid connections, it was assumed that a tertiary grid connection was needed to satisfy the demands of a 1MtCO₂/yr DACCS facility. It is assumed that this size DACCS facility would require around (or more) 30MW of continuous demand. A base connection cost was assumed, with an additional per kilometre cost to account for distance to the substation. These were based upon the National Grid Connect Now tool¹⁹, and internal ESC data and estimates.

Smaller DACCS facilities or scaled deployment based on smaller module sizes ($\approx 50\text{KtCO}_2/\text{yr}$) should be investigated. This should include assessments where tertiary connections are not required but local grid constraints might exist.

Costs for all infrastructure was assumed to remain constant over time. Only capital costs for the pipelines and grid connection were considered; ongoing operating costs were not factored into the costing formula.

Table 6.2: Costs for CO₂ pipelines, waste heat pipelines and electrical grid connections as used in the DACCS siting formula.

Item	Basis	Cost £GBP
CO ₂ Pipeline	Per kilometre of pipe	£983,259
Waste Heat Pipeline	Per kilometre of pipe	£1,386,000
Electrical Grid Connection	Base cost	£13,050,000
Electrical Grid Connection	Per kilometre from substation, in addition to base cost	£11,812,352

6.4.2. Waste heat sources

¹⁷ Element Energy, 2020, “CCS deployment at dispersed industrial sites”. Appendix A4, Table 26.

¹⁸ Department for Energy & Climate Change, 2015, “Assessment of the Costs, Performance, and Characteristics of UK Heat Networks”. Table 8.

¹⁹ <https://www.nationalgrid.com/electricity-transmission/how-to-get-connected/building-the-connection/how-much-will-it-cost>

6.4.2.1. Power generation

ESME results for power generation technologies are at a NUTS1 regional level and have been allocated to specific sites using the large power generation disaggregation method in the ESME Infrastructure Toolkit.

ESME specifies the construction of new capacity for each technology by region and "build period." Build periods relevant to the large plant allocation method are five-year intervals dividing the period 2020 to 2050. The large plant allocation method is applied for each region separately. Its inputs are:

- The ESME total new build in the region for the relevant power generation technologies for broken down by build period, and
- A list of sites in the region. This list of sites has attributes specifying, for each site:
 - The kinds of technologies which may be built there (for example, is nuclear allowed),
 - The amount of existing electricity infrastructure available to convey electrical power from the site.
 - Where appropriate, information on existing capacity and the site and its likely retirement date.
 - The list of sites has been compiled with reference to existing and brownfield power generation sites derived from DUKES.
- A minimum unit size given for each technology.

Based on these inputs, the large plant method creates a schedule for each site of units built by technology and build period, such that:

- At the end of each build period, the cumulative new build of each technology over sites in the region is at least as large as the cumulative new build given by ESME (in MW capacity).
- The minimum unit sizes are respected when deciding what is built at each site in each build period.
- A nominal cost is minimised which consists of:
 - A cost associated with building new capacity with a nominal time discounting factor. This serves to make sure that amount built at sites is not in excess of, or in advance of, that required to satisfy the above constraints.
 - A cost associated with the amount by which the capacity of the electrical infrastructure capacity at a site exceeds the pre-existing amount. This distributes the sites in such a way that favours the re-use of existing transmission capacity.

Nuclear generation plants are large waste-heat producers and their allocation to specific sites using this methodology was a key part of the analysis. The location of the potential nuclear sites is shown in Figure 6.4. The dot size represents existing electrical infrastructure capacity (maximum 3.5GW).

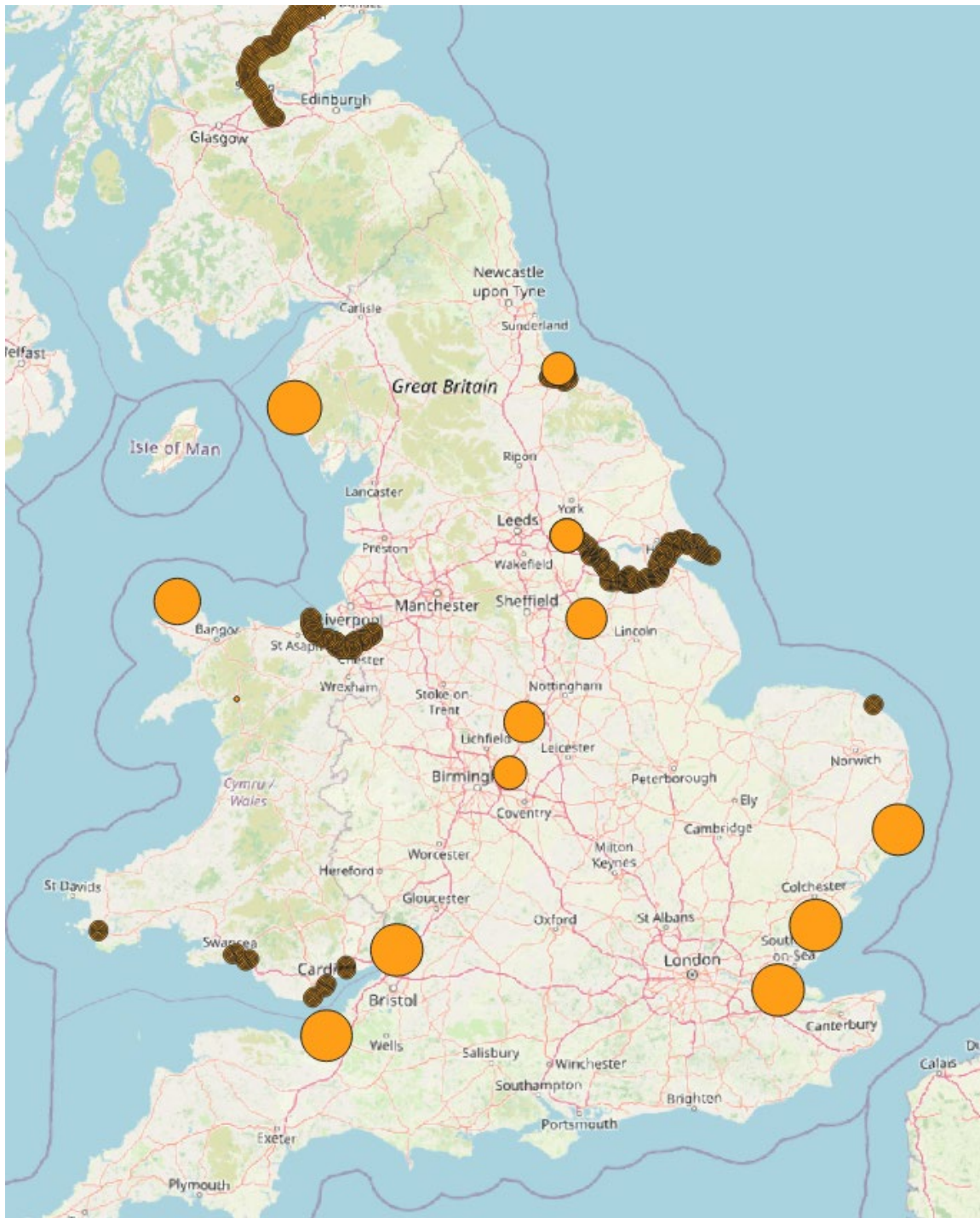


Figure 6.4: Location of current and potential nuclear sites. Dot size represents existing electrical infrastructure capacity (maximum 3.5GW).

6.4.2.2. Industry

The industrial waste heat by sector figures presented in section 4.2.2 were disaggregated to sites using the 2019 NAEI point source data²⁰. A "contribution factor" for each site was determined based on how much that site contributed to the overall emissions for the sector. The contribution factor was used to approximate how much waste heat could be available from that site.

²⁰ <https://naei.beis.gov.uk/data/map-large-source>

$$\text{Contribution Factor}_{\text{site}} = \frac{\text{Total CO}_2 \text{ Emissions}_{\text{site}}}{\text{Total CO}_2 \text{ Emissions}_{\text{sector}}}$$

$$\text{Waste Heat}_{\text{site}} = \text{Contribution Factor}_{\text{site}} \times \text{Waste Heat}_{\text{Sector}}$$

Figure 6.5 illustrates the distribution of industrial waste heat potential across the UK. The exact waste heat quantities and locations aren't intended to be decipherable but are presented here for visualisation purposes only.

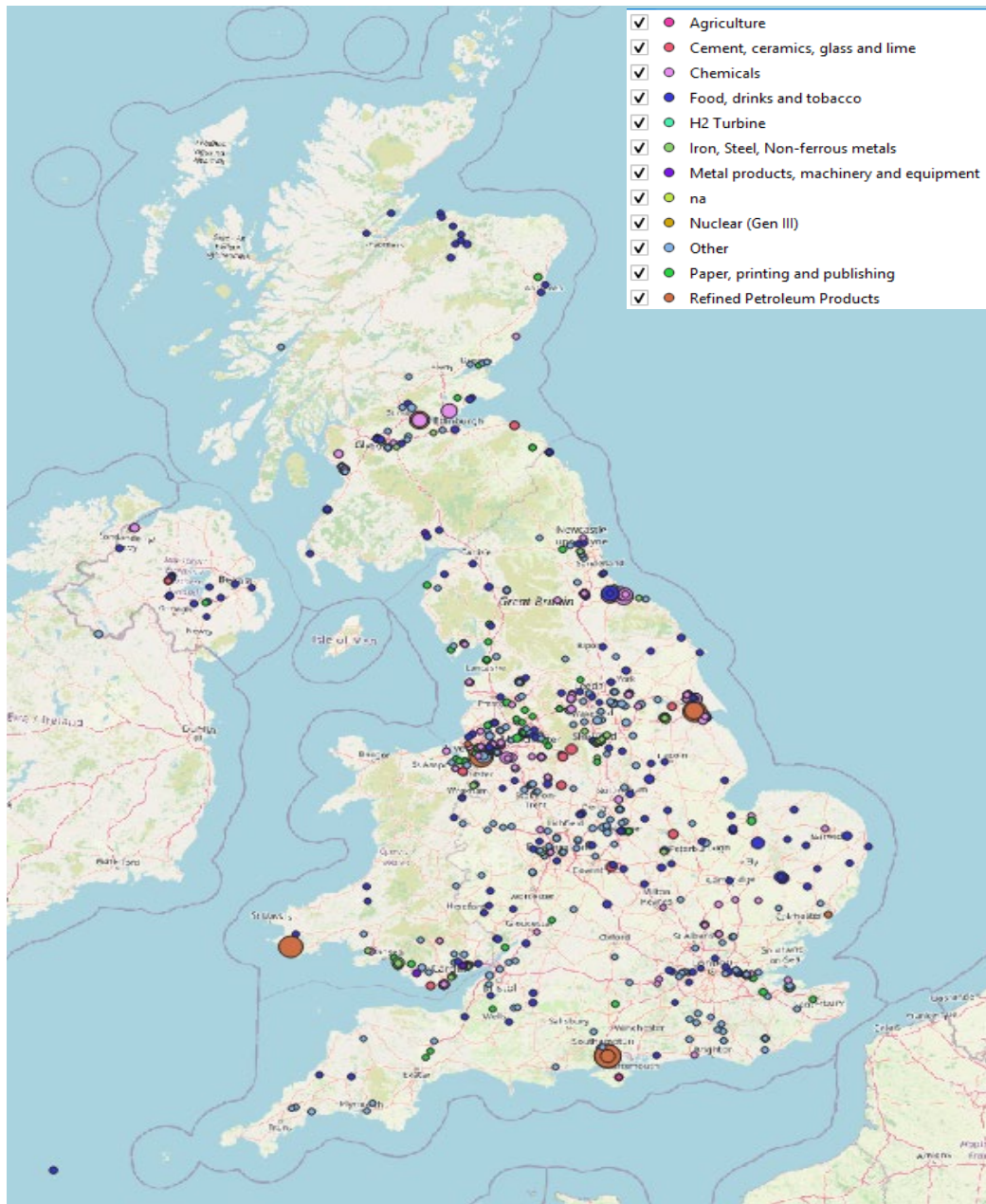


Figure 6.5: Industrial waste heat source distribution across the UK.

As mentioned in section 5 it is not known how industrial waste heat availability will develop over time. One would expect industry to strive to utilise as much waste heat as possible to improve efficiency through process improvements and integrations such as those with carbon capture plants. A reasonable assumption to make is that industrial processes remain similar with changing fuel vectors or additional plant such as carbon capture. For the purposes of analysing industrial waste heat for DAC industrial waste heat was assumed

to remain constant. Providing industrial waste heat projections, also noted in section 4.2.4, would provide benefits beyond just DACCS (e.g., for future district heating networks) and although out of scope for this analysis should be an area for further work.

The largest amount of waste heat potential comes from refineries such as the Pembroke Refinery in the south-west of Wales, which has an estimated 600GWh/yr of waste heat released each year. For reference a representative value of heat needed for a 1MtCO₂/yr DACCS facility is around 1600GWh/yr (1.6TWh/yr).

6.5. DACCS siting optimisation methodology

Least-cost locations for DACCS technology were determined by proximity to an indicative CO₂ pipeline route, a waste heat source and existing electrical infrastructure. A linear optimisation model was built to determine the sites that would have the lowest infrastructure cost, whilst ensuring the required amount of DACCS was built. For the reference case each waste heat source was assumed to be directly coupled to a DACCS plant, i.e., all the waste heat was supplied directly to DACCS rather than any being used for other requirements, such as district heating or industrial process carbon capture plants.

An initial review of siting options for DACCS, the spatial footprint (i.e., 80-100 acres for a 1MtCO₂/yr site) did not appear to be a major constraint. Therefore, land requirement for DACCS facilities was not explicitly considered in this siting optimisation, though could be a subject for future work. Moreover, there are limited estimates on land area required for DACCS facilities, and the required land for DACCS may reduce over time with different air contactor designs, the ability for modules to be “stacked,” as well as locational factors such as altitude and planning constraints.

All infrastructure was assumed to be built in a straight line. The next step would be to analyse the feasibility of doing so, as technical, geographical, and planning realities would very likely necessitate a non-linear pathway and incur additional costs beyond just additional length of piping.

In addition, to reduce the complexity of the initial DACCS siting modelling, the optimisation was performed for 2050 only (the final realisation of the DACCS deployment and the most challenging to meet for infrastructure) but rollout potential is also included in section 6.6.1.

6.6. Results

6.6.1. Reference case

Initial results from the ESME Infrastructure Toolkit, after allocating the large power generation, are shown in Figure 6.6, where the size of the circle reflects the amount of waste heat generated from each site. Potential waste heat available from individual nuclear sites is far larger than industrial sites or other power generation technologies.

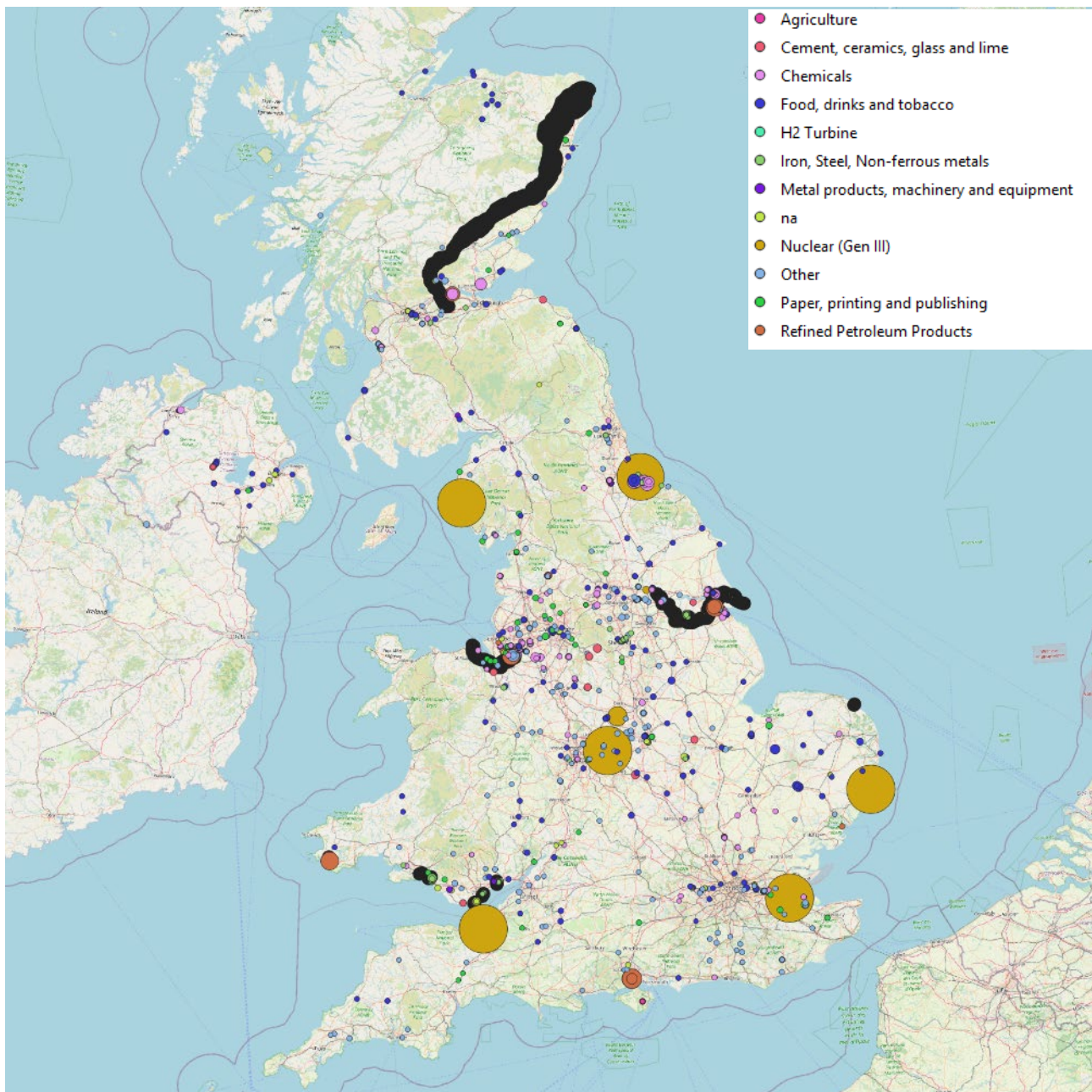


Figure 6.6: Waste heat sources from the reference case. Shown to visualise the potential for waste heat from nuclear generation compared with other technologies/industrial sites.

Figure 6.7 shows the optimal locations for building DACCS plants, optimised to minimise infrastructure cost. Waste heat sources are 3rd generation nuclear power stations. Table 6.3 shows the associated waste heat produced, DACCS plant size and capital cost of infrastructure in each location. Table 6.4 shows the waste heat and DACCS potential through the years.



Figure 6.7: Reference case optimal site locations (nuclear waste heat sources).

Table 6.3: Nuclear waste heat and DACCS siting combinations.

Site	Capacity (GW)	Waste Heat (GWh/year)	CO ₂ pipeline distance (km)	CO ₂ Pipeline Capital Cost (£m)	Electrical Connection Cost (£m)	Total Infrastructure Capital Cost (£m)	DACCS Size (Mt/year)
Hinkley	3.2	10317	30	30	15	46	8
Sizewell	3.6	11636	73	73	15	87	9
Hartlepool	1.5	4842	2	2	15	17	4

To reduce infrastructure, build out and costs the fewer the amount of DACCS sites the better. This leads to very large DACCS sites across the country. The largest is located at Sizewell: a 9Mt/year DACCS facility. Such a facility would require 720-900 acres of land per current estimates and may be impractical in practice, especially in the UK. Although there are limited estimates on land use for DACCS and this requirement may be reduced with different technologies, air contactor designs and heights of contactors, and location/climate. Plants of this size may be feasible, Project Bison²¹ in Wyoming is planned to capture 5MtCO₂/yr by 2030. Land areas of this amount being repurposed for future energy infrastructure in the UK are also possible. The proposed solar farm at Botley West being around 1400 hectares²².

Another consideration is the amount of electricity required. The total 19.5Mt/year of DACCS consumes a total of 4TWh electricity/year. The three new build nuclear generation sites produce a total of 67TWh electricity/year. Therefore, around 6% of the electricity produced (and 100% of the waste heat) from the nuclear generation sites would be required to run the DACCS plants. There is therefore the potential to directly couple both the waste heat and electricity from nuclear generation to power the DACCS facilities. This would alleviate electrical connection costs to the sub-station.

The optimisation does not favour building DACCS sites at the industrial clusters. The relatively low amount of waste heat available at individual sites would necessitate smaller DACCS facilities and thus more infrastructure construction and cost. The current siting methodology could be expanded in future work to consider usage of waste heat from multiple sites into one DACCS facility, which would hence reduce CO₂ pipeline and electrical connection costs. Alternatively smaller DACCS facilities could be considered which are optimised for size based on the waste heat available at each industrial site.

Table 6.4 shows the intended DACCS rollout and the potential DACCS plant sizes that could be coupled with each nuclear generation site, based on the ESME infrastructure large power generation method discussed in section 6.4.2.1. For simplicity the efficiency improvements of the DACCS technology was not built in to these calculations. There is enough waste heat potential from the nuclear generation sites to power the rollout of DACCS. It also shows that Hinkley may be the best site to first build the DACCS technology in 2030.

There are caveats attached to this; whilst Hinkley may be the best site for initial deployment from an optimisation perspective, the only DACCS facility planned in the UK at present is the Dreamcatcher project in Scotland by Storegga and Carbon Engineering, a planned facility of 0.5-1MtCO₂/yr, operational in 2026 (Storegga, 2022). Therefore, while it is possible to build a very large DACCS site, the constraints in the UK would suggest it is unlikely that all 3MtCO₂/yr of projected DACCS deployment capability would be deployed solely at Hinkley in this timeframe. It should also be noted that based on current

²¹ <https://www.carboncapture.com/project-bison>

²² <https://www.carboncommentary.com/blog/2023/1/12/c1d9rhg8s4j3t88vdkqi5d26epwpfd>

announcements, the largest planned single DACCS facility in the world in 2030 would be Project Bison. Each country has their own challenges and there will be different opportunities for each country deploying DACCS. There will be no one size fits all solution.

Table 6.4: DACCS rollout over time at the three nuclear locations supplying waste heat. All units MtCO₂/yr

Year	DACCS Rollout	3-Site Potential Total	Hinkley Potential	Sizewell Potential	Hartlepool Potential
2030	3.0	3.9	3.9	-	-
2035	6.0	13.1	6.9	3.6	3.5
2040	10.0	15.5	7.8	4.9	3.7
2045	14.5	16.2	7.8	5.5	3.7
2050	19.5	19.5	7.8	8.8	3.7

There are significant infrastructure considerations to deploying DACCS at Hinkley. Referring to Figure 6.7 and Table 6.4 it is clear that long CO₂ pipelines would need to be built to connect the Hinkley and Sizewell nuclear generation sites to the ports in Bacton and South Wales. Another option, as both sites are located next to the coast, could be to ship the CO₂. A period of planning permission and build-time would therefore be required to enable DACCS facilities in these locations, which should be considered as soon as possible.

The Hartlepool site has the lowest infrastructure costs due to its close proximity (2km) to the indicative CO₂ pipeline locations. It may therefore be a good use-case for a further investigation into the potential for coupling DACCS with Nuclear and building the CO₂ network required.

A significant challenge for all future electrical needs which will directly affect how quickly DACCS can be sited is the extremely long wait times for electrical connections to the National Grid. This is a well-known problem in the industry and Octopus Energy have recently authored a report with recommendations to address the issue²³. It is recommended this is addressed so that DACCS can be sited in an appropriate time frame.

6.6.2. Size constrained (reference case)

This section shares results when the maximum DACCS plant size is constrained. This shows the siting solution if the large plant sizes discussed in section 6.6.1 are not feasible due to the area footprint (as to be looked at in further work).

²³ <https://octopus.energy/press/more-news-press-releases/end-the-gridlock-octopus-energy-report-reveals-how-to-speed-up-green-grid-connection/#:~:text=Five%2Dpoint%2Dplan%20to%20speed,done%27t%20take%20up%20space>

When the DACCS plant size is constrained at a nuclear generation site, unlike the results in section 6.6.1 where all nuclear waste heat is made use of by DACCS, there will be excess waste heat which could be used elsewhere. In which case to still exploit this waste heat potential more infrastructure would be required, for example to build and connect to a district heat network.

When the reference case was constrained to a maximum plant size of 1MtCO₂/yr the 19.5MtCO₂/yr requirement in 2050 could not be satisfied in the UK. Primarily due to the limited amount of waste heat from industry and when the nuclear generation sites are capped to 1Mt/year the full requirement cannot be fulfilled.

Figure 6.8 shows the results when the plant size is limited to 3MtCO₂/yr. All but one of the nuclear sites is being utilised for DACCS technology (6x3MtCO₂/yr). The remainder of the waste heat requirements are made up by the refining sites (3x~0.5 MtCO₂ /yr).

There are evidently very large considerations here from an infrastructure point of view. Especially from the nuclear sites that were not discussed in section 6.6.2. Connecting sites in Birmingham, East London and Barrow would require an extensive CO₂ pipeline network.

The refining sites are far easier to connect as they are located near to the indicative CO₂ pipelines which are planned to be built out around the clusters to satisfy any CCS requirements.

Again, connecting up various industrial waste heat sources to one DACCS facility and also investigating smaller DACCS plants with associated lower electrical connection costs might change the results of this optimisation and can be investigated in future work.

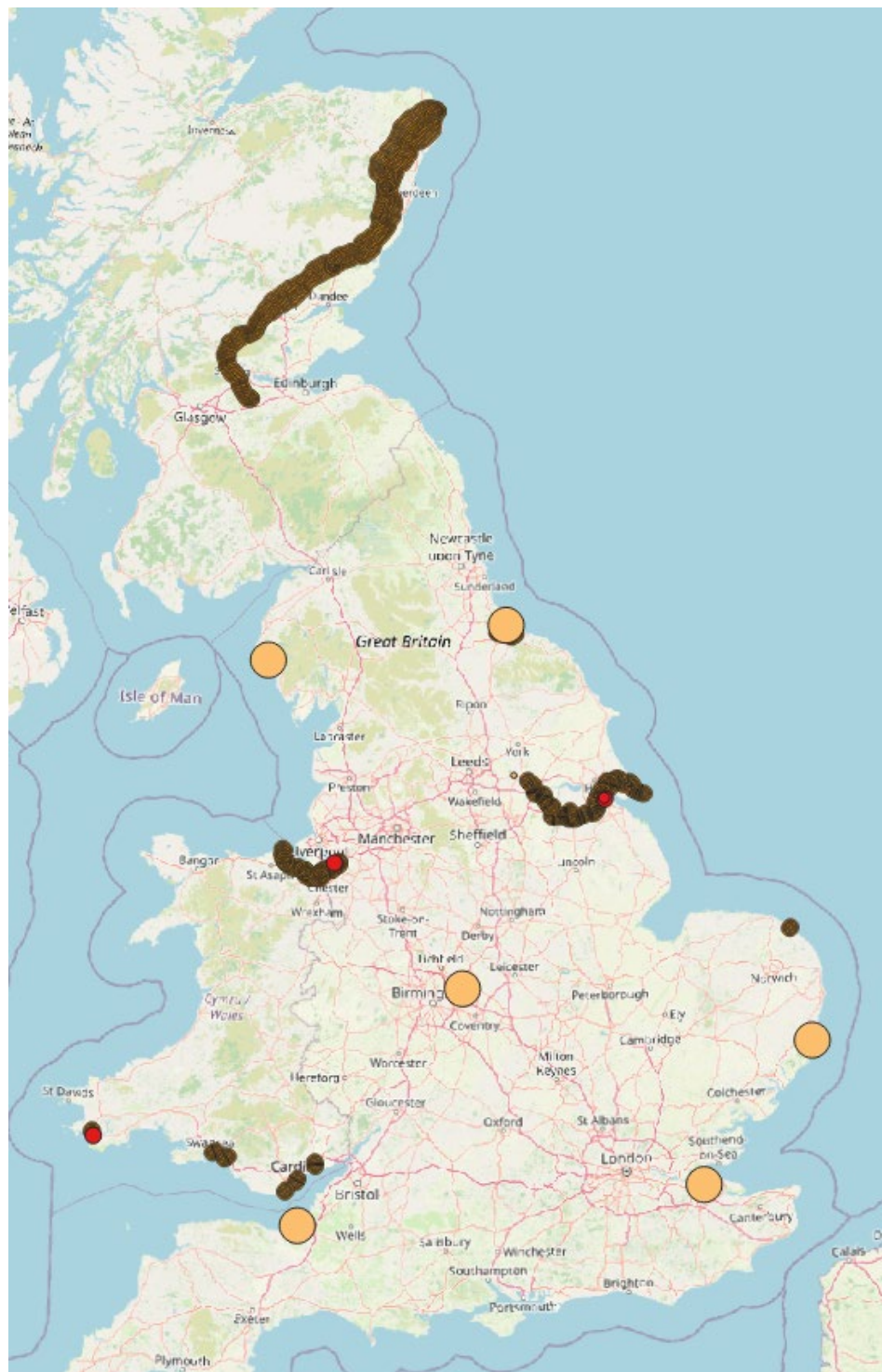


Figure 6.8: DACCS Siting Results (Size Constrained)

6.6.3. No nuclear

Batch 6 evaluated the DACCS roll-out in a scenario where there was no nuclear deployment. In the simulations where net zero was reached, 19.5MtCO₂/yr of waste heat DACCS was still deployed with a requirement of approximately 26TWh/year of waste heat.

In a no nuclear waste heat scenario the majority of the DACCS waste heat requirements are fulfilled from Biomass Fired Generation with CCS and IGCC Biomass with CCS (BECCS) and Energy from Waste with CCS (EfW with CCS). For the scenarios that reach net zero, EfW with CCS generates around 16.8TWh/year of waste heat and BECCS generates between ~5.2TWh/year and ~16TWh/year. For BECCS the 16TWh/year of waste heat corresponds to a power output capacity of ~5.6GW.

Both of these technologies have CCS components and will therefore need to be located close to CCS networks, with or without their waste heat being used to power DACCS technologies. Also, like nuclear generation there is the potential to connect to and use the electricity and electrical infrastructure of the power station.

There are plans to transition some of the existing biomass sites to add a carbon capture element. Drax power station, which is the largest biomass power station in the UK by a significant margin, with four 660MW biomass units, is one of these sites. Drax have made clear their intentions to become a BECCS power station, as early as 2027, dependent upon the availability of government support for BECCS. A reasonable assumption would be that two of these 660MW units are BECCS enabled by 2030 in line with Drax's stated plans²⁴, with all four biomass units BECCS enabled by 2035.

All four biomass units, if directly coupled to a waste heat DACCS plant, has a power output of 2.6GW, the waste heat output would be ~7.4TWh/year which would generate enough waste heat to power ~5.5MtCO₂/yr DACCS.

The conversion of other existing biomass power stations to BECCS would primarily be dependent on proximity and access to CO₂ pipeline networks, which would likewise be a requirement for new-build BECCS power stations. Therefore, given Track 1 cluster plans, BECCS developments would be most likely to occur within the Teesside, Humber, and HyNet Northwest clusters.

For EfW with CCS the decisions on where to site new build energy from waste (EfW) powers stations with CCS is likely to be more complex. There will need to be a balance between distance to population centre, to minimising waste transport costs, and distance to the CO₂ pipeline network, to minimise the cost of bespoke CO₂ pipeline connections. Intuition suggests that being closer to the CO₂ network and transporting waste will be cheaper and more feasible than building an extensive pipeline in to the population centres, but it is recommended that this is investigated further as an area of future work.

6.7. Siting other DACCS technologies

6.7.1. Hydrogen

Interestingly, from the Batch 1 Monte Carlo results, hydrogen powered DACCS facilities were deployed in the majority of the simulations that reached net zero. The amount of hydrogen powered DACCS deployed varied from between ~0.1 – 8 MtCO₂ /yr.

²⁴ Drax: "BECCS and Negative Emissions". <https://www.drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/>

In an 8 MtCO₂ /yr scenario a 12TWh/year of hydrogen supply would be required. This corresponds to a constant supply from a 1.4GW output hydrogen production facility. Figure 6.9 below shows the potential future hydrogen sites²⁵ and indicative hydrogen network from Project Union²⁶. The size of the green dots represents the target size of the production facility, and the black dots are where the target size is unknown.

The largest green dot corresponds to an output of 1.75GW. This indicates that an 8 MtCO₂ /yr DACCS facility could be and might best be, from an infrastructural point of view, sited close to and directly coupled with a large hydrogen production facility.

²⁵ <https://usmart.io/org/esc/discovery/discovery-view-detail/2b29ee19-5f0a-487c-b351-38fb593bd03f>

²⁶ <https://www.nationalgas.com/document/139641/download>



Figure 6.9: Indicative Hydrogen Network and Production facilities (Green dots represent target size in GW (maximum 1.75GW) and black dots the target size is unknown).

6.8. Infrastructure conclusions

A new methodology was developed to investigate the optimal location for siting the waste heat DACCS technology. The methodology was based on proximity to waste heat sources, electrical sub-stations and indicative CO₂ pipelines (located around the industrial clusters).

It was found that the DACCS plants are best suited to be built close to nuclear generation 3 sites. This is because of the large amounts of waste heat available. A 3.6GW nuclear generation site has enough waste heat to power 9MtCO₂ /yr of DACCS. This is more than the available waste heat estimated from all of the industrial clusters which was estimated as being enough to power approximately 6MtCO₂ /yr.

The electricity requirement for the DACCS technology can also be directly fulfilled by the nuclear generators (approximately 6% of the electricity produced would have to be utilised).

From an infrastructure cost perspective, the fewer DACCS sites the better. The optimal solution for the reference case, was to build 3 DACCS plants. A $\sim 9\text{MtCO}_2/\text{yr}$ site coupled with Sizewell, an $\sim 8\text{MtCO}_2/\text{yr}$ site at Hinkley and a $\sim 4\text{MtCO}_2/\text{yr}$ site at Hartlepool. This also utilises all available waste heat.

Major considerations for larger DACCS sites should be on the land availability, the loss of negative emissions due to any outage/maintenance being required and the transportation of the CO_2 ; Hartlepool is relatively close to the North East cluster (2km) but Sizewell and Hinkley are relatively far, 70km and 30km respectively, and the planning permission process to either build pipelines or shipping infrastructure would be extensive, hence in the near term having the necessary infrastructure in place to build these sites might be difficult.

The land required for a $9\text{MtCO}_2/\text{yr}$ would be around 720-900 acres based on current estimates (though this may reduce). It is recommended that this land requirement availability is investigated in a future package of work. Hartlepool might be a good site to begin the investigation with as it is far closer to the planned CO_2 network than Sizewell or Hinkley,

In case such land requirements are not available, a scenario with a maximum DACCS plant size of $3\text{MtCO}_2/\text{yr}$ was considered. It was found that the nuclear generation sites were still favoured for located DACCS, followed by some of the industrial refineries. In this scenario not all the waste heat would be utilised, and another network might need to be built to utilise the waste heat elsewhere (for example in district heating).

Due to the relatively low amounts of waste heat generated from industrial sites they have not been favoured by the optimisation. It is recommended that in a future work package connecting multiple sources of waste heat from industrial sites (which are already close to the planned CO_2 corridors) up to one DACCS plant is investigated as this will reduce on the infrastructure requirements.

In a scenario where no Nuclear Generation 3 sites are built then the waste heat from BECCS and EfW with CCS plants will need to be utilised to fulfil the waste heat DACCS requirements. Coupling a DACCS plant with these technologies is suitable from an infrastructural point of view because they will already require CO_2 transportation, and like nuclear the electricity generated could be utilised directly to power the DACCS technology.

DRAX, is by far the largest biomass power station in the UK and if all four power stations were fully converted to BECCS would have enough waste heat to power $5.5\text{MtCO}_2/\text{yr}$ DACCS.

An investigation will need to take place to determine the most appropriate sites to locate the EfW with CCS sites. The trade-off will be between the length of pipeline required and how far the waste is transported away from population centres. Intuition suggests that it

would be cheaper and more feasible to build the sites close to the CO₂ network, to reduce on the CO₂ pipeline requirements and transport the waste.

In ESME scenarios where hydrogen powered DACCS technology was deployed the maximum amount of hydrogen DACCS was roughly 8MtCO₂/yr, this requires a hydrogen input of roughly 12TWh/year. This is the equivalent of a constant supply from a ~1.4GW production facility. Such scale facilities are in the pipeline but whether it would be appropriate to direct this hydrogen directly to DACCS ought to be evaluated.

7. Conclusions

The conclusions are part of the executive summary.

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9. Appendix

9.1. Relevant organisations and projects

Through the course of our literature review, a list of major organisations involved in development of DAC technologies, or the storage or utilisation of CO₂ from DAC technologies was collated, as well as key projects of interest. In total, 44 organisations were identified globally, alongside 22 notable examples of pilot scale or deployment projects. A list of organisations identified is given in Table 9.1, whilst example projects are listed in Table 9.2. The vast majority of organisations and projects are based in North America or Europe. It should be noted that the DAC sector is currently a rapidly moving space, with new companies, technologies and organisations continually emerging, therefore this should not be considered a comprehensive list of all entities within the sector. This list of organisation and projects (Table 9.1, Table 9.2) was collated in early 2022.

Table 9.1: List of DAC organisations identified.

#	Organisation	Type	Location
1	Climeworks	Technology Developer	Switzerland
2	Antecy	Technology Developer	Netherland
3	CarbonCapture	Technology Developer	California, USA
4	CarbFix	Storage	Reykjavík, Iceland
5	Carbon 180	NGO	USA
6	Carbon Engineering	Technology Developer	Vancouver, Canada
7	Carbon Collect Ltd	Technology Developer	USA & Dublin, Ireland
8	Greyrock Energy	Application	USA
9	Storegga	Storage	UK
10	1PointFive	DAC Commercialisation	USA
11	Carbyon	Technology Developer	Netherlands
12	DACCITY	Technology Developer	California, USA
13	Global Algae	Application	California, USA
14	Global Thermostat	Technology Developer	New York, USA
15	Heirloom Carbon Technologies	Technology Developer	San Francisco, USA
16	Highly Innovative Fuels	Application	Chile
17	Hydrocell	Technology Developer	Finland
18	Mission Zero Technologies	Technology Developer	London, UK
19	Mosaic Materials	Technology Developer	California, USA
20	Nordic Electrofuel	Utilisation	Norway
21	Noya	Technology Developer	San Francisco, USA
22	Origen Power	Technology Developer	Walsall, UK
23	Prometheus Fuels	Application	USA

#	Organisation	Type	Location
24	Rolls-Royce	Resource	UK
25	Skytree	Technology Developer	Netherlands
26	Soletair Power	Application, Technology Developer	Finland
27	Sunfire	Application	Germany
28	Sustaera	Technology Developer	North Carolina, USA
29	Verdox	Technology Developer	Woburn, USA
30	Zenid Fuel	Application, Commercialisation	Netherlands
31	Oak Ridge National Laboratory	Technology Developer	Tennessee, USA
32	Cambridge Carbon Capture Ltd	Technology Developer	Cambridge
33	RedoxNRG OU	Technology Developer	Estonia
34	Solid Carbon	Commercialisation	Victoria, Canada
35	Praan Inc	Commercialisation	India & USA
36	Noya Inc	Commercialisation	San Francisco
37	8 Rivers Capital LLC	Technology Developer, Commercialisation	North Carolina
38	Protostar Group Ltd	Storage	UK & Oman, UAE
39	CarbonBuilt INC	Utilisation	CA, USA
40	Carbfix Corporation	Utilisation	USA
41	AirCapture	Technology Developer	USA
42	Kawasaki Heavy Industries	Technology Developer	Japan
43	Ocean Networks Canada	Storage	Victoria, Canada
44	CarbonCure	Utilisation	Canada

Table 9.2: Example DAC projects identified.

#	Name	Location	Company(s)	Scale	Key Date(s)
1	CAIR (Carbon from Air)	University of Twente	Climeworks	Pilot	
2	Mechanical Trees for Passive DAC	USA	Carbon Collect Ltd		
3	GreyRock Air to Fuels	Squamish, British Columbia	Carbon Engineering, GreyRock		

#	Name	Location	Company(s)	Scale	Key Date(s)
4	DAC-1	Ector County, Midland Basin, West Texas, USA	1PointFive, Carbon Engineering, Worley	Commercial 1MtCO ₂ /yr	FEED stage, operational target 2024
5	Global Thermostat Pilot Plant	Huntsville	Global Thermostat	Pilot	Closed 2019
6	Soletair	Finland	VTT Technical Research Centre of Finland Ltd, LUT, Hydrocell	Pilot	
7	ORCA	Iceland	Climeworks, Carbfix	Demonstration 400tCO ₂ /yr	Operational since 2021
8	Sizewell C DAC	Suffolk, UK	Sizewell C (EDF), Nottingham University, Strata Technology, Atkins, Doosan Babcock	Initially 100tCO ₂ /yr, potential to expand to 1.5MtCO ₂ /yr	
9	Dreamcatcher	St Fergus Gas Plant, Scotland	Storegga, Carbon Engineering, Acorn	Demonstration / Commercial 0.5-1MtCO ₂ /yr	Operational target 2026
10	DRIVE	Humber Region, UK	Mission Zero Technologies, Optimus, Equinor, OCO Technologies	Pilot 365tCO ₂ /yr	
11	Direct Air CO ₂ Capture and Mineralisation	UK	Cambridge Carbon Capture Limited	50ktCO ₂ /yr	
12	Passive Lime Carbonation Project	UK	OrigenPower Ltd		

#	Name	Location	Company(s)	Scale	Key Date(s)
13	HIF Haru Oni eFuels Pilot Plant	Chile	Global Thermostat, Siemens Energy, HIF, Porsche, Enel, Green Power, ExxonMobil, ENAP, Empresas Gasco, Johnson Matthey	250kgCO ₂ /hr	Pilot 2022 Phase 1 Commercial 2024
14	Norsk e-Fuel AS	Heroya, Norway	Climeworks, Sunfire GmbH, SMS Group (Paul Wurth SA), Valinor (Morsk Vind)	Commercial 250ktCO ₂ /yr	Operational target 2023
15	Rotterdam The Hague Airport	Rotterdam	Rotterdamn The Hague Airport, Climeworks, SkyNRG, Uniper, Zenid		
16	STORE&GO	Troia, Italy	27 European partners including Climeworks		
17	8 Rivers & Lhoist	Arizona, USA	8 Rivers, Lhoist	Commercial 10ktCO ₂ /yr	Operational target 2024-25
18	SMART-DAC	UK	CO2Circul Air, Heriot-Watt University, Optimus, OGTC	Pilot 100tCO ₂ /yr	
19	Direct Air CO ₂ Capture and Mineralisation	UK	Cambridge Carbon Capture Limited	50ktCO ₂ /yr	
20	Environmental CO ₂ Removal	UK	Rolls Royce, CSIRO (Australia)	Pilot 100tCO ₂ /yr	

#	Name	Location	Company(s)	Scale	Key Date(s)
21	Modular DAC	UK	Carbon Neutral Petrol		
22	Project Bison	Wyoming, USA	CarbonCapture Inc Frontier Carbon Solutions Inc.	Phase 1: 10ktCO ₂ /yr Phase 2: 200ktCO ₂ /yr Phase 3: 1MtCO ₂ /yr Phase 4: 5MtCO ₂ /yr	Phase 1: 2023-24 Phase 2: 2025-26 Phase 3: 2027-28 Phase 4: 2029-30

9.2. WP2: National scale requirements

For the national scale scenarios, scenarios within the recent Element Energy report for BEIS on GGR removals (Element Energy, 2021) and the CCC's 6th Carbon Budget (Climate Change Committee, 2020) were used. These gave a broad range of deployment scales for 5 MtCO₂/yr to 30 MtCO₂/yr. Scenarios within these reports that did not call for DACCS deployment were excluded.

National scale requirements for electricity, heat, water, and land are shown across Figure 9.1-Figure 9.4 respectively. These are based on the listed 2050 scenarios produced by CCC in the 6th Carbon Budget (Climate Change Committee, 2020) and Element Energy (2021) in their recent GGR Removals Technology assessment report for BEIS. The DACCS CO₂ removal requirements under these scenarios was used to scale the resource requirements collated in this report.

Looking first at Figure 9.1 electricity requirements and the Element Energy "Balanced" case of 18MtCO₂/yr removal, the non-electrified solutions naturally have lower electricity demands (<7TWh/yr) than the electrified alternatives; 27TWh/yr in the case of HT electrified DAC. To put this into perspective, the Dogger Bank wind farm will generation ~18TWh/yr when all three phases are completed (Dogger Bank Wind Farm, 2021). Once again, the electrochemical DAC technology has a significant low-high range but shows substantial potential if the low bound can be achieved with future development.

Heat requirements are shown in Figure 9.2, and naturally LT and (non-electrified) HT DAC technologies have significant requirements. Taking the Element Energy "Balanced" case of 18MtCO₂/yr removal as a reference case again, heat requirements vary between 26-44TWh/yr. For HT DAC solutions however, the heat is currently generated within the process via natural gas (i.e. Carbon Engineering). Therefore, the LT DAC range of 27-36TWh/yr is of more interest, as technology developers have expressed interest in using waste heat to fulfil heat demands. Estimates of industrial waste heat availability in the UK are 48TWh/yr on the upper end (Table 4.1), though studies making assumptions around the technically feasible quantity that can be recovered are around 10-20TWh/yr (Table 4.2).

Therefore, for LT DAC in the 18MtCO₂/yr case, heat would have to be generated by other means, e.g., electrically, increasing resource needs elsewhere.

Water requirements are shown in Figure 9.3. In the highest case, i.e., Engineered Focus, this demand can be high at 141Mt/yr though is not infeasible. This equates to ~0.4Mt/day, or 0.4bn litres per day and in the case of HT DACCS, which has this high demand, does not have to be potable water. As noted before, Thames Water supplies 2.6bn litres per day for reference (Thames Water, 2022).

Land requirements are shown in Figure 9.4. These vary from under 500 to 3000 acres depending on the scenario. Once again, it is worth noting that this is the area for the DAC facility only and that other infrastructure (e.g., dedicated electricity generation, CO₂ transport and storage) would be in addition to these requirements and these additional requirements may vary substantially.

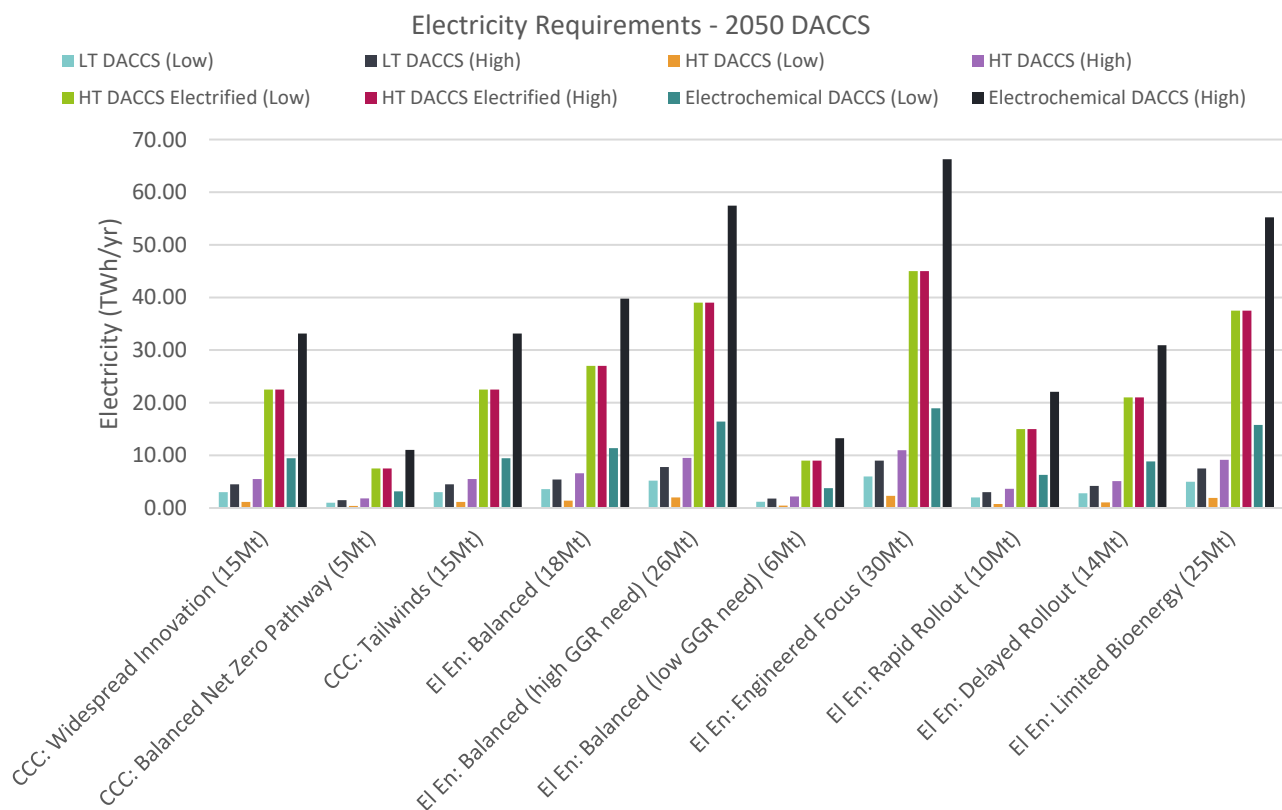


Figure 9.1: National scale electricity needs for different DAC technologies in 2050, using various DACCS removal pathways by CCC (2020) and Element Energy (2021).

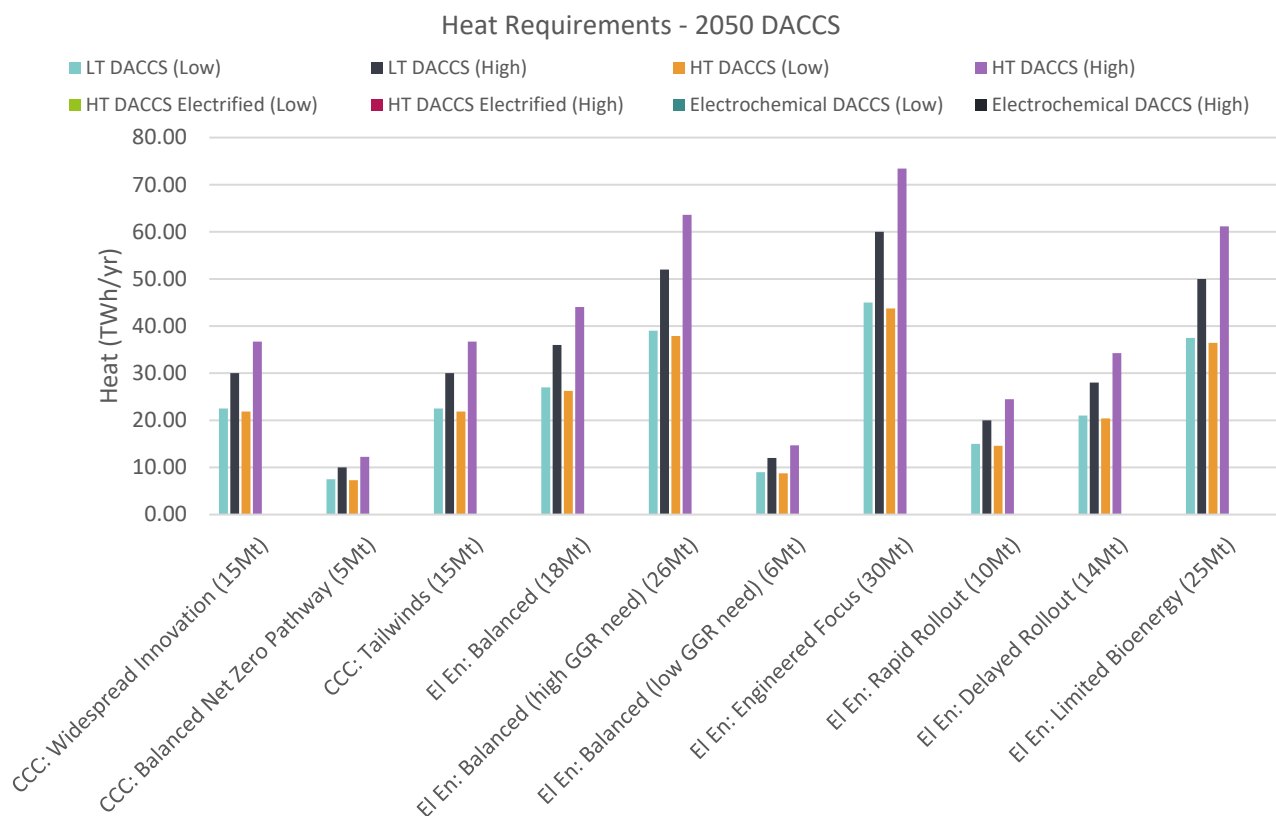


Figure 9.2: National scale heat needs for different DAC technologies in 2050, using various DACCS removal pathways by CCC (2020) and Element Energy (2021).

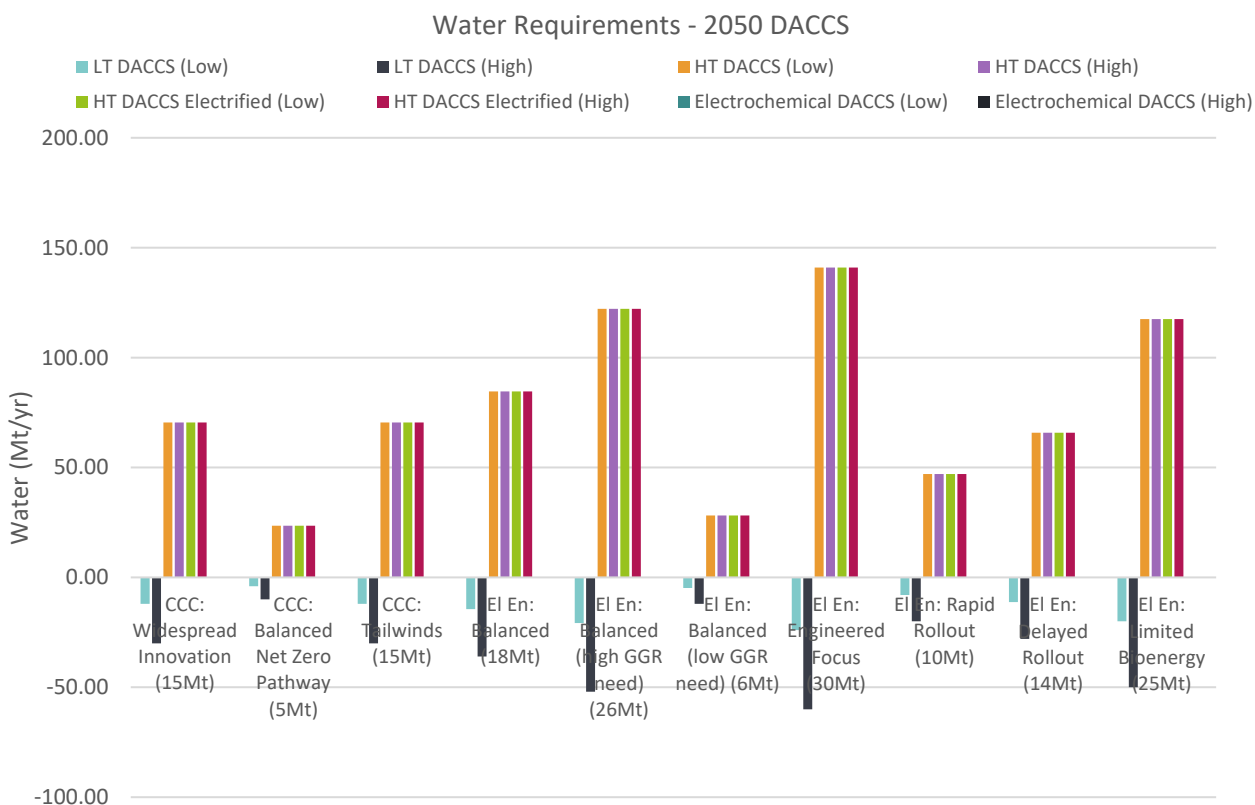


Figure 9.3: National scale water needs for different DAC technologies in 2050, using various DACCS removal pathways by CCC (2020) and Element Energy (2021).

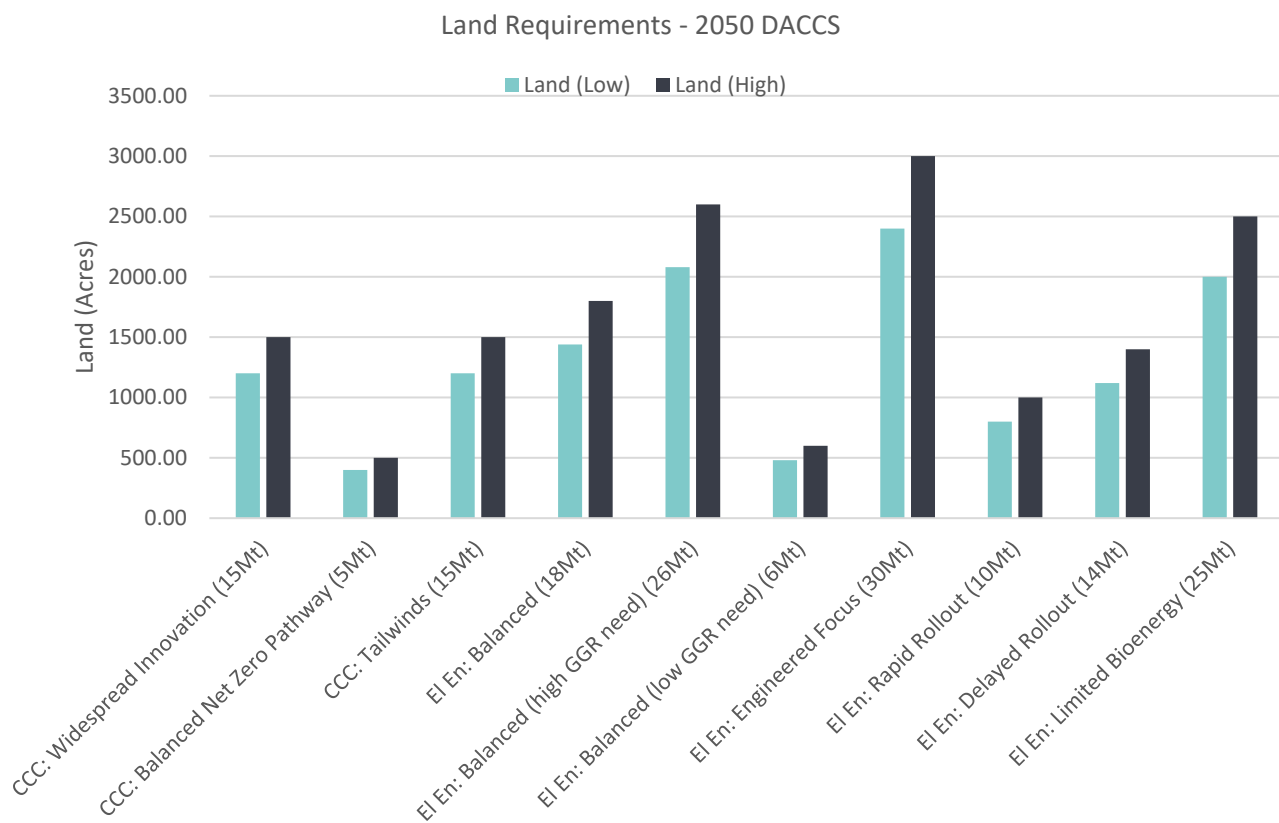


Figure 9.4: National scale land needs for DACCS in 2050, using various DACCS removal pathways by the CCC (2020) and Element Energy (2021).

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