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Review of International Delivery of Negative Emission Technologies (NETs)

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1 Executive Summary

1.1 Aims

Negative Emissions Technologies (NETs) are technologies which remove greenhouse gases from the atmosphere, resulting directly or indirectly in net negative emissions. The Scottish Government is currently considering two main forms of engineered NETs:

- direct air capture with carbon capture and storage (DACCS); and
- bioenergy with carbon capture and storage (BECCS), which can take many forms and configurations.

Whilst other options for NETs may develop in the future these technologies are considered as having greatest potential for deployment in Scotland by the mid-2030s.

The Scottish Parliament has legislated ambitious climate targets to reach net zero by 2045 and achieve a 75% emissions reduction by 2030. In 2020, the Scottish Government published an update to its Climate Change Plan, which identified NETs as a key component to meeting its emissions targets. The plan includes an envelope for NETS which would see these technologies scale up to deliver 5.7 $MtCO_2e$/year of negative emissions by 2032. In 2022, the Scottish Government will commence a feasibility study to explore NETs and ways to incentivise early NETs development to reach the 2032 envelope.

This report looks at international case studies relevant to NETs projects covering DACCS and a wide range of BECCS configurations seen in current projects, and explored their applicability to deployment in Scotland.

1.2 Findings

The case studies in this review, while being diverse in background, scope, maturity, and targets, have shown to have a few consistent high-level similarities. These similarities lead to the following conclusions:

1) **Implementing a commercial business model** through the sale of CO_2 credits, licensing of the technology, or the creation and sale of co-products, makes scalability easier and reduces risk.
2) **Availability and contribution of public funding** can enable projects to start with lower private investment. This is particularly the case for projects with a higher capital costs.
3) Successful projects are often **located near long-term storage locations**, minimising cost of transport and storage.
4) Schemes which capture **higher purity CO_2 streams** are likely to be more economically viable, with lower associated costs (particularly operating costs).
5) Many BECCS projects require **secure, local and sustainable feedstock** supplies which meet the plant capacities, quality and biogenic content requirements.
6) **Higher carbon prices, carbon taxes or tax credits** in some countries have created markets where NETs are more commercially viable.

After evaluating the applicability for Scotland of each case study, a tentative indication of potential of different NETs emerged. In terms of raw delivery of negative emissions and early deployment we found that:

- DACCS and BECCS Energy from Waste (EfW) show the most immediate promise.
- Medium-sized early opportunities for negative emissions exist in BECCS Power, Industry, and Biomethane.
- Finally, the smallest immediate opportunity, based on the available evidence in this horizon scan, initially appears to be in BECCS Biofuels and Hydrogen due to lower retrofit opportunities and relatively lower current CO_2 emissions from their targeted industrial/production processes in the country.

1.3 Recommendations

Our analysis has highlighted specific areas to explore further:

1) **Explicitly quantify the short/medium-term NETs potential in Scotland** - Update previous work by Scottish Carbon Capture and Storage (SCCS), which is Scotland's point of coordination for CCS research and development. Given the critical nature of this sector, this should be reassessed and extended to ensure calculated potentials are based on robust and recent data (e.g. future waste availability/composition). A focus on the short-medium term would help to ensure targeted and actionable outputs for Scottish Government.

2) **Brief evaluation of Scottish NETs costs** - Update costs from international projects with consideration of the local context. For example, Scottish electricity and CO_2 T&S costs, and CO_2 transport options for larger NETs plants including indicative costs.

3) **Evaluation of plant specific techno-economics** - Estimate specific costs and technical NETs conversion feasibilities of potential large NETs opportunities. This may allow for prioritisation of short-term efforts.

4) **Assess build-out rates and supply chain limitations** - Understand the realistic timeframes for deploying NETs in the short and medium terms.

5) **Create a priority list of high-potential options** – Pursue project options based on the economic, technical and practical limitations identified, moving beyond the initial general categorisation of opportunities provided here.

6) **Explore long-term NETs potential of Scotland, focusing on the 2045 target** - Bring in a long-term perspective, breaking out of short term build out rates and envisioning wider technological transitions, such as BECCS hydrogen or biofuels.

7) **Identify key policy enablers and actions for the Scottish Government** - Identify the levers available to the Scottish Government as a devolved administration, and emerging UK-wide Greenhouse Gas Removal (GGR) support mechanisms.

Contents

2 Negative Emission Technologies (NETs) Introduction and Context

2.1 NETs: What are they and why are they needed?

There are a range of methods for the extraction and long-term storage of carbon from the atmosphere. Some of these methods, such as afforestation, soil carbon sequestration, and ecosystem restorations, are known as nature-based solutions. These are generally lower cost and well-known methods to remove CO_2, but come with higher risks of greenhouse gas re-emission (e.g. due to fires). Other methods which include the specific use of technology to capture and store carbon are referred to as Negative Emission Technologies (NETs).

NETs can provide an advantage over traditional emissions reductions strategies by decoupling decarbonisation efforts from the source of emissions. This allows for mitigation of hard-to-abate emissions within an economy, eventually reaching net-negative emissions as opposed to just net zero emissions. NETs are defined differently based on different governments and decision-making bodies and are also known as carbon dioxide removal (CDR) or greenhouse gas removal (GGR) by the UK Government. While some NETs (such as biochar, enhanced weathering, and ocean fertilisation/alkalisation) are promising, the environmental impacts are less understood. However, direct air capture with carbon storage (DACCS) and bioenergy with carbon capture and storage (BECCS) are emerging as two engineering-based NETs with a high potential to deliver early, long-term and secure CO_2 removal.

The importance of engineered NETs is becoming increasingly recognised around the world. The International Energy Agency (IEA) estimates a need to remove 325 $MtCO_2$ by 2030 and 2,010 $MtCO_2$ by 2050 through the combination of BECCS and DACCS to achieve global net zero emissions by 2050[1]. Similarly, BEIS have suggested that 70 – 87 $MtCO_2$ (approximately 13 - 17% of the UK's emissions in 2019) may need to be removed by engineered NETs to reach net neutrality by 2050[2]. Specifically, the CCC has estimated that Scotland is likely to need 3-9 $MtCO_2$/year of CO_2 removal through engineered NETs (including a small quantity of NETs from wood in construction) to reach net zero in 2045.

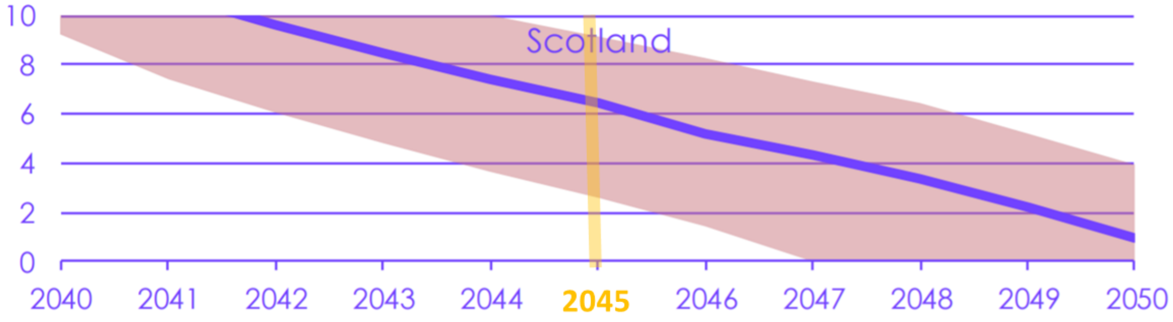

Figure 1: Range of engineered NETs needed ($MtCO_2$/year) in Scotland to reach net zero in different years[3], with 2045 highlighted.

Given the importance of the role of engineered NETs in decarbonising the Scottish economy, this study investigates the current global state of different DACCS and BECCS technologies with a focus on their applicability in the Scottish context. Specifically, the

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[1] Net zero by 2050: a roadmap for the global energy sector. IEA, 2021.

[2] Net zero strategy: build back greener. BEIS, 2021.

[3] CCC 6th Carbon Budget, 2020

study reviews DACCS and the application of BECCS in industry, power, energy from waste, hydrogen, biomethane and biofuels production.

2.2 Role of NETs in National Decarbonisation Strategies

The size and types of NETs required to meet long term national decarbonisation targets is highly uncertain for most countries. Figure 2 shows the portion of emissions countries propose/imply to mitigate through NETs or purchasing international carbon credits in their long-term climate strategies submitted to the UN[4]. These represent a range from 15% (Sweden and Canada) to 44% (Marshall Islands), although the specific contribution of NETs is unknown. All the reviewed strategies acknowledge the benefits of NETs and are open to their implementation, however, nature-based CO_2 removal options appear to be preferred over engineered NETs, as 24 of the countries explicitly reference nature-based solutions (NBS), while 10 reference BECC(U)S and only 4 countries reference DACC(U)S. Currently no country has separate emissions reduction and removal targets, but the EU has recently introduced a cap of 225 $MtCO_2$/year (2.2%) for contributions from carbon removal on route to its 55% GHG reduction target by 2030[5] . The EU is also looking to develop detailed NETs accounting frameworks by 2023[6].

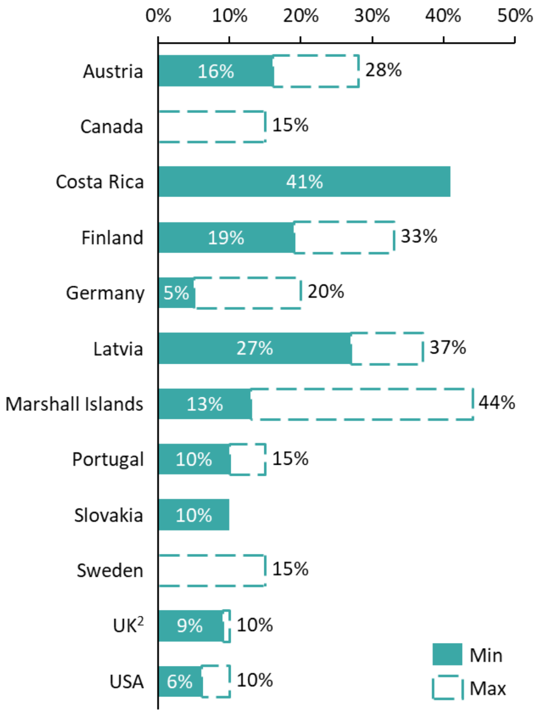

Figure 2: Portion of emissions different countries commit to mitigate through methods other than direct reduction[4]

2.3 Current R&D and Financial Support for NETs

Although some forms of more dedicated support have recently emerged, most of the current global policy support for engineered NETs is in the form of general research and development (R&D) grants and semi-specific funding for early demonstration projects. Some notable examples include NETs and DAC R&D funding in the US through the Energy Act of 2020 and FY22 Appropriations, the UK's GHG R&D Programme, Zhejiang University's DAC R&D Programme in China and the EU's general research and innovation support through the Horizon Europe programme. Furthermore, the US has recently decided to support large-scale NETs projects through grants for front end engineering design (FEED) studies and DAC commercialisation prizes. The UK's GHG Removal Innovation Competition aims to demonstrate multiple NETs and the Canadian government invested directly into Carbon Engineering to promote DAC. Further detail on notable R&D and demonstration policies can be found in Appendix 2.

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[4] Based on the long-term low emission development strategies of countries (except the UK) as explored in the paper «Cancel (Out) Emissions? The Envisaged Role of Carbon Dioxide Removal Technologies in Long-Term National Climate Strategies», Buylova A., et al., 2021. UK data is from BEIS's Net Zero Strategy (2021) based on 1990 emissions levels.

[5] EU Proceedings agreement, 2021 - Link.

[6] Leaked EU strategy – Link.

Deployment of DACCS and BECCS at scale inevitably requires significant financial incentives, which have largely been absent to date. Many countries have some sort of carbon price, which are largely still too low to incentivise NETs (e.g., EU ETS prices only reached €60/tCO_2 in September 2021). Moreover, none of these systems recognise negative emissions and require developing specific NETs monitoring, measurement, and accounting standards for their future inclusion.

There are several notable policies in the US - such as 45Q tax credits, California's Low Carbon Fuel Standards, and the Buy Clean California Act which can provide financial incentives to NETs, among other technologies. So far, the level of support has been modest, but amendments submitted to the Congress hope to increase the level of 45Q tax credits significantly. The Swedish Government has also taken a notable step to enabling negative emissions by announcing plans for purchasing up to 2 MtCO_2/year of BECCS removals through a reverse auctioning process[7].

2.4 Voluntary Corporate Support for NETs

In the absence of reliable financial incentives to deploy and operate large-scale engineered NETs, to date, many start-ups had to rely on voluntary bilateral CO_2 removal purchases by corporations. Microsoft, Stripe and Shopify emerged as some of the major early movers in the carbon removal space with significant purchases of negative emissions via DACCS and innovative BECCS processes. Additionally, Carbon Engineering and Climeworks, two of the main DAC technology developers, have started selling credits directly to individual customers to finance their early plants. One significant philanthropic contribution to the NETs space has been the recent $100 million XPrize Carbon Removal Competition, which will fund four scalable NET start-ups after a four-year evaluation period.

2.5 General Public Views on NETs

As with many novel technologies, public attitudes towards NETs in relation to other decarbonisation options are very important to ensure delivery of successful projects and maximising public benefits. The literature on public perception of different CO_2 removal technologies is scarce, but Climate Assembly UK's study[8] in 2020 sheds some light on British attitudes towards engineered NETs. As illustrated in Figure 3 below, nature-based solutions had very high approval ratings, whereas engineered NETs were openly favoured by only 42% of the participants. The reasons for this discrepancy were co-benefits of nature-based solutions and the perceived higher CO_2 leakage risk of BECCS and DACCS sequestration approaches. This public misconception regarding the higher leakage risk of engineered NETs is likely a key hurdle for engineered solutions to overcome in order to gain wider public acceptance and support.

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[7] *Government auctions for captured carbon dioxide* – Link.

[8] The path to net zero. Climate Assembly UK, 2020.

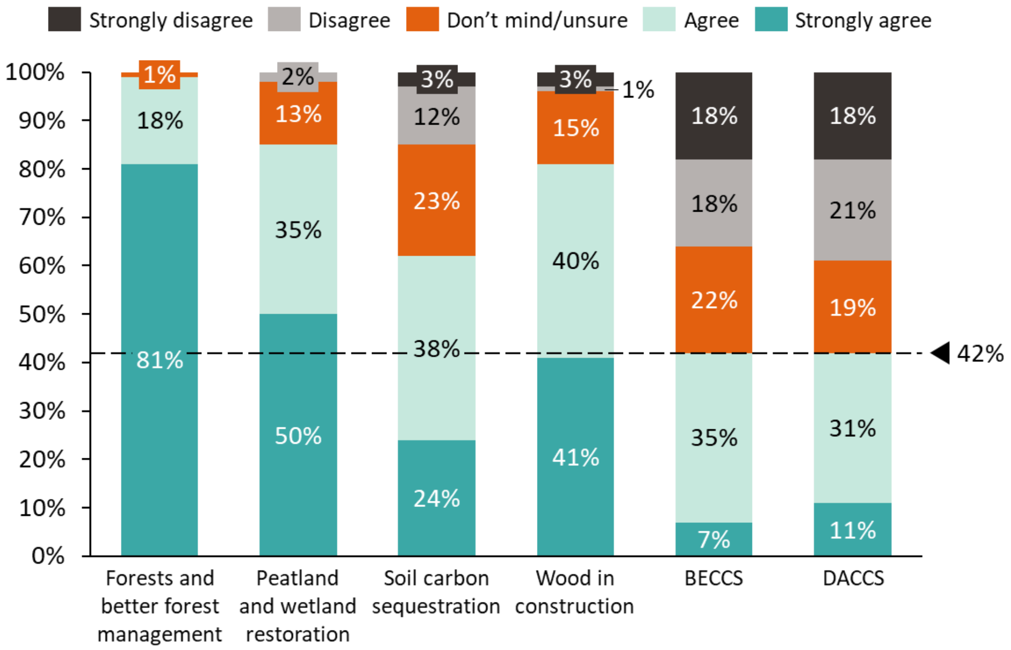

Figure 3: Summary of UK citizens' attitudes toward inclusion of various NETs in the UK's future decarbonisation plans (adapted from the Climate Assembly UK's report)[8].

Figure 3 may suggest that public opinion could be a barrier to further NETs deployment. However, it is critical to note that the percentages of participants whom had heard of BECCS and DACCS projects were significantly lower than those of their nature-based counterparts. Furthermore, most early BECCS and DACCS projects around the world have not faced significant public backlash to date. Therefore, many technology developers are optimistic that with a greater focus on public education and dissemination of early project learnings and climate benefits, support from the general public will increase.

3 Scottish Background

3.1 Scotland's NET Targets and Activities

3.1.1 Scotland's NETs Envelope

In 2019, the Scottish Parliament legislated ambitious climate targets to reach net zero by 2045 and achieve a 75% emissions reduction by 2030. In 2020, the Scottish Government published an update to its Climate Change Plan[9], which identified NETs as a key component to meeting its emissions targets. The plan includes an envelope for NETS which would see these technologies scale up to deliver 5.7 $MtCO_2e$/year of negative emissions by 2032. In 2022, the Scottish Government will commence a feasibility study to explore NETs and ways to incentivise early NETs development to reach the 2032 envelope.

3.1.2 Engineered NETs Projects in Scotland

There are no DACCS or BECCS projects currently operational or under construction in Scotland[10], however there are some NETs activities in Scotland with potential for deployment later in this decade:

- **Carbon Engineering**, one of the leading global DACCS companies, signed a memorandum of understanding with the Acorn CCS project to explore the potential to develop a large-scale DACCS facility in the future Scottish industrial CCS cluster. The future facility located near St Fergus gas terminal could have the potential remove 0.5-1.0 $MtCO_2$/year and be operational by 2026[11].
- **Project Dreamcatcher** is a feasibility study funded by the BEIS GGR Programme[12]. The study is led by Storegga in partnership with Carbon Engineering, and with support from Universities of Cambridge and Edinburgh. It aims to explore replacing natural gas in Carbon Engineering's DAC plants with alternative energy sources. If successful, this new design may be used in the future Scottish DACCS project.
- **Heriot-Watt University Research Centre for Carbon Solutions** is a key partner in delivering the SMART-DAC project[12], funded by BEIS, which aims to develop a very low-cost membrane separation technology for DACCS applications.
- **University of Edinburgh** leads another BEIS funded project[12] aiming to use solar energy to capture CO_2 from air and destroy other greenhouse gasses simultaneously.

3.2 Future Potential for CCS and Hydrogen Utilisation in Scotland

The timing, scale, and locations of future CCS and hydrogen projects in Scotland are very influential for engineered NETs, which utilise the same CO_2 infrastructure and may supply some of the hydrogen demand through biomass conversion.

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[9] Update to the Climate Change Plan 2018-2032. The Scottish Government, 2020.

[10] The North British Distillery in Edinburgh used to capture its biogenic CO_2 for use in food and drinks industries - news article.

[11] Carbon Engineering web news.

[12] A project selected for Phase 1 funding for the BEIS GGR Programme in 2021 - Link

Figure 4: Map of the proposed Acorn CO_2 transport and storage project[13].

The main CCS project in Scotland is Acorn, which aims to enable wider CCS deployment in the region through building a shared CO_2 transport and storage (T&S) infrastructure[13]. This will be performed by repurposing the existing gas terminal at St Fergus, with the associated gas pipelines travelling to the offshore storage site and transporting CO_2 from central Scotland to the terminal. A new pipeline is proposed from the Peterhead port to St Fergus, which will enable delivery of CO_2 shipments from the rest of the UK and neighbouring countries. The storage project is expected to be operational until 2060, with a capacity to capture 12 $MtCO_2$/year. In Phase 1, the project will store 300 $ktCO_2$/year from processing of natural gas at St Fergus. In Phase 2, CO_2 from additional sources is expected to be stored from the Acorn Hydrogen project (a new DACCS plant in the region) and any potential CCS projects which may be deployed in Scotland or the North Sea region.

Scotland has also identified hydrogen as a strategic decarbonisation option due to its versatility as an energy vector and its potential to reduce emissions in transport, domestic heating and a variety of industrial processes. Apart from the Acorn Hydrogen project (which aims to convert natural gas from the North Sea to hydrogen) multiple supply and demand side projects have recently emerged in Scotland which plan to produce hydrogen from renewable energy to decarbonising transport and industries in major cities. Please see Appendix 3 for more detail on notable projects.

Recent modelling carried out for Scottish Government on the long-term Scottish CCS potential and hydrogen demand indicates that Scotland's CO_2 storage potential is high and the hydrogen demand in 2050 is sufficient to allow for BECCS hydrogen deployment[14]. However, the maximum level of BECCS and DACCS capacities which was modelled in 2050 was 5-6 $MtCO_2$/year, which is similar to Scotland's 2032 NETs envelope, emphasising the need to prioritise NETs over some other CO_2 sources, such as imports. Please see Appendix 3 for more information on this study.

3.3 Scottish Bioenergy Demand and Resources

Large-scale deployment of BECCS in Scotland will demand more sustainable biomass resources to be used than are currently used in low-carbon projects in Scotland. However, Scotland currently produces significantly more biomass than is used within the country. According to the CCC's scenarios developed for the Sixth Carbon Budget[15] (Figure 5), Scottish biomass supplies (plus Scotland's share of biomass imports into the UK) could total 26-37 TWh/year, far exceeding projected bioenergy demands including those from

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[13] Acorn website.

[14] Scottish CCUS Economic Impacts Study. By Element Energy for the Scottish Government and Scottish Enterprise, 2021.

[15] CCC (2020) Sixth Carbon Budget Dataset ("Sector level data explorer" tab, selecting Balanced Net Zero Pathway, Scotland, Final bioenergy demand) contains Scottish bioenergy demand estimates. Scottish biomass resource estimates received via personal communication with CCC, based on unpublished Sixth Carbon Budget analysis. The fossil fraction of waste is not shown in either chart.

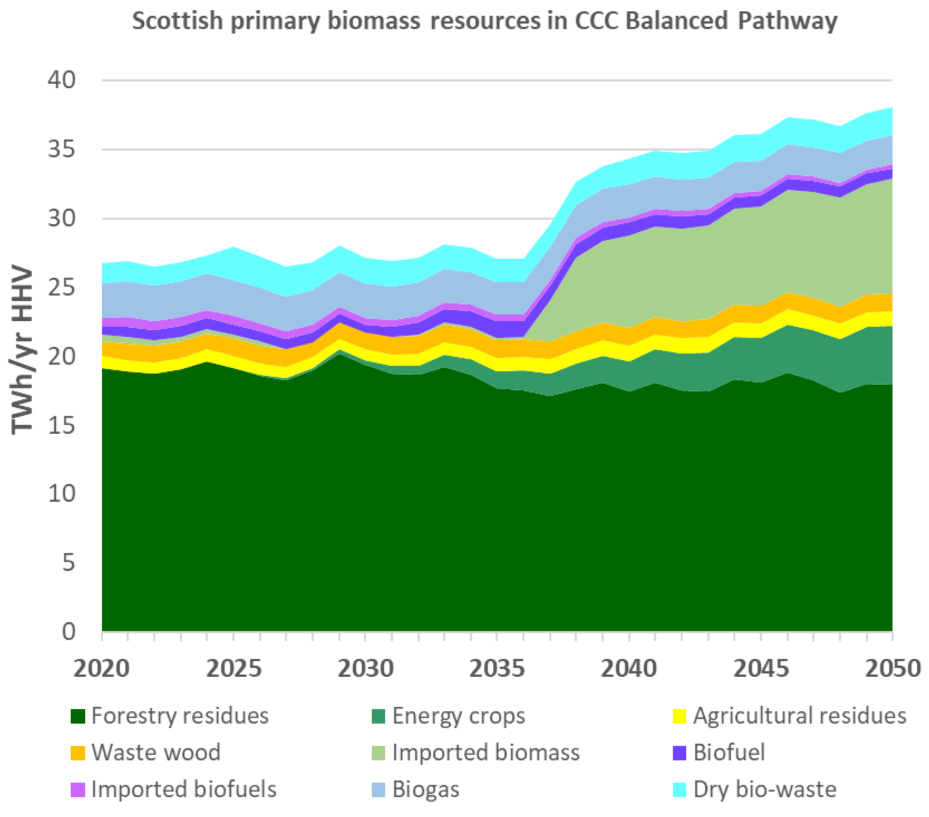
Scottish NETs. For instance, in the CCC's Balanced Pathway, final bioenergy demand in Scotland is projected to be only ~20% of primary bioenergy supply up to 2035 and ~33% up to 2050.

However, Ricardo (2019)[16] estimates indicate that competing uses and other constraints in accessing these biomass resources means the overall supply potential available to bioenergy uses might only reach 14 TWh/year in 2030, meaning around half of Scottish domestic biomass supplies are estimated to not be available for bioenergy. This reduced supply level is still likely to be sufficient to meet Scottish bioenergy demands in 2030.

This factors-in conversion losses for the modest amount of biomass that is converted to hydrogen or liquid fuels[17]. Most biomass & biowastes are used directly in power, heat and industry, or already given in final form (biogas, crop-based biofuels), and not all biomass supplies go to bioenergy demand.

Topics beyond the scope of this study which are recommended to be explored are:

- how biomass potentials in different Scottish regions align to competing uses and proposed CCS infrastructure
- what share of Scottish biomass could be consumed by NETs
- how intra-UK and extra-UK trade in biomass (imports/exports) might further impact Scottish availability estimates



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[16] Ricardo (2019) The potential contribution of bioenergy to Scotland's energy system

[17] These conversion losses are a difference between primary resources on the top chart and final resources on the bottom.

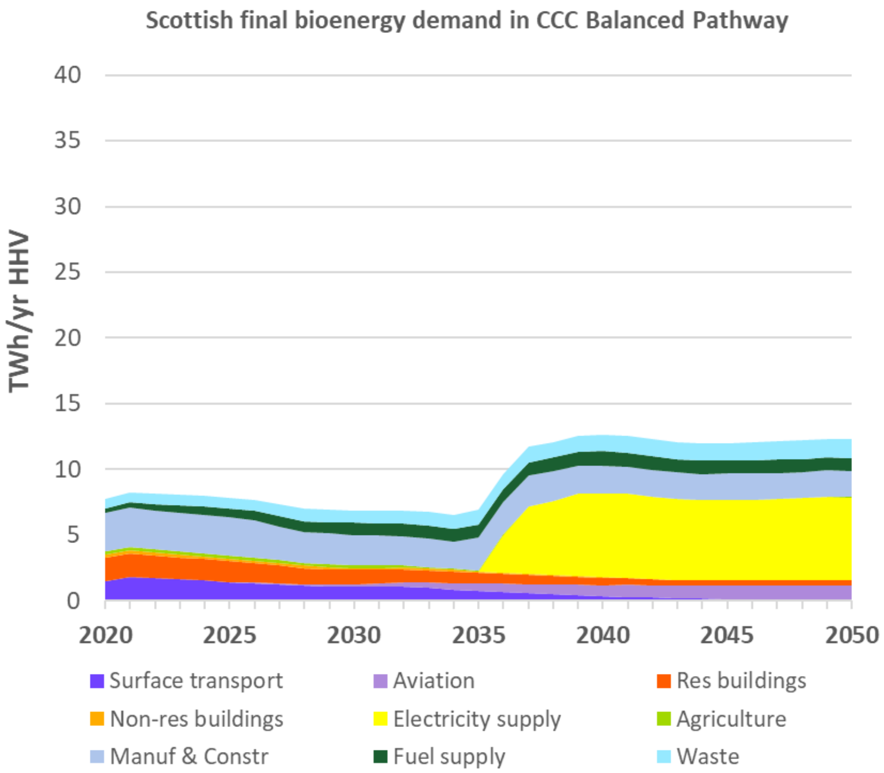

Figure 5: Bioresource supply (top) and demand (bottom) in Scotland in CCC's Sixth Carbon Budget Balanced pathway (TWh/year)[15].

4 Global NETs Horizon Scan

This section provides a brief overview of the status of different engineered NETs and includes a selection of international case studies representing some of the most mature projects. For these studies we have performed an extensive horizon scan by investigating published literature, collating publicly available information on websites, forums, and seminars, and speaking with relevant stakeholders in some of the NETs processes.

Other NETs configurations are possible (particularly for many different configurations of BECCS), with the final selection based on the availability of information, scalability of the processes and applicability to the Scottish context.

More information on timelines and technical details of individual case studies can be found in Appendix 4.

4.1 Global Status of DACCS

4.1.1 Technology Description

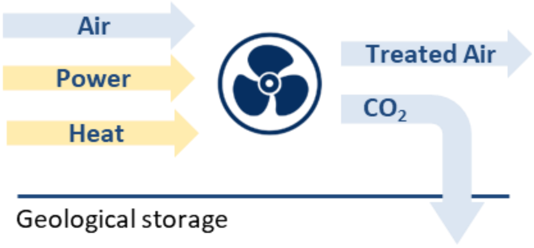

Figure 6: Schematic representation of direct air capture with carbon storage (DACCS).

Direct air capture (DAC) refers to a set of technologies which use chemicals to isolate and capture CO_2 from ambient air. The two most mature technologies use liquid absorbents and solid sorbents. Negative emissions are achieved when DAC is combined with traditional carbon storage methods (DACCS).

Current systems require both heat and power input, but future plants are expected to be able to run on electricity alone[18]. It is estimated that processes using low-carbon energy sources may emit 5%-15% of the captured CO_2 throughout their lifecycles[19].

The environmental impact of DACCS plants is likely to be minimal compared to other NETs, but significant land area and material consumption may be needed for dedicated solar or wind plants to power these facilities. The best locations for siting DACCS plants are near CO_2 Transport and Storage (T&S) infrastructures with low-cost low-carbon energy resources.

Currently DACCS plants are around Technology Readiness Level[20] (TRL) 4-6, with multiple innovative approaches in earlier R&D stages. DACCS costs are highly site dependent, but Element Energy estimates that early projects may cost 350-700 $/tCO_2$[19]. The long-term target of the international industry is \$100/tCO_2, which may be achievable in favourable locations after significant scale-up.

Currently there are 16 operational DAC plants, mostly across Europe and the US, with a total capacity of 15.3 $ktCO_2$/year. Around 52% of this capacity is for permanent storage of CO_2 (DACCS)[21]. The largest and newest of such facilities is Climeworks' Orca plant in Iceland, which came online in September 2021. Furthermore, Carbon Engineering is currently undertaking FEED studies for a megaton scale plant in Texas[22].

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[18] Systems operating with low temperature heat inputs could use heat pumps to meet this demand. More innovative electricity-based processes need to be developed for technologies using high temperature heating.

[19] Global assessment of direct air capture costs. A report by Element Energy for IEAGHG, 2021 (to be published).

[20] Information on TRLs can be found in *Emerging Industrial Applications* Chapter 13.3

[21] Based on Carbon 180's The DAC MAPP and the new 4 $ktCO_2$/year Ocra plant by Climeworks.

[22] A FEED is an early design process typically undertaken shortly after an initial feasibility study. Additional information can be found here - Link

4.1.2 DACCS Case Study: Carbon Engineering

Carbon Engineering (CE) is one of the three major DAC technology developers and specialises in liquid absorption applications. In 2019, Oxy Low Carbon Ventures, a subsidiary of the US based oil and gas company Occidental, agreed to deploy CE's DAC technology in Texas. As of September 2021, the FEED study for the 1 $MtCO_2$/year plant was halfway complete[23]. Construction is expected to start in 2022, with the plant potentially reaching operational level by 2025. The captured CO_2 is expected to be partially used for enhanced oil recovery, with the remaining CO_2 permanently stored to generate negative emissions credits. The enhanced 45Q tax credits and California's Low Carbon Fuel System credits are expected to be the main financial drivers behind the plant, with CE's preferred commercialisation route largely involving the licencing of its technology to developers.

CE estimates their net cost of carbon removal, without transport and storage of CO_2, to be \$250/tCO_2, which can reduce to \$100- \$150/tCO_2 removed in the future[19]. CE's first major carbon removal customer was Shopify, which ordered 10,000 tonnes of CO_2 removal credits in 2020. CE is currently offering CO_2 removal credits to retail customers[24], although prices are not made public. Some of the other projects CE is pursuing include a DAC innovation centre in Squamish, British Columbia which will feature a DAC pilot plant, and a pre-FEED study investigating the potential to build a 0.5-1 $MtCO_2$/year DACCS plant in Scotland as part of the Acorn project.

4.1.3 DACCS Case Study: Climeworks Orca Plant

Orca is the world's first commercial scale DACCS plant, with a capacity of 4 $ktCO_2$/year, which actively creates negative emissions with permanent CO_2 storage. Owned by Climeworks, it was commissioned in September 2021 in Hellisheidi, Iceland. Climeworks specialises in solid adsorbent DAC technologies which are relatively modular and can operate with heat sources around 100°C, enabling use of waste heat resources. Orca runs on geothermal energy sourced from the nearby plant of ON Power. The captured CO_2 is transported to another partner, Carbfix, which specialises in rapid mineralisation[25] of CO_2 in underground basalt formations.

Climeworks' business model largely revolves around owning or co-owning removal plants and selling credits to customers. Orca is constructed with an investment in the range of \$10-\$15 million, which is expected to translate to costs around \$600-\$900/tCO_2 removed, considering operational expenses. By 2020 Climeworks raised more than CHF 100 million (appx. £80m) in an investment round, and from May 2020 - August 2021, the company made carbon removal agreements with multiple notable corporations including Stripe, Audi, Shopify, Microsoft, the Economist, and Swiss Re[23]. Climeworks is also currently selling carbon removal credits on their website[26] for approximately €960/tCO_2. These subscriptions are fulfilled by the Orca plant, and Climeworks has announced that most of their current capacity has already been contracted out[23].

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[23] Presented in Climeworks' 2nd DAC Conference, 2021. Link

[24] CE's website – Link.

[25] Mineralisation refers to the geochemical process of the conversion of CO_2 to minerals, mostly carbonates. This is considered one of the most secure forms and "end goal" of storage in most instances.

[26] Climeworks website subscriptions page.

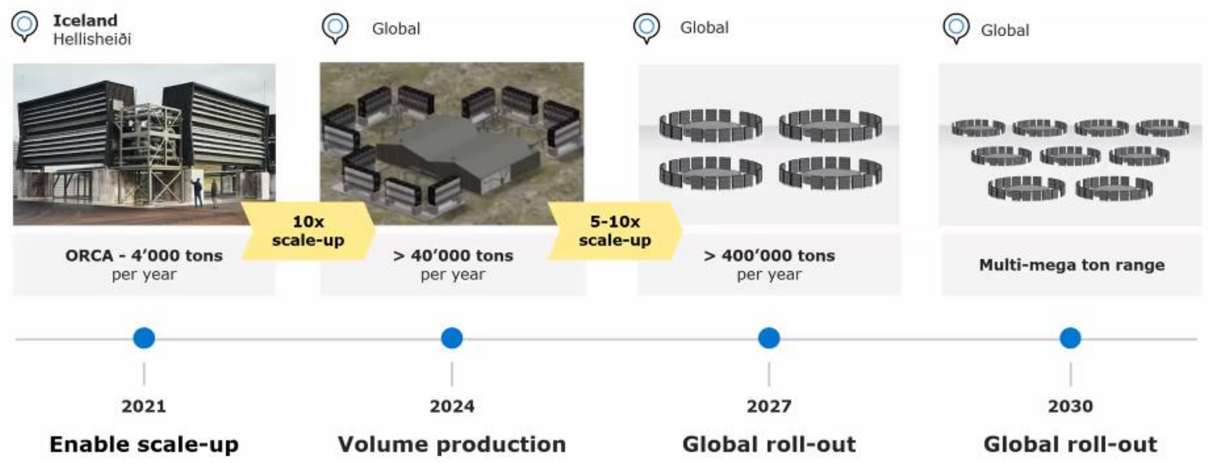

Figure 7: Illustration of Climeworks' scale-up and commercialisation timelines starting from the Orca plant and including the plans for a new plant 10 times the size of Orca[23]

Key enablers behind the success of the Orca plant were direct private investment and voluntary corporate purchases by early movers in the NETs space. The project also benefitted from direct credit sales to individuals, co-location of renewable energy and rapid CO_2 storage resources in Iceland. Adversely, major barriers which slowed progression (inferred from public statements on the project), were high costs of the early plant, ongoing technical uncertainties which can only be resolved through demonstration, lack of direct funding support from the government and lack of an established market for CO_2 removals.

The locations of future DACCS plants heavily depend on CO_2 infrastructure availability and distribution of low-carbon energy sources. **In Scotland, while DAC CO_2 is not expected to be used for Enhanced Oil Recovery (EOR) activities, many existing large industrial facilities may be ideal locations for DACCS if residual waste heat can be used**. Most of these facilities are around the industrial belt or close to shores, allowing for shipping CO_2 or connecting to a future cross-country pipeline.

Climeworks plants can also operate solely on electricity by using heat pumps. This allows greater flexibility for locations as **Scotland's offshore wind energy may be paired with DAC facilities**. The St Fergus terminal, where the Acorn project is building out its T&S infrastructure, may be a suitable location for combining storage and offshore wind elements. Compared to the baseload geothermal energy available to the Orca plant, the intermittent nature of wind energy may require onsite battery storage (or other balancing measures) adding to project costs. **Ultimately, DACCS deployment in Scotland has fewer physical restrictions than BECCS, and costs are likely to be the only factor determining deployment.**

4.2 Global Status of BECCS – Power

4.2.1 Technology Description

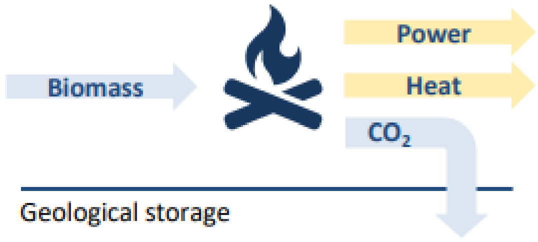

Figure 8: Schematic representation of BECCS power processes.

BECCS Power refers to processes which utilise biomass as a feedstock to produce electricity (and on occasion heat), and then capturing and permanently storing the resulting CO_2 emissions. Negative emissions are achieved through BECCS, as CO_2 is sequestered from air through photosynthesis. Therefore, lifecycle emissions relating to land use change, plant growth and transportation must be accounted for when determining the volume of negative emissions achieved.

Emissions from BECCS power may be captured via either pre- (approx. TRL 3) or post-combustion (approx. TRL 8). As the BECCS power plant engineering is very similar to most conventional power plants, retrofitting hydrocarbon or biomass plants can provide suitable options for this NET. The BECCS power plants may then also benefit from nearby local biomass sources and proximity to CO_2 T&S infrastructure.

Prominent examples of BECCS retrofits to power plants are Drax power station in North Yorkshire, and the Toshiba Mikawa Power Plant in Japan. Neither of these examples currently utilise a fully realised BECCS chain (although Drax plans to do so by the late 2020s if investment is secured), meaning no BECCS power plants currently result in negative emissions. Furthermore, although a BECCS power plant itself may not have a considerable local environmental impact, it may create competition for scarce biomass supplies or cause land use change related impacts, especially if dedicated energy crops are used.

BECCS power costs are estimated to be £70 – £130/tCO_2 when using local biomass, and between £150 – £200/tCO_2 when the biomass is imported[27]. However, the sale or use of the generated electricity in this NET is somewhat expected to offset some of these costs. In BECCS Power, baseload operation (the minimum demand on an electrical grid over a period of time) has been shown to be more economically feasible than lower load factor operation due to maximising both electricity generation and negative emissions[28].

4.2.2 BECCS Power Case Study: Toshiba Mikawa Plant

The Mikawa BECCS power plant in Omuta, Japan is a BECCS power project operated by Sigma Power Ariake Corporation, a subsidiary of Toshiba ESS. The plant captures and stores the CO_2 emissions resulting from the incineration of a palm kernel shell (PKS) feedstock. The current capture capacity on the 50 MW plant is over 450 tCO_2/day[29,30], making it the first operational large scale BECCS power project in the world (though only temporary storage is currently in place).

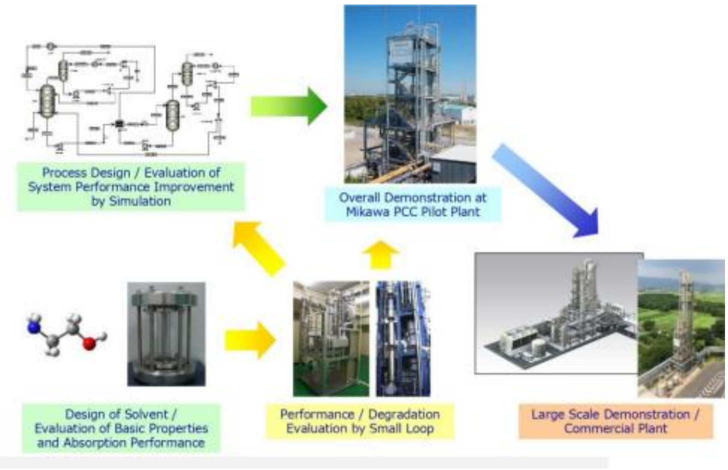

Figure 9: Illustration of the high-level project delivery outline[33].

The current capacity of the project is an upscaling of an initial pilot scheme (storage capacity of ~10 tCO_2/day) which began in 2009 and was designed to verify and demonstrate the performance, operability and maintainability of the carbon capture system[29,30]. The project is in part sponsored by Japan's Ministry of the Environment (MOE) as part of the 5 year "Demonstration of Suitable CCS Technology Project" designed to promote Japanese clean energy generation[31]. Within this project, the MOE is also evaluating CO_2 transport by sea, CO_2 injection into an offshore geological formation, the stability of undersea CO_2 storage, and the Japanese social environment for CCS. Toshiba, meanwhile, is using the facility to evaluate the CO_2 capture technology's performance, cost, environmental effects, and operational integration with the power plant. Additionally, the group is using the plant to test new high

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[27] UKERC Technology and Policy Assessment: BECCS and DACCS, 2019. Link
[28] Global Future Role of Power CCS Technologies, IEAGHG 2020
[29] Toshiba announcement of Large-Scale Carbon Capture Facility. Link
[30] Babin et al, 2021 (Biomass and BioEnergy)
[31] Mizuho Group Press Release, 2016. Link.

efficiency carbon capture solvents, which have shown to reduce solvent degradation and emissions[32].

The active involvement and funding of the Japanese MOE has been critical for the success of the project, as the project outcomes will be incorporated into the larger MOE project. In turn, relevant information from the MOE project (such as suitable offshore storage locations and cost-effective CO_2 shipping mechanisms) will be fed back to the Mikawa project to direct future development in a private-public sector symbiosis.

As a coal plant retrofit, the Mikawa BECCU facility was initially fed by a coal/biomass feedstock. However, engineering developments such as the circulating fluidised bed (CFB) biomass boilers and new amine solvents resulted in a BECCS facility capable of operating on 100% biomass feedstock with >90% CO_2 capture rate[32,33].

However, until the MOE project is completed, there is no current identified long-term storage location for the captured CO_2, potentially jeopardising long-term project viability. Furthermore, while support and input from the MOE was vital for project development, it also introduces cross-chain risk. A detailed environmental impact assessment is being reviewed within the MOE, which could introduce stalls and barriers to further CCS development should the full CCS chain be proven environmentally detrimental. Furthermore, Japan's waste hierarchy (similar to the waste hierarchy in the EU and UK) prioritises reduction, reuse, or recycling over simple thermal recovery[34], which could threaten the security of PKS feedstock should a more preferential composting solution be proposed and developed for the biomass.

Since the closing (and subsequent demolition) of Longannet power station in 2016, **Scotland no longer has any operational coal-fired power plants**, making a direct one-to-one applicability to Mikawa unrepresentative. However, Scotland currently has three medium sized biomass power plants which, if outfitted with CCS, could represent a very significant BECCS contribution to the NETs envelope. These three biomass plants (Markinch CHP Biomass Plant, Steven's Croft Power Station, and Westfield Biomass Plant) had a **combined emission of 944 ktCO_2 in 2019**[35]. Based on previous emissions data, it is estimated that over 95% of these emissions are biogenic[36], which could result in significant yearly negative emissions should carbon capture be implemented in these plants, and the CO_2 safely transported and stored (e.g. within a future Fife T&S CCS corridor). Further details on these three biomass power plants and an additional case study can be found in Appendix 4.

4.3 Global Status of BECCS – Energy from Waste

4.3.1 Technology Description

BECCS energy from waste (EfW) operates similarly to BECCS power plants, producing power and heat, but consuming waste (usually household and commercial) rather than pure biomass. Also, like the BECCS power generation process, waste may be initially combusted with subsequent capture of CO_2 (which is a

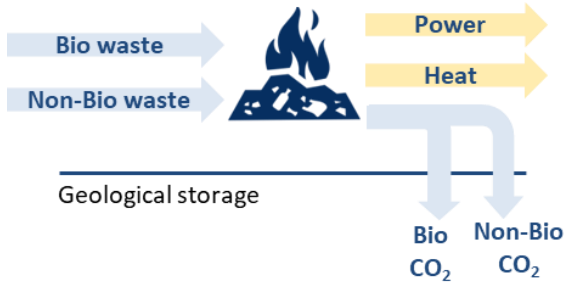

Figure 10: Schematic representation of BECCS EfW.

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[32] Fujita et at, 2021 (GHGT-15)
[33] Japan CCS Forum, 2019. Link.
[34] Dept. of Urban Policy and Science Hierarchy of Waste Management. Link.
[35] SEPA SPRI Database. Link.
[36] Brownsort, 2018. "Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions"

mature process around TRL 8) or may be initially gasified (pre-combustion capture at around TRL 3).

Waste usually contains roughly equal parts biogenic and inorganic carbon, though this might change in the future due to increases in recycling or food waste reduction. Any uncaptured emissions from the inorganic proportion of feedstock are treated as positive emissions, while the biogenic portion of CO_2 emissions is treated as negative emissions once stored.

EfW plants have positive environmental impacts since it allows waste to avoid landfill. However, permanently destroying waste is only a form of energy recovery and undermines circular economy principles if recyclable waste is incinerated. BECCS EfW requires secure long term waste supplies, so ideally plants should be sited close to population and industrial centres as well as CO_2 storage locations. BECCS EfW costs are highly site dependent with one study[37] estimating the costs being similar to regular EfW plants with a carbon price of £90/tCO_2.

Currently there are no operational large-scale BECCS EfW plants delivering negative emissions. However, several projects are at advanced planning stages, such as Fortum Oslo Varme's plant in Norway and AVR's EfW plant at Duiven in the Netherlands capturing 15% of its emissions for use at a local greenhouse. Recently several BECCS EfW feasibility and planning projects have been announced in the UK, such as SUEZ-BP (Teesside), Veolia/Carbon Clean and Redcar Energy Centre.

4.3.2 BECCS EfW Case Study: Fortum Oslo Varme

Fortum Oslo Varme (FOV) owns an EfW plant at Oslo, which currently incinerates 350k tonnes of household and commercial waste to produce power and heat for the local district heating system. It expects to emit 460 ktCO_2/year in the future and capture 400 ktCO_2/year via a new CCS system it plans to retrofit[38]. Around half of the waste incinerated is estimated to come from biogenic origins, so the project would result in 200 ktCO_2/year of negative emissions.

Together with the Norcem cement factory, FOV BECCS plant forms part of the CO_2 capture components of a wider Norwegian full-chain CCS project called Longship. The CO_2 is proposed to be carried from FOV to the Port of Oslo by trucks and later shipped to an onshore facility at the west coast of Norway to get pressurised and injected to an offshore pipeline. The CO_2 will ultimately be stored offshore in the North Sea[39] (Figure 11). The T&S component of Longship is called the Northern Lights Project, which will be open to accepting CO_2 from other sources in the future.

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[37] Energy from Waste Plants UK with Carbon Capture. Energy Systems Catapult, 2020.

[38] FOV FEED Study Report DG3 (redacted version). Carbon Capture OSL, 2020.

[39] DNV website on Northern Lights – Link.

Figure 11: Map of the Norwegian Longship CCS project including the Northern Lights CO_2 storage component, FOV's BECCS EfW plant and Norcem's BECCS cement plant[39].

FOV BECCS is expected to reduce Oslo's emissions by 14%[40], which is essential for the city to reach its very ambitious target of 95% emissions reduction by 2030 compared to 2009.

Total capital investment in the FOV carbon capture process (including short term storage and trucking) is estimated to be $580 million (2018 values) and operational expenditure (opex) is estimated at $29 million per year. Over 25 years, a discount rate of 8%, and an average shipping and storage costs of $140/t$CO_2$, the total cost of the project is expected to be $362/t$CO_2$ stored[41]. The Norwegian government agreed to pay around $344 million to cover half of the project costs, and the remainder is expected to be co-funded by the EU Innovation Fund[42].

Some of the key factors enabling this BECCS project were the City of Oslo's ambitious climate targets, Norway's strategic prioritisation of CCS since late 2000s, direct funding provided by the government (and potentially the EU) to cover capital and operational expenses, and Norway's developed offshore CO_2 storage resources in the North Sea. Furthermore, waste is likely to be a reliable source of biomass due to Norwegian waste export indicating a high supply. Alternatively, some barriers to this project were relatively high capture costs (due to low CO_2 flue gas concentrations and transport via trucks), dependence on European co-funding, and strict environmental regulation which required additional pilot testing and dependence on shared T&S infrastructure.

There are currently six household waste incineration facilities in Scotland (Baldovie, Dunbar, Millerhill, Glasgow, Shetland and Levenseat) with a combined capacity of processing 988 ktonnes of waste per year[43,44]. Another three plants with a total capacity of 500 ktonnes are expected to complete within a year. **Viridor recently announced[45] their plans to install CCS to their Dunbar EfW plant by 2035.** Dunbar is the largest EfW plant in Scotland with an annual capacity of 325 ktonnes/year, but is still smaller than FOV, which will have a capacity of 410 ktonnes. All of these EfW plants are relatively close to the Feeder 10 pipeline and may deliver their CO_2 to a future T&S infrastructure via trucks. Shipping to the Peterhead Port may be another viable option, especially for Dunbar, Millerhill and the future Earls Gate plants. Compared to the FOV BECCS plant, **the key missing enabler in Scotland is direct funding or another financial model to justify investment**.

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[40] FOV's CCS brochure - Link

[41] The Norwegian full scale CCS demonstration project: potential for reduced costs for carbon capture, transport and storage value chains (CCS). DNV GL, 2020.

[42] FOV is currently shortlisted for the EU Innovation Fund and results are expected to be announced in Q4 2021.

[43] UK energy from waste statistics 2020. Tolvik, 2021.

[44] Friends of the Earth Scotland website on incineration – Link.

[45] Decarbonising our waste: Viridor's roadmap to net zero and net negative emissions. Viridor, 2021.

4.4 Global Status of BECCS – Industry

4.4.1 Technology Description

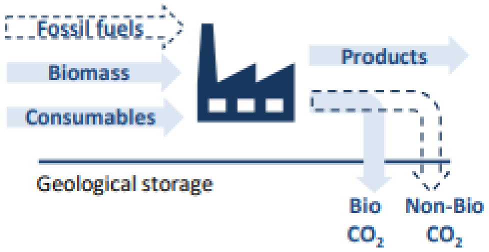

Figure 12: Schematic representation of BECCS industry processes.

BECCS industry refers to a wide set of processes which use biomass as feedstock or energy source in industrial applications (such as steel, cement, pulp and paper) and subsequently capture and store the CO_2.

The TRL for the BECCS process ranges between 5-8. Most industries still rely on fossil fuels to some extent, and therefore may only co-fire biomass. With the resulting negative CO_2 emissions only being derived from the biogenic portion of the feedstock, the balance of fuels is important if net negative emissions are to be achieved.

Globally, only 6% of heat for cement production is estimated to come from bioenergy[46]. While integrating CCS to biomass-fed industrial plants is estimated to have a minimal adverse environmental impact, additional fuel switching to bioenergy may put pressure on bioenergy resources and potentially negatively impact land usage. Additionally, CCS integration may impose additional financial and technical restrictions in some sectors, such as steel, where emissions occur from multiple locations in the plant. Some industries, such as cement, have smaller and more distributed plants potentially farther away from industrial clusters, imposing additional CO_2 T&S restraints.

BECCS industry costs are very project-specific, due to variation in emissions, size, and commercialisation potential between projects. For instance, the costs of CO_2 capture and storage for pulp mills have been estimated to be €52 – €66/tCO_2, but other applications are likely to be more expensive[47]. While there are no current BECCS industry projects generating negative emissions, there are two notable industry projects with a carbon capture element. The Norcem cement plant in Brevik, Norway is currently co-firing 30% biomass and is planning to retrofit a CCS unit to capture 50% of its emissions (totalling 400 ktCO_2/year), and Resolute's Saint-Felicien Pulp Mill in Quebec, Canada has installed a CCS plant in 2019 to capture 11 ktCO_2/year after successful demonstration of individual components of the value chain.

4.4.2 BECCS Industry Case Study: Norcem Cement Plant

Heidelberg Cement Group, the sole cement producer in Norway, is currently constructing a carbon capture plant at its Norcem factory in Brevik. Although the facility's carbon footprint (600 kgCO_2/tonne of cement) is below the global cement industry average, the facility still emits approximately 800 ktCO_2/year[48]. Expected to be operational by 2024, the CCS plant will capture 50% of these emissions, and because a small portion of the emissions are biogenic, approximately 36 ktCO_2/year would be net negative. Norcem CCS, a subsidiary of Heidelberg, is part of a wider full-chain CCS project in Norway called Longship. The Norcem cement plant, along with the Fortum Oslo Varme EfW CCS plant, will be the two initial capture projects feeding captured CO_2 into the transport and storage business (dubbed "Northern Lights") of the Longship project.

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[46] Deployment of BECCS/U value chains. IEA Bioenergy, 2020.

[47] Onarheim et al, 2017. Link

[48] New business models for carbon capture and storage. ZERO, 2019.

After a FEED study was completed in 2019, the Norwegian Government decided to fund \$1.9 billion for the Longship programme, which is expected to cover over 80% of the Norcem CCS costs[49], estimated at \$380 million. When shipping and storage costs are taken into account, the total cost of storage for the project is estimated at \$273/tCO_2 stored[41]. In addition to government funding, Norcem (listed on the EU ETS) is expected to benefit from reduced compliance costs due to the CCS installation once its free emissions allowances are reduced[50]. Norcem is also an advocate of recognition of negative emissions in the EU ETS, as well as protection from carbon leakage through a carbon border adjustment mechanism (CBAM)[49].

Critical to the success of this project is the Norwegian strategic prioritisation of CCS since the late 2000s, which has allowed for significant national knowledge to be developed with multiple demonstration projects, and financial support of these projects through direct public funding. Furthermore, higher flue gas CO_2 concentrations and available onsite waste heat have reduced capture costs for Norcem. It is inferred from publicly made statements and project timelines that while the proximity to the Northern Lights transport project has reduced operational expenses, dependence on shared transport and storage infrastructure have slowed down Norcem CCS, and carbon leakage combined with alternative decarbonisation pathways (i.e., electrification or fuel switching) make final investment decision into CCS more difficult.

Scotland currently operates a single cement plant (in Dunbar), which is in close proximity to Viridor's Dunbar EfW plant. Owned by Tarmac since 1963, the plant has undergone multiple upgrades, including a new high-efficiency mill. Similar to Norcem, the plant currently consumes a small amount of waste feedstocks[51], and overall CO_2 emissions are estimated at approximately 570 ktCO_2/year. Further fuel switching to a full biomass feedstock and installing CCS could result in up to 260 ktCO_2/year of negative emissions[52]. However, realising this potential would require further R&D into alternative production pathways using the increased percentage of biogenic fuel.

4.4.3 BECCS Industry Case Study: Resolute Saint-Felicien Pulp Mill

In 2019, Resolute Forest Products installed a carbon capture plant on their Saint-Félicien pulp mill in Quebec, Canada. The plant captures approximately 30 tCO_2/day, which, after a six-month demonstration phase, is now sent to the adjacent Toundra Greenhouse complex for commercial reuse in cucumber growth[53]. In addition to CO_2, the Saint-Félicien mill has a power cogeneration capacity of approximately 43MW[54], and supplies excess heat to the greenhouse complex, reducing natural gas consumption of the Toundra complex by 25%[55].

Resolute officially deployed the CO_2 capture unit in March of 2019 after a successful six-month demonstration period. The capture unit is supplied by Canadian-based company, CO_2 Solutions, which offers a unique enzymatic capture process in their engineering setup.

The project is a vital component in Resolute's decarbonisation goals, and the company has since pledged to reduce its 2025 scope 1 & 2 GHG emissions by 30% against its 2015 values[56]. Resolute owns the Saint-Félicien mill and holds a 49% interest in the form of a joint venture (JV) in the Toundra complex, and expects to provide \$400,000 annually to

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[49] Presentation by Karin Webb on CCS at Heidelberg. Link

[50] Norwegian CCS Demonstration Project Norcem FEED redacted version, 2020.

[51] Tarmac's response to Scotland's Climate Change Bill. Link

[52] Deep decarbonisation pathways for Scottish industries. Element Energy, 2020.

[53] Pulp and Paper Canada, 2019. Link

[54] Resolute Saint-Félicien datasheet Link

[55] Resolute Economic Profile, 2020. Link

[56] Resolute emissions reduction announcement. Link

CO_2 Solutions from the sale of captured CO_2 and any associated carbon credits[57]. The mill itself uses 369,000 metric tons of Northern bleached softwood kraft pulp as a feedstock[54], but critically, however, the CO_2 is used for commercial vegetable development and is not permanently stored. Therefore, the captured CO_2 emissions from the pulp mill cannot be considered negative emissions. This is an example of carbon capture and utilisation (CCU) rather than CCS.

Despite the commercial benefits of CCU, the project still required support from Government of Canada's ecoENERGY Innovation Initiative (ecoEII) and Alberta's Climate Change and Emissions Management (CCEMC) Corporation, a $2.4 million non-refundable grant from Sustainable Development Technology Canada, and a further $300,000 and $100,000 from Resolute and Toundra, respectively[57]. While public funding for the project was critical, the delays in acquiring the grants exposed the project to inflation and fluctuation between USD/CAD, which caused the project to increase from $7.4 million to $8.4 million in a 3-4 year period[58].

For Scotland to achieve negative emissions, long-term storage would need to be prioritised over utilisation options which only have short term storage. **Scotland's six largest paper and wood mills produced approximately 676 ktCO₂ in 2019**. Based on previously reported ratios of biogenic content[36], it is estimated that approximately 83% of these emissions are biogenic. Successful NETs deployment could mean implementation of CCS on the three largest plants, which by emissions size are the Caledonian Paper Mill in Irvine, the Norbord mills in Cowie and Inverness. Combined, these mills contributed to 86% of the sector's 2019 emissions[35]. Although not co-located near any major storage sites, **CCS on these sites could be complemented by their relative proximity to nearby major motorways, rail lines, and the Feeder 10 pipeline[36]**, which all could serve to transport captured biogenic CO_2 to storage hubs.

4.5 Global Status of BECCS – Hydrogen, Biofuels, and Biomethane

4.5.1 Technology Description

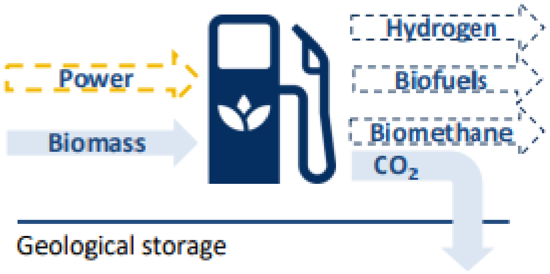

Figure 13: Schematic representation of BECCS processes producing hydrogen, biofuels, and biomethane

Gaseous and liquid forms of bioenergy (such as biomethane, bioethanol, and biogenically-sourced hydrogen) can be made via thermochemical conversion routes including gasification and pyrolysis. Alternatively, fermentation can be used to produce alcohols, and anaerobic digestion (AD) can be used to produce biohydrogen or biogas (which can be upgraded to biomethane). These routes may be net negative if the residual biogenic carbon that does not make it into the final fuel is captured as CO_2 and securely stored, and outweighs the emissions associated with input power and lifecycle emissions of the feedstock. Some biogenic CO_2 will be emitted and not captured in the process plant, and CO_2 will also be released when hydrocarbon-based biofuels/biomethane are combusted (e.g. in transport), but these emissions would be deemed carbon neutral.

Each process results in streams with varying concentrations of CO_2, which impacts the cost of CO_2 capture. Environmentally, BECCS fuels technologies have minimal direct impact when compared to plants without incorporated CCS, especially if any external

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[57] Pulp and Paper Canada, 2016. Link
[58] CO_2 Solutions Update on Carbon Capture Project. Link.

energy requirement is supplied through sustainable means. However, they may divert scarce biomass resources from other BECCS alternatives.

BECCS hydrogen has a triple constraint consisting of availability of biomass, proximity of CO_2 transport and storage infrastructure, and proximity of demand for hydrogen. Existing AD and fermentation plants, which are at higher TRLs of 8-9 globally, would be ideal locations for early projects given high CO_2 concentration streams are already being captured for CCU applications at several plants. BECCS biofuel and BECCS hydrogen would also likely be attractive given similar high CO_2 concentrations, but these conversion pathways are globally at a lower TRL (4-6). One study[27] identifies global BECCS costs in the range of £12-£315/tCO_2, where lower values typically correspond to high CO_2 concentration applications such as biofuels and biomethane.

Prominent examples of BECCS Biofuels are ADM's Illinois Industrial CCS project in the USA (already storing ~0.5 $MtCO_2$/year from corn ethanol production), KEW Technology (who are currently carrying out a feasibility study for integration of CCS and hydrogen production into their biomass gasification process), and Future Biogas (who have plans for at least 200 $ktCO_2$/year to be captured from AD biomethane upgrading plants in the UK by the mid-2020s, for sequestration in the North Sea). In addition, by 2019 there were 8 smaller operational BECCS ethanol demonstration projects across the US and Europe with a combined capacity of 1 $MtCO_2$ /year[59].

4.5.2 BECCS Biofuels Case Study: ADM

ADM have carried out two BECCS projects at their corn bioethanol facility in Illinois, USA. The site has several ethanol fermentation tanks, which result in CO_2 and water as the main gaseous by-products[60]. A gas-liquid separation step removes most of the entrained water, with the CO_2 then being further dehydrated and compressed to a super-critical phase and piped 1 mile to an onshore injection location in the Mt Simon sandstone formation.

The first project – the Illinois Baseline-Decatur Project (IBDP) – ran from 2011 to 2014 and succeeded in storing 1 $MtCO_2$ over a 3-year period[61]. This project aimed to research the feasibility of CO_2 storage in saline formations and demonstrate the safety and permanence of storage. The second project – the Illinois Industrial CCS Project (IL-ICCS) – began in 2017 and aims to show capacity for 1 $MtCO_2$ /year storage[62]. Although annual stored volumes have been approximately 0.5 $MtCO_2$ /year, the project has indicated an operational capacity to reach the desired 1 $MtCO_2$/year target.

In the second phase of CCS at this site, the project aims to demonstrate commercial viability of CCS and develop more advanced modelling tools and techniques. The project will run until the end of 2022, where future work is currently uncertain. Although the capture project capacity was limited by the total biogenic CO_2 emissions generated onsite from ethanol fermentation (up to 1.0 $MtCO_2$ /year), there are several other operations at the Decatur facility (making sugars, organic acids, lysine), and total facility fossil fuel emissions of approximately 4.4 $MtCO_2e$/year (mainly due to natural gas) therefore exceed the negative emissions achieved from only the IL-ICCS project[62]. To date, the combined storage of both the IBDP and IL-ICCS projects is estimated at 3.4 $MtCO_2$[62].

The majority of funding for both projects came from US Department of Energy (US DOE), with the remainder covered by ADM and partner companies[63]. The IBDP received $106m from DOE, and ADM and partners funded a further $21m. For IL-ICCS, $141.4 million was provided by the US DOE, with the remaining $66.5 million paid for by ADM and its partner

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[59] Bioenergy and Carbon Capture and Storage, GCCSI 2019

[60] Bioenergy International, 2017

[61] Locke IEAGHG presentation, 2012. Link.

[62] US EPA GHG Data. Link.

[63] Hettinger, Midwest Center for Investigative Reporting, 2020. Link.

Schlumberger Carbon Services. The project is additionally supported by a \$20/tCO_2 tax credit, and the bioethanol produced with CO_2 capture is blended with gasoline to lower emissions from road transport. This credit (which has now increased to \$50/tCO_2 with the new 45Q regulations), as well as the US DOE public sector funding were critical to the success of the project. Furthermore, the proximity of the CO_2 capture to a long-term storage location, and the high-purity CO_2 resulting from the fermentation process resulted in lower opex costs when compared to most other BECCS processes. However, the project did have to go through a 6-year permitting process due to rounds of permit draft applications and public hearing consultations[64], and their permit to inject CO_2 expires in 2022. Furthermore, there was difficulty in achieving the desired capacity of 1.0 MtCO_2/year storage with this project, with only 0.5 MtCO_2/year currently being successfully sequestered at present[62], due to dependency on the bioethanol plant output.

In Scotland, there are currently no bioethanol plants, so direct replicability of this case study relies on future bioethanol expansion. Future bioethanol demands in Scotland are uncertain, impacting the commercial viability of bioethanol production in Scotland. Whilst blending bioethanol in petrol will increase to 10% (E10 grade) this year and stimulate short-term demand, in the mid-term the roll-out of electric vehicles is likely to lead to rapid contraction in petrol and bioethanol use. However, other bioethanol uses for chemicals manufacture or ethanol-to-jet conversion are being developed.

Celtic Renewables are building a 0.5 ML/year biobutanol fermentation plant in Grangemouth which will also produce bioethanol and bio-acetone co-products. The plant will have an estimated emissions of 660 tCO_2/year from fermentation at high concentrations[65], although no plans have yet been announced to capture this CO_2. The demonstration plant will use 50 ktonnes/year of pot ale and draff feedstocks, which are biogenic wastes from whisky production, and once operational, also plans to trial feedstock wastes from the paper and bakery industries. New funding and planning re-approval for the £5.2m project was secured in 2020 and construction is now underway. **Should the plant be retrofitted with CCS, negative emissions could be achieved** on the biogenic CO_2 emissions**.** If the technology is successfully demonstrated at Grangemouth, then scale-up and expansion to larger facilities could be foreseen, utilising the 750 kt/year of draff residues and 2.75 Mt/year of pot ale produced from Scottish whisky distilleries[66,67].

New Scottish bioethanol/biobutanol plants are likely to require CO_2 transport over relatively significant distances to UK CCS sites, increasing costs compared to the ADM hyper-local set-up in Illinois. However, these CO_2 transport costs could be manageable if the plants are integrated into future Scottish CCS infrastructure (e.g. if the Feeder 10 pipeline is converted).

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[64] Illinois Industrial Sources CCS Project Update. Link.
[65] Estimate based on 3:6:1 ABE production and 0.79kgCO_2/litre
[66] Napier University news, 2017. Link.
[67] Ricardo Presentation for Zero Waste Scotland. Link.

4.5.3 BECCS Hydrogen Case Study: KEW Technology

KEW Technology is a UK-based firm which has developed a compact and modular process for conversion of biomass to hydrogen-rich syngas. The company has won Phase I funding for the UK Department of Business, Energy, and Industrial Strategy (BEIS) DAC and GGR programme for their Carbon Capture and Hydrogen Production from Biomass (CCH_2) project. This project is developing designs for additional modules to upgrade the syngas to produce separate high-purity hydrogen and CO_2 streams[68].

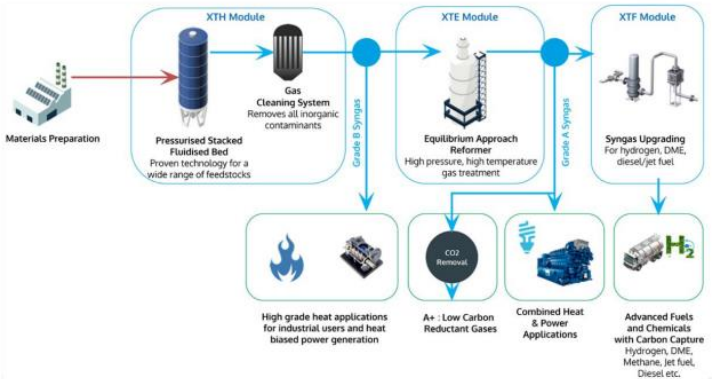

Figure 14: Kew high level technology and end-application process description.[69]

The KEW process takes biomass or refuse derived fuels (RDF) blended with biomass and converts it into raw syngas. The heavy hydrocarbons are then broken down to methane (CH_4), hydrogen (H_2), carbon monoxide (CO), and CO_2. The gas can then be upgraded in a hydrogen production module to form two high-purity streams of CO_2 and H_2. Further research is taking place into adding a pressure-swing absorber (PSA) to the process to bring hydrogen purity to 99.999% for commercial applications[69].

The KEW process, as well as other BECCS hydrogen techniques, creates a low-carbon synergy between carbon capture, hydrogen production, and waste valorisation. The biogenic percentage of the captured and sequestered CO_2 would be the negative emissions portion of the process. Critically, the KEW gasifier can access lower-quality forms of biomass which currently can go unutilised by EfW schemes[69]. However, if the process opts for municipal solid waste for feedstock, the biogenic content percentage of the waste would have to be large enough to meet syngas production requirements.

100 fully upgraded KEW gasifier modules (7 MWt each) or 10 higher-pressure KEW plants would be required to supply the volume of hydrogen as the base SMR (steam methane reformation – the most popular hydrogen production process)[69,70]. KEW's by-products can be re-incorporated in the design (such as heat production) or sold (such as hydrogen), thus lowering opex or offsetting T&S costs. This is complemented by a lower capex to create one hydrogen-producing module, with the highest output 70 MWt plant with 80% carbon capture having an estimated capex of approximately £73 million, which compares favourably to the baseline SMR plant (H_2 purity 99.999%) with 90% carbon capture of approximately £237 million[69,70]. This may lower the barrier of entry of hydrogen production for some companies, which has previously been gatekept in part by higher capex. For biomass-fed KEW plants, the price of biomass and a potential carbon tax both have significant impact on the levelised cost of hydrogen (LCOH)[69]. Should the end-use of the hydrogen require 99.999% purity, then a PSA will have to be built, likely increasing capex.

There are **no currently operating plants in Scotland where BECCS Hydrogen could be directly applicable**. Any development of BECCS hydrogen capability would require new build plants. Additionally, as the technology is at an earlier stage of development compared to some other BECCS options, it is likely that a technology demonstration phase will be required before large scale plants are built. However, it could present an opportunity to valorise previously unexploited bioenergy feedstock, especially as competition for

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[68] UK BEIS Phase 1 Project. Link.

[69] H_2 Zero Carbon Bulk Supply. Link.

[70] BEIS 2020 Wood Report. Link.

suitable feedstock materials for other bioenergy purposes makes high-grade biomass feedstock rarer. There is an estimated 6.7 TWh/year of biomass used for bioenergy purposes in Scotland. 75% of this is wood, with the remaining 25% being from lower quality resources in tallow, food waste, poultry litter, used cooking oil, sewage sludge, animal manures and by-products/wastes from the whisky and dairy industry. There is an additional estimated 5.3 TWh per year of currently unutilised lower quality biomass resources in straw, animal manures, forestry brash residual waste, waste wood, food waste, sewage sludge, and by-products/waste from the whisky industry[71], which would have to be aggregated and transported for use in BECCS processes.

4.5.4 BECCS Biomethane Case Study: Future Biogas

Future Biogas is a UK-based anaerobic digestion and biomethane company which plans to develop 25 new BECCS plants between 2021-2028, using anaerobic digestion of maize, rye or grass from local farmers to generate biomethane and CO_2[72]. The company currently operates 10 AD facilities (mostly in the East of England), with plans to retrofit these with CCS capability. The company also plans to retrofit 10 existing third-party biogas facilities with CCS, bringing the total number of planned biomethane plants with CCS to 45 in the UK. CO_2 liquefaction will occur onsite at the biomethane plants, with the liquid CO_2 trucked to the Humber estuary for storage. From here it is planned to be shipped to an onshore terminal in Norway before being piped to the Northern Lights CCS facility for permanent storage.

Commercially, the biomethane will be sold on bilateral contracts to industrial users via the UK gas grid, and Future Biogas are planning not to rely on any guaranteed premium feed-in rate from the UK Government's Green Gas Support Scheme (GGSS). Additionally, Future Biogas plans rely on receiving valuable carbon credits from the stored biogenic CO_2 (from a currently unspecified voluntary scheme) which they then would sell to corporations looking to offset their emissions. The pipeline of projects will be funded in part by Future Biogas' IPO in 2021, which aims to raise £31 million[73].

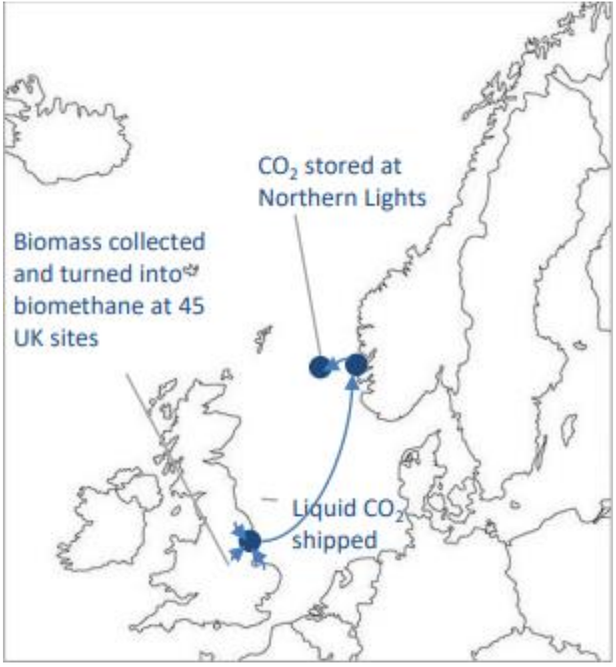

Figure 15: Illustrative CO_2 movements for Future Biogas.

The company initially plans to ship 200 ktCO_2/year to the Northern Lights facility by the end of 2024, and scale this up further to 2028. Each new facility is planning to use ~60 kt/year of biomass feedstocks, secured with 15-year long term contracts with local farmers. Each biomethane upgrading plant is estimated to be able to capture 15-18 ktCO_2/year. Currently, an estimated 60 kt/year of biogenic CO_2 goes uncaptured from their 10 existing plants. If all 45 UK projects succeed by 2028, total biogenic sequestration might reach 545 ktCO_2/year.

There are number of drivers advantaging BECCS biomethane at the moment, including very high fossil gas prices, a fast expanding UK biomethane injection market, and high

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[71] Ricardo Report for ClimateXChange, 2018. Link.
[72] Farmers Weekly news, 2021. Link.
[73] Gasworld new, 2021. Link. Personal Communication

CO_2 concentrations meaning low cost capture. However, this roll-out will rely on selection of locations with good gas grid availability, and pairing with local farmers (or waste operators) to provide the feedstock. Significant uncertainties still remain with financing. Future Biogas's IPO in 2021, initially scheduled for July, has been delayed, which may impact hiring, project development and investment decisions. Furthermore, the details, demand and pricing for sale of their biogenic CCS credits is yet to be confirmed, as schemes such as the UK ETS do not currently permit negative emissions, and other UK policies regarding negative emission support are still in development.

UK policy or public sentiment may move further against purpose grown-crops like maize and rye due to sustainability concerns (land use, water use, soil impacts), although avoiding relying on the GGSS means Future Biogas is not constrained by GGSS' minimum 50% waste feedstock proportion rule and Future Biogas have specified cultivation rules for farmers to protect their soils. Default GHG emissions of 35-44 gCO_2e/MJ biomethane for maize, rye and grass silage are relatively high compared to other bioenergy routes, and therefore net negative emissions when applying CO_2 capture will be significantly less than the gross biogenic CO_2 captured. Finally, the project currently relies on using third party and partner CO_2 infrastructure, and CO_2 trucking from small rural plants will likely be expensive. Shipping CO_2 out of the Humber is the initial plan, but for larger volumes in the future, Future Biogas plan on using either of the Humber CCS projects to store CO_2 in closer UK CCS sites which are still in development.

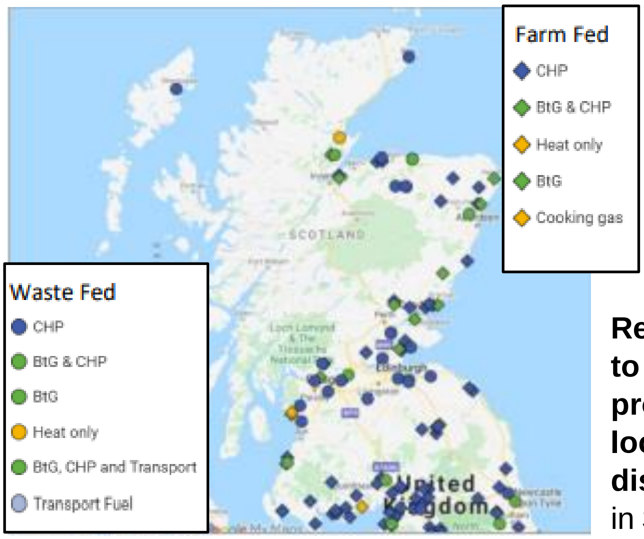

Figure 16: of current AD facilities in Scotland (BtG = Biomethane to Grid, CHP = Combined Heat & Power)[74].

A large number of AD facilities have been built in Scotland recently[74], with AD plant numbers doubling from 42 in 2016 to ~84 at present. However, of these only 20 are currently confirmed to be upgrading biogas, producing 716 GWh/year of biomethane (and ~140 $ktCO_2$/year).

Retrofitting biomethane upgrading units to other AD sites would be possible provided there is a gas grid connection locally (or short biomethane trucking distances). Assuming half of the AD plants in Scotland could have or retrofit biomethane upgrading in the near-term[75], this may increase to ~290 $ktCO_2$/yr.

CCC scenarios also have the Scottish biomethane sector at least tripling in size from 2019 to 2030[76]. Whether via retrofits or new projects, this suggests **a sizable contribution to overall Scottish NETs from BECCS biomethane plants is plausible**, provided the downstream CO_2 distribution chains are

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[74] NNFCC - Official Biogas Map - Link

[75] Indicative estimate based on the potential for retrofit.

[76] CCC (2020) Sixth Carbon Budget – UK's path to Net Zero report, page 154. This specifies a more than trebling in UK biomethane injection, and unpublished CCC CB6 data on Scottish biomass resources has the Scottish share of UK biogas production slowly increasing over time, which together indicate that Scottish biomethane production in CCC scenarios at least trebles by 2030. This biomethane injection trend is also visible from the CCC (2020) Sixth Carbon Budget dataset, "Sector level data explorer" tab, if selecting "Balanced Net Zero Pathway", "Scotland" and "Final bioenergy demand" compared to the "Baseline final bioenergy demand" (for an estimate of 2018 levels), and looking at the Fuel Supply row results.

established. Such facilities would ideally be developed and integrated into a national CCS network (either by pipe or by truck over short distances) – biomethane is already both injected into the gas grid and trucked, depending on AD plant location.

5 Conclusions

The case studies in this review, while being diverse in background, scope, maturity, and targets, have shown to have a few consistent high-level similarities which should be noted.

1) Uncertainty in the policy mechanisms/business models potentially available in the future can create significant commercial risk in upscaling, longevity, and attracting private investment in certain projects.
2) Lack of downstream CO_2 storage locations and current CO_2 transport infrastructure creates uncertainty in a fully integrated CCS chain and viability of long-term storage for some projects.
3) Shared pipeline/other transport infrastructure contributes to reduced costs in T&S activities, however can also contribute to counter-party risk.
4) Competition from other carbon emissions reduction projects or other CO_2 removal projects causes uncertainties in funding, storage locations, and feedstock availability.
5) While funding may be necessary from both public and private sources for early project financing, several projects have shown that relying on diverse funding sources can cause delays to initially targeted project timelines.
6) Technical uncertainties remain in some NETs schemes at larger, commercial scales (i.e., boiler conversion, precise energy consumption, adsorber performance, and cost of capture).
7) Additional environmental concerns remain over some projects (e.g. permits for land usage, upstream methane emissions, etc).

These similarities lead to a few high-level enabling actions which have proven consistent throughout the case studies at varying points in project timelines.

1) Implementing a commercial business model through the sale of CO_2 credits, licensing of the technology, or the creation and sale of co-products, is making scalability easier and reduces risk.
2) Availability and contribution of public funding has enabled many projects to reduce the private investment needed to begin projects, particularly allowing projects with a higher capex to begin activities.
3) Successful projects are often located near long-term storage locations, minimising cost of transport and storage.
4) Schemes which capture higher purity CO_2 streams are likely to be more economically viable, with lower associated costs (particularly opex).
5) Many BECCS projects require secure, local and sustainable feedstock supplies which meet the plant capacities, quality and biogenic content requirements.
6) Higher carbon prices, carbon taxes or tax credits in some countries have created markets where NETs are more commercially viable.

Depending on the NETs, Scotland has varying levels of immediate application and readiness. Building on the Scottish applicability from each case study, some initial indications emerge on areas with a larger potential for more immediate and larger-scale impact.

In terms of raw delivery of negative emissions, DACCS and BECCS EfW show the most immediate promise. The proposed DACCS project associated with Project Acorn is estimated to deliver 0.5 – 1MtCO_2/year in negative emissions.

For DACCS technology, the primary barrier to further unit deployments is investment costs (including clarity on UK ETS) and deliverability of the plant. A theoretical deployment of 6-12 further DAC units of a similar size to the Carbon Engineering unit could deliver on the 5.7 MtCO_2/year 2032 negative emissions envelope. However the high capex, lack of current direct government incentivisation, and unproven business models would make this development highly optimistic in a 2032 timeframe. Based on the current delivery rate and development timelines of the first Scottish DACCS plant, 2-3 further plants would be a more reasonable maximum.

For BECCS EfW, the potential for negative emissions will depend on the biogenic content in the processed waste.The largest operational facility at Dunbar has already announced plans for a CCS retrofit[45]. Incentivising further CCS implementation on the other EfW plants, as well as their supporting the economic and technical capability to do so, should be explored further to maximise this negative emissions potential.

Medium-sized opportunities for short term negative emissions exist in BECCS Power, Industry, and Biomethane. For BECCS Power, CCS retrofit onto Scotland's three largest biomass plants could deliver in the region of over 0.8 $MtCO_2$/year, assuming permanent storage and successful retrofits could be achieved. For BECCS Industry, two initial opportunities warrant further investigation. Retrofitting the three largest paper and wood mills with CCS could yield in the region of >0.5 $MtCO_2$/year and implementing CCS on the cement facility at Dunbar could yield up to 0.26 $MtCO_2$/year. BECCS Biomethane potentials will depend on the ambitions of Future Biogas and other similar developers, the scale-up of biomethane injection and retrofit of existing Scottish AD facilities, and plant locations in relation to the gas grid and CCS infrastructure – estimates for 2030 could be in the range 0.14-0.87 $MtCO_2$/year.

The opportunities with the lowest immediate potential, based on the available evidence in this horizon scan, initially appears to be BECCS Biofuels and BECCS Hydrogen. BECCS Biofuels is due to both the limited number of operating projects in Scotland, as well as the limited volume of CO_2 emissions from potential projects and uncertainty as to future transport fuels demand in Scotland. There is also a lack of current commercial hydrogen projects. However, this NET pathway could potentially unlock some of the 5.3 TWh of currently unutilised biomass resources in Scotland. If technology development on BECCS Hydrogen proceeds at pace and becomes a significant contributor to hydrogen production in Scotland, significant negative emissions could result from this route.

6 Recommendations

The global horizon scan of international NETs projects has given early indications of technologies to further explore, and technologies which require further primary research/demonstration before further high-level analysis is warranted. For example, demonstration and further development is required before estimates of cost or technical parameters of the relatively immature NETs, can be significantly improved.

The need for NETs in Scotland is relatively well established, and requiring whole economy analysis similar to the CCC's 6th carbon budget work to provide further depth. Scottish geological storage of CO_2 has been significantly appraised elsewhere, and since storage of NETs-derived CO_2 does not differ significantly from fossil CO_2, This is not a likely priority for further study. Legal requirements, including permitting, are better suited for study at later stages or by individual projects. Finally, identifying bioresource availability, mobilisation, and degree of utilisation is vital to unlocking many of the BECCS solutions explored in this review.

This review has given indications on topics to explore further. Guided by pertinent information and consistent themes from the case studies, there are several high-level topics which are suggested for exploration in further work listed below.

6.1 Topics Recommended for Further Work

1) **Explicitly quantify the short/medium-term NETs potential in Scotland** - Update previous work by Scottish Carbon Capture and Storage (SCCS)[36], which is Scotland's point of coordination for CCUS research and development. Given the critical nature of this sector, this should be reassessed and extended to ensure calculated potentials are based on robust and recent data (e.g. future waste availability/composition). A focus on the short-medium term would help to ensure targeted and actionable outputs for Scottish Government.

2) **Brief evaluation of Scottish NETs costs** - Update costs from international projects with consideration of the local context. For example, Scottish electricity and CO_2 T&S costs, and CO_2 transport options for larger NETs plants including indicative costs.

3) **Evaluation of plant specific techno-economics** - Estimate specific costs and technical NETs conversion feasibilities of potential large NETs opportunities. This may allow for prioritization of short-term efforts.

4) **Assess build-out rates and supply chain limitations** - Understand the realistic timeframes for deploying NETs in the short and medium terms.

5) **Create a priority list of high-potential options** – Pursue project options based on the economic, technical and practical limitations identified, moving beyond the initial general categorisation of opportunities provided here.

6) **Explore long-term NETs potential of Scotland, focusing on the 2045 target** - Bring in a long-term perspective, breaking out of short term build out rates and envisioning wider technological transitions, such as BECCS hydrogen or biofuels.

7) **Identify key policy enablers and actions for the Scottish Government** - Identify the levers available to the Scottish Government as a devolved administration, and emerging UK-wide Greenhouse Gas Removal (GGR) support mechanisms.

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8 Appendices

8.1 Appendix 1: Indicative initial potential of NETs in Scotland

This project focused on reviewing the international delivery of NETs, rather than the specific short term Scottish context for NETs. However, as part of the international context and case studies, the applicability of each case study or technology to the Scottish context was broadly assessed. Through this, indicative estimates of the short term potential of NETs in Scotland were drawn up, shown in the table below[77]. However these are **tentative assessments of the short term potential opportunity based on easily available public information**, and further exploration and validation of these is a high priority for Scottish government's upcoming NETs feasibility study.

Table 1: The RAG assessment of various NETs based on their short-term opportunity to deliver negative emissions for Scotland.

NET Category	Scottish Short-Term Opportunity Description	Short-Term Opportunity
DACCS	• Current potential would be the completion of the Acorn project as scheduled at the rate of CO_2 direct air capture proposed **(0.5 – 1 MtCO_2/year)** with Storegga/Carbon Engineering DACCS units. • Primary barrier to further unit deployments is investment costs (including clarity on UK ETS) and deliverability. • A theoretical deployment of 6-12 further DAC units of a similar size to the Carbon Engineering unit could deliver on the 5.7 MtCO2/year 2032 negative emissions envelope, however the high capex, lack of current direct government incentivisation, and unproven business models would make this development highly optimistic in a 2032 timeframe. Based on the current delivery rate and development timelines of the first Scottish DACCS plant, 2-3 further plants would be a more reasonable maximum.	High
BECCS EfW	• Six household waste incineration facilities in Scotland **(Dunbar, Baldovie, Millerhill, Glasgow, Shetland and Levenseat)**. ○ Combined **processing capacity** (not emissions) of 988 ktonnes of waste per year. ○ Further three plants with a total processing capacity of 500 ktonnes expected to complete within year. • Combined household waste incineration facilities processing capacity = c. 1488 kt waste/year. • Current NET potential would be for CCS to be implemented on all nine of the household waste incineration plants (up to ~1MtCO_2/yr). ○ **CCS retrofit plans already announced for Dunbar**	High

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[77] While this assessment of the short term potential is qualitative, low, medium and high approximately represent <0.1 MtCO_2/yr, <1 MtCO_2/yr, ~1 MtCO_2/y respectively.

BECCS Power	• Scotland has three medium-size biomass plants which are primarily energy-generating facilities which are **Markinch Biomass Plant**, **Steven's Croft Power Station**, and **Westfield Biomass Plant** ○ 2019 combined emissions: **944.11 ktCO_2** ○ **Average biogenic content of 93%** (based on 2016 data) • Current NET potential would envision CCS implemented on all three plants.	Medium
BECCS Industry	• There is only one cement plant in Scotland at Dunbar with **570 ktCO_2/year** emissions (mostly fossil based). • Scotland has three paper or board mills contributing to 86% of all CO_2 emissions from the sector. These are **Morayhill Mill, Cowie Board Mill, and Caledonian Paper Mill.** ○ 2019 combined emissions: **676 ktCO_2** ○ **Average biogenic content of 85%** (based on 2016 data) • Current NET potential would envision CCS being implemented on these biogenic CO_2 emissions in addition to Dunbar implementing CCS.	Medium
BECCS Biomethane	• Future Biogas is planning to develop **25 new BECCS plants** between 2021-2028 in the UK. • The project aims to initially store **200 ktCO_2/year**. • Scotland has **84 operational and planned AD plants**, with the Central Belt and East Scotland sites having close proximity to proposed T&S infrastructure. • Current NET potential would be for all of the current operational plants in Scotland to store the same amount of CO_2 per plant per year as the Future Biogas plants.	Medium
BECCS Biofuels	• **Currently no bioethanol or other biofuel plants that produce concentrated CO_2 streams in Scotland.** • Construction of a biochemicals demonstration plant is currently underway in Grangemouth by Celtic Renewables that will produce biobutanol, bioethanol and bioacetone from whisky distillery wastes, along with **c. 0.660 ktCO_2/yr** (no plans to capture this at present). • Electric vehicles likely to lead to rapid contraction in petrol and bioethanol use. • Other bioethanol uses for chemicals manufacture or ethanol-to-jet conversion are being developed.	Low

BECCS Hydrogen	• As of 2018, **6.7 TWh biomass/year** are used for bioenergy purposes in Scotland, and there is an additional estimated **5.3 TWh/year** of currently **unutilised lower quality biomass resources**. ○ BECCS Hydrogen could potentially use a **broader range of lower quality biomass** materials (if primary process is gasification). • Current NET potential is **zero** as there are **no current plans for this in Scotland**, and the technology is at relatively low maturity. • Core use for industrial fuel switching in Grangemouth, Aberdeenshire and Aberdeen, Fife/East Coast, and Upper Forth, as well as transport/heating conversion in Aberdeenshire may require **9.2 TWh/year hydrogen** in 2050. ○ A total conversion of the wider Scottish transport and heating sectors would increase this demand to **60.6 TWh/year.** • If technology development on BECCS Hydrogen **proceeds at pace** and becomes a significant contributor to hydrogen production in Scotland, **significant future negative emissions could result from this route.**	Low

8.2 Appendix 2: NETs Introduction and Context

8.2.1 Selected global R&D and demonstration programmes for NETs

Below are some of the more notable global research and development policies which directly or indirectly support engineered NETs:

- **US Energy Act 2020**: A total of $447 million was authorised to be used in the next 4 years, FY21-24, for RD&D of NETs, including DAC, BECCS and agricultural options.
- **US FY22 Appropriations**: Discussions around an additional funding of at least $175 million for R&D on DAC, CO_2 mineralization, storage, and monitoring.
- **UK's** £8.6 million GHG Research and Development Programme (2017-2021), co-funded by NERC, BEIS, EPSRC and ESRC.
- **China- Zhejiang University**'s DAC R&D programme involves utilisation of captured gas as a fertiliser for crop growth in a greenhouse.
- **EU RD&D Programmes**: Horizon Europe is the EU's main R&I programme for funding NETs research, among many other technologies. Further funding is available for supporting innovative low-carbon companies through the European Institute of Innovation and Technology (EIT) and the European Innovation Council (EIC), although historically funding directed at NETs has been very low.

Several other global schemes aim to support engineered NETs through providing financial support for early demonstration projects:

- **The US Energy Act of 2020**
    - Grants for FEED studies and large-scale pilot demonstrations through the $447 million fund.
    - DAC prizes for pre-commercial ($15 million) and commercial ($100 million) technologies.

- **The UK's GHG Removal Innovation Competition** which provides £100 million to fund development of multiple NETs feasibility studies and a few demonstration plants.
- **The Canadian government's direct investment** of CAD$25 million into Carbon Engineering to demonstrate their emerging technologies.
- **Australian CCUS Development Fund** which will provide AUS $50 million to CCS and CCU pilot and demonstration projects in the next 3 years.
- **Germany's CO_2 avoidance and use funding directive** will mobilise €585 million until 2025 for CO_2 T&S infrastructure around North Sea, CCS, CCU, DACCS and BECCS projects.
- **Germany's support for a pilot synthetic liquid fuels plant**, commissioned by Federal Ministry of Transport, will supply at least 10,000 tonnes of fuel per year and may use CO_2 from air.
- **Several other EU funds**, such as the Innovation Fund and Connecting Europe Facility, offer financial support for deploying CCS projects and infrastructure.

8.3 Appendix 3: Scottish Background

8.3.1 Future Hydrogen Projects in Scotland

Some notable examples of future hydrogen supply and demand projects in Scotland are:

- **Acorn Hydrogen** which aims to convert natural gas from the North Sea to blue hydrogen at the St Fergus terminal and store CO_2 through the wider Acorn system. The first phase of the project may come online in 2025 and would blend hydrogen into the National Transmission System. A dedicated pipeline may carry hydrogen to the rest of Scotland in the future.
- **Dolphyn Project**, which is combining offshore wind energy with bulk hydrogen production off the coast of Aberdeen
- **BIG HIT** project which is exploring creation of a hydrogen territory in the Orkney Islands
- **H100 Fife**, which is developing a full-chain process to convert renewables to hydrogen for heating in Levenmouth
- **Aberdeen Vision Project** which aims to establish a world leading green hydrogen hub, initially for the transport sector, eventually converting other industries to green hydrogen.
- **Ineos Group Ltd** have recently pledged an additional £1 billion further investment in its petrochemicals plant in Grangemouth in order to reduce emissions by 60% by 2030 via hydrogen production and use with carbon capture and storage.

8.3.2 Future CCS and Hydrogen Demand Projections in Scotland

Various CCS deployment scenarios have previously been investigated for Scotland in a 2050 timeframe[14]. The scenarios, as shown in Figure , represent different ambition levels and deployment rates.

Annual CO_2 storage in 2050 is predicted be in the range of 10-22 $MtCO_2$/year, where cumulative storage would reach 190-370 $MtCO_2$ in the next 29 years. Imports are expected to be the dominant source of CO_2, considering Scotland's current emissions and the large offshore storage potential. Sources are relatively evenly split between capture from power plants, industrial sites and DACCS. Capture from hydrogen production facilities are dependent upon future decarbonisation strategies. Most of the CO_2 is expected to be delivered from Peterhead port through shipping, however, in the Ambition Scenario also includes sizable CO_2 delivery from central Scotland via the Feeder 10 or other regional ports.

BECCS and DACCS capacities in this study (maximum of 5 $MtCO_2$/year by 2050) fall short of the 2032 desired envelope set in Scotland's updated climate change plan, indicating a need to prioritise NETs over some other sources (e.g., imports). However, it must be noted that the BECCS capacity modelled was related to capture of biogenic CO_2 from the distilling and waste sectors, and did not consider bio-hydrogen.

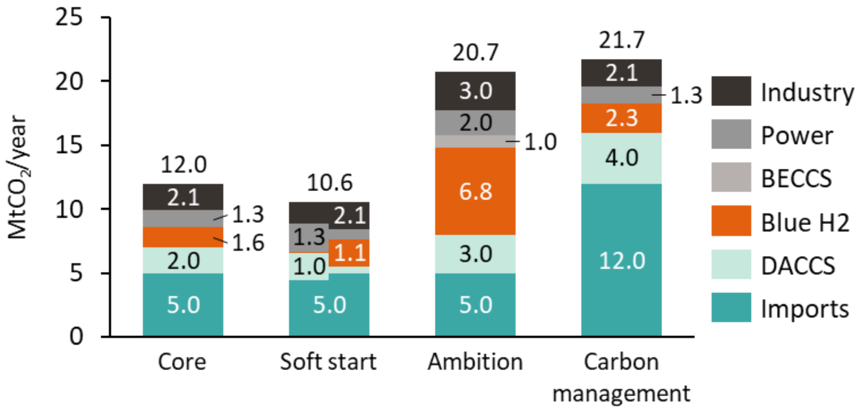

Figure 17: Projected breakdown of CO_2 sources that could be stored by the Acorn project in 2050 in Scotland, for various scenarios[14].

It is also estimated that core level hydrogen use for industrial fuel switching in Grangemouth, Aberdeenshire and Aberdeen, Fife/East Coast, and Upper Forth, as well as transport/heating conversion in Aberdeenshire may require 9.2 TWh hydrogen in 2050, as shown in Figure. A total conversion of the wider Scottish transport and heating sectors would increase this demand to 60.6 TWh. Lastly, a further 27 TWh/year hydrogen export potential is identified for 2050.

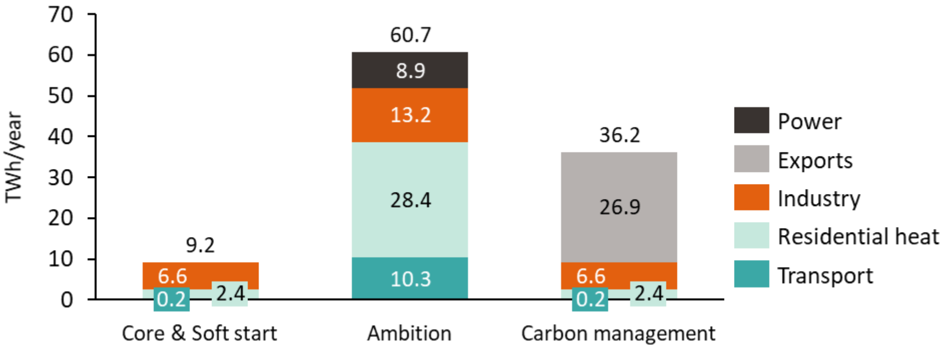

Figure 18: Breakdown of projected hydrogen use under different scenarios in 2050 in Scotland[14].

As per DUKES, BEIS/Ricardo and CCC model conventions, the supply chart (Figure 5) is a mix of solid biomass, biogas and crop-based biofuel resources (not necessarily “primary energy”), whereas the demand chart is only given in “final energy” so gives biofuel values (used in transport and building heating) after any conversion losses from solid biomass. In practice, the difference in energy accounting between the two charts is relatively small, as only a modest proportion of the biomass is converted into biofuels, and most of the resources given in the supply chart are used “as is” in the final end-use sector.

8.4 Appendix 4: Additional technical information and timelines for case studies

The below sections present illustrated timelines of NETs projects and provide further technical descriptions of the eight case studies covered in this study.

8.4.1 DACCS – Climeworks

Climeworks was found in 2009 and won multiple start-up awards in its early years. It established a partnership with Audi in 2013 and raised significant investment by 2017 which allowed to commission world's first commercial DAC plant in Switzerland to use waste heat for supply CO_2 to a greenhouse[78]. Since 2020, Climeworks received investment and carbon removal orders from well-known brands such as Microsoft, which allowed for construction of the Orca plant. Climeworks is now planning to announce its plans for a new plant 10 times the size of Orca.

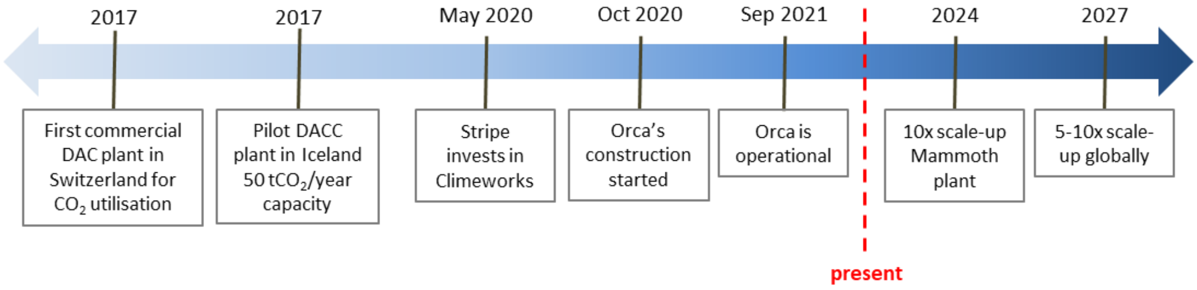

Figure 19: Climeworks development timeline.

Climeworks uses modular air contactor units which capture CO_2 through adsorption on solid filter materials. Electricity is used to move the air via fans. The unit is then sealed and heated to around 100°C to release the CO_2 and prepare adsorbents for a new cycle. Concentrated CO_2 is then collected, treated, and sent to downstream processes.

Carbfix receives the CO_2 and stores it in underground basalt formations. CO_2 is first dissolved in water and is injected in rock formations. It is trapped beneath regular water due to its higher density and is solidified within 2 years.

A third party LCA study[79], using Climeworks data from the pilot plant, found that construction, operation and decommissioning of the plant is likely to emit 10% of the captured emissions, with potential for future reductions.

Some of the adsorbents considered for DAC include amines and potassium carbonates on supporting materials or anionic resins[79]. However, the exact sorbent used by Climeworks is kept as a trade secret.

Compared to the pilot project, Orca reduced the amount of steel used in contactors by a half[23]. It is expected to increase DAC TRLs from 4-6 to 5-7.

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[78] Presentation by Jan Wurzbacher at TU Dresden, 2017.

[79] Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Deutz, S., Bardow, A. Nat Energy 6, 203–213, 2021.

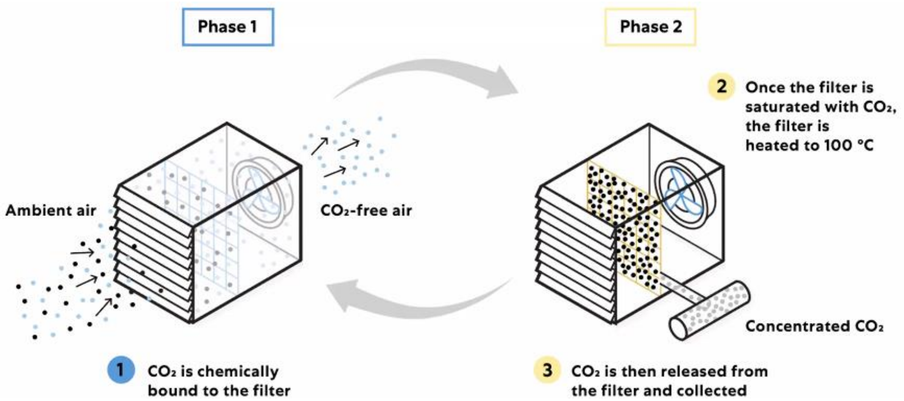

Figure 20: Schematic representation of Climeworks' DAC technology[23].

8.4.2 BECCS Power – Mikawa power plant

The Mikawa BECCS project represents the incorporation of the Toshiba broader decarbonisation focus into the Japanese MOE "Demonstration of Suitable CCS" project. Toshiba, having already completed a pilot CCS plant on the coal fired Mikawa facility and EfW Saga City facility, retrofitted the Mikawa plant to rely on a majority biomass feedstock and tested new amine solvents, both feeding in to the MOE project to evaluate Japanese CCS value chains.

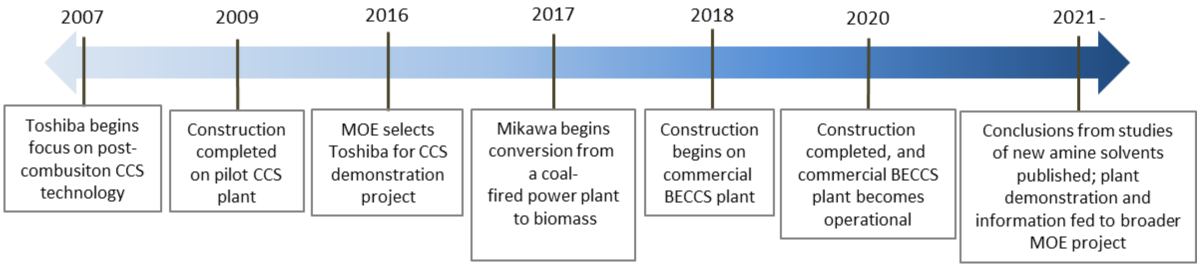

Figure 21: Mikawa Power Plant timeline.

Initial power plant (coal fired) utilised flue-gas slipstream with a 10t CO_2/day pilot post-combustion amine absorption CCS scheme integrated to test system configurations and novel amine solvents[29,30].

After a verified system stability of over 2800 hours, the pilot plant had a CO_2 Recovery Energy of >2.4 GJ/ tCO_2 at a 90% CO_2 capture rate for a CO_2 concentration of ~12%). As of March 2021, the pilot plant accumulated up to 13,000 hours of operation on live flue gas of biomass / coal fired thermal power plant[33].

The power plant achieved a 100% biomass PKS feedstock capability in 2020 with the completion of the BECCS plant with CFB biomass boilers.

The CO_2 capture is performed via post-combustion amine absorption with a novel Toshiba-developed amine solvent (TS-1) rather than the previously amine solvent 30 wt% monoethanolamine (MEA) aqueous solutions[32].

The facility uses a unique fuel gas desulfurization technology (CT-121) as a pre-treatment device for CO_2 separation and recovery[80].

The CCS design is fully integrated with the power plant, with turbine extraction steam feeding the energy for regeneration of CO_2 at the stripper tower[33].

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[80] Bioenergy International Toshiba Announcement

Toshiba has developed two further innovative amine solvents at the Mikawa pilot plant which have demonstrated significant potentials to reduce amine emissions and amine degradation while maintaining low CO_2 removal energy[32].

8.4.3 BECCS EfW – Fortum Oslo Varme

Since 2015, FOV BECCS completed several feasibility, FEED and demonstration studies to deliver an investment ready project[81]. In 2020, the Norwegian Government agreed to provide 3 billion NOK (c. $344 million) of funding to the project, with a condition of finding co-funding of ~3.8 billion NOK. The EU Innovation Fund is the most likely source for this funding and FOV is currently one of 70 shortlisted projects. The results of the funding application are expected to be announced later in 2021, and project execution may consequently start in 2022.

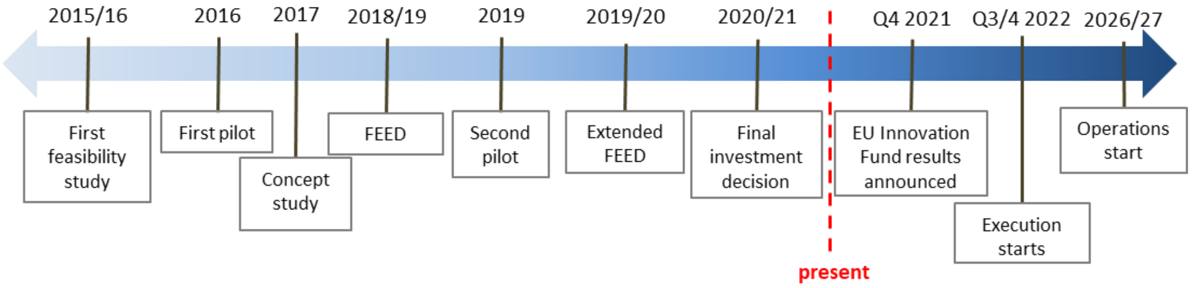

Figure 22: Timeline of Fortu Oslo Varme EfW plant.

FOV plant started its operations in 1985 with two lines, which since gone through several life extension processes. A third line opened in 2011. All lines have individual grate fired boilers and feed into two steam turbines[38].

Waste incinerated at FOV is made up of 1/3 household waste, 1/3 commercial and industrial, and 1/3 RDF imported from the UK[81].

The CCS project will have an expected lifetime of 25 years, and will capture 90% of emissions, with a capability to capture more. The capture plant will have 95% of availability and will be designed to run independently of the EfW plant, so that regular operations would not be disturbed by the introduction of CCS[38].

After considering different capture technologies, post-combustion capture using Shell's amine based proprietary DC-103 solvent was chosen for the project[82]. This is a well-known technology already implemented in the Boundary Dam coal fired power plant since 2014.

A pilot plant in a 1:350 scale was built and operated for more than 5000 hours in 2019 to measure the performance and emissions using the DC-103 solvent with EfW flue gas for the first time[82]. The demo plant proved achievement of 95% capture rates, where amine emissions were within regulatory ranges. Amine degradation was initially slow, reaching 3 wt% in 4000 hours, increasing to 6 wt% by the end of the trial[83].

Individual components of the BECCS project are relatively mature, but together with Norcem, FOV is expected to move EfW CO_2 capture from TRL 9 to TRL 10, and CO_2 shipping and storage in saline aquifers from TRL 10 to 11. Another innovation of the project is transport of liquid CO_2 via zero emission trucks[41].

The project will store 200 $ktCO_2$/year of biogenic emissions. If the capture rate is only 90%, net negative emissions would be 178 $ktCO_2$/year considering uncaptured fossil

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[81] Deployment of bio-CCS: case study on Waste-to-Energy. IEA Bioenergy, 2021.

[82] Performance of an amine-based CO2 capture pilot plant at the Fortum Oslo Varme Waste to Energy plant in Oslo, Norway. Fagerlund, J. et al. International Journal of Greenhouse Gas Control 106, 2021.

[83] Pilot Plant Test Report Extended Phase. Carbon Capture OSL, 2020.

emissions. A modest amount of further emissions are likely to be caused by implementation of BECCS on the site.

8.4.4 BECCS Industry – Norcem cement plant

The very first desktop-based study involving a CCS plant at Norcem was in 2005. Further funding from the European Cement Research Academy and the Norwegian Government allowed for additional concept and pilot plant studies[50]. An initial FEED study was completed in 2018/19, resulting in the Norwegian Government's decision to fund >80% Norcem CCS's costs along with the Northern Lights project. Detailed planning and construction is expected to start soon to start operations in 2024.

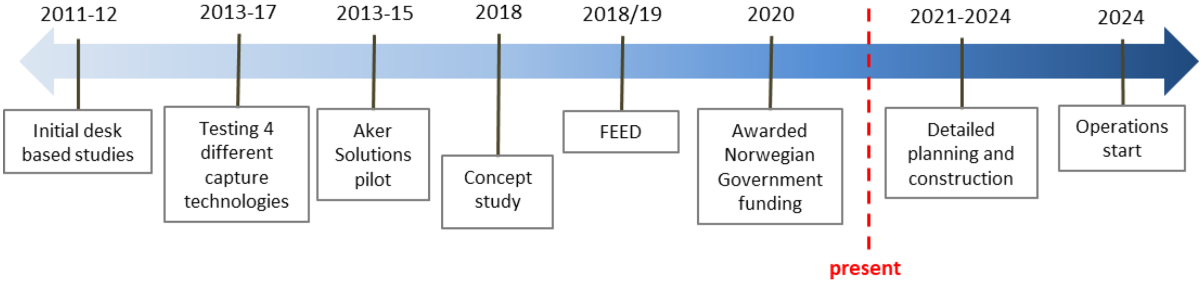

Figure 23: Timeline of Norcem cement plant.

Approximately two thirds of emissions from the Norcem plant are related to the decomposition of limestone ($CaCO_3$) to CaO. The rest of the emissions are due to fuel use to heat up various processes. As shown on the figure to the right[50], some biogenic waste is used as fuel, resulting in 72 $ktCO_2$/year of emissions, which are not counted by accounting frameworks.

The CCS project at Norcem will use Aker Solutions's proprietary carbon capture technology, which is post-combustion capture via amine solvents. The technology was trialled for more than 7,400 operating hours specifically using real flue gas from the plant[50].

The concentration of CO_2 in the kiln gas is estimated to be 22%, which is relatively high, reducing project costs. The plant is expected to capture 50% of the emissions or 400 $ktCO_2$/year. This is chosen as a result of cost benefit analysis, considering that all the heat energy for the capture process will be provided by the excess waste heat of the plant. Only a small amount of electricity will be used for carbon capture when waste heat availability is low[50].

Norcem plant is expected to operate 7400 hours a year, and the capture plant is designed to be fully operational (capturing 55 tCO_2/hr) for 7300 hours[50].

Individual components of the BECCS project are relatively mature, but Norcem is expected[41] to move industrial CO_2 capture from TRL 9 to TRL 10, and CO_2 shipping and storage in saline aquifers from TRL 10 to 11.

In 2020, alternative fuels (mostly prepared waste and waste biomass) made up 26% of Heidelberg Cement's overall fuel composition[84]. Biomass accounted for 39% of alternative fuels and Heidelberg has a target to increase the portion of alternative fuels to 43% by 2030. Electrification of the heating process, conversion to hydrogen and alternative feedstocks to limestone are identified as potential next steps to achieve zero emissions cement[85].

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[84] Heidelberg Sustainability Report 2020 - Link
[85] Leading the way to carbon neutrality. Brochure by Heidelberg - Link

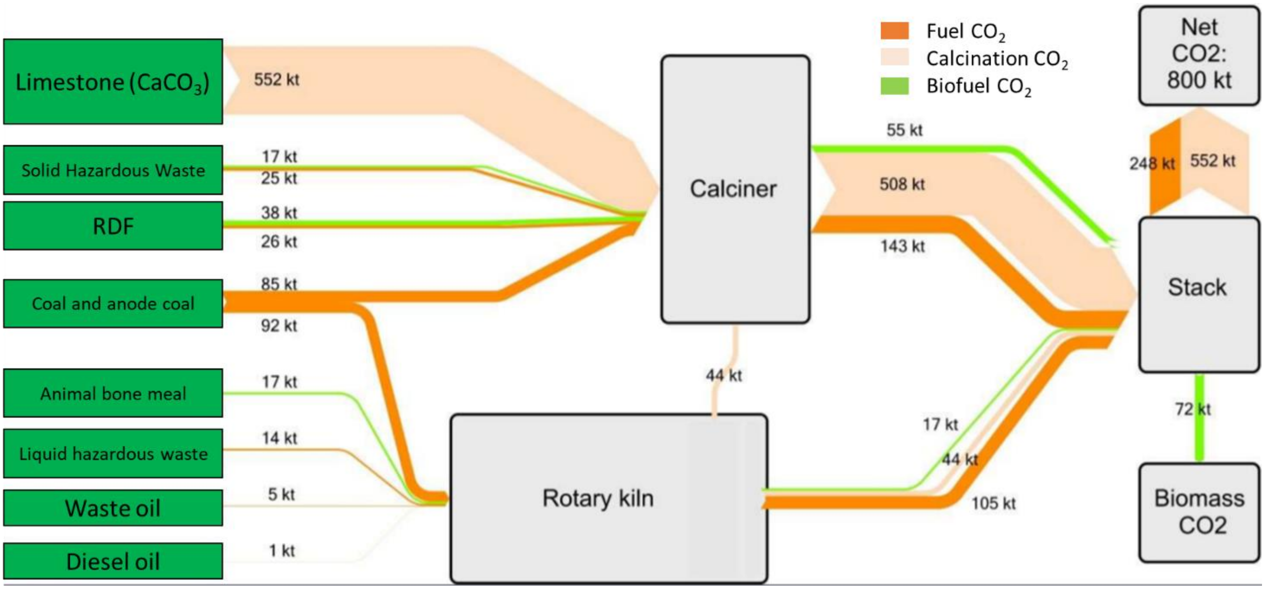

Figure 24: CO_2 balance of the Norcem Brevik plant[50] in 2017.

8.4.5 BECCS Industry – Resolute Saint-Felicien pulp mill

The timeline below shows the relatively rapid project progression (~7 years) of the Saint-Felician CCU scheme from the creation of the enzymatic CO_2 capturing process to the deployment of the CO_2 capture unit in the commercial partnership with Toundra. The success of this project (among other emission reduction ventures) has fed into the announcement of further emission reduction targets[56] from Resolute by 2025.

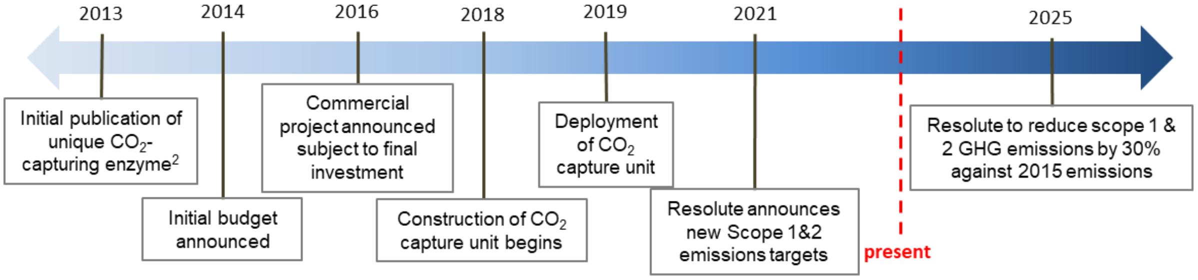

Figure 25: Timeline of Resolute Saint-Felicien pulp mill.

The mill produces is 369,000 metric tons of Northern bleached softwood kraft pulp (NBSK) and has an installed cogeneration capacity of 43MW[54].

Unique capture process which utilizes a carbonic anhydrase (CA) enzyme (named 1T1). This has catalytic properties that accelerates CO_2 capture. It does this using salt solutions rather than the solvents used by other capture technologies. The CA enzyme is the most powerful enzyme for the hydration of CO_2 (converting CO_2 to bicarbonate and H+)[86].

Unlike CO_2 capture processes that use amine chemicals, CO_2 Solutions' enzymatic technology produces no hazardous emissions or wastes. The enzyme is used in a disruptive industrial process described by CO_2 Solutions as the 'Industrial Lung'[87].

The process captures ~30 metric tonnes of CO_2 per day which is transported to Serres Toundra (Resolute owns 49% of the JV), reducing the natural gas consumption of the Serres Toundra by 25% and reduces the carbon footprint of the plant by 10,000 metric tonnes[55].

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[86] Green Car Congress, 2014

[87] CO_2 Solutions 'Industrial Lung' webpage

The quantity of thermal energy required by the reboiler is 2.4 GJ/tCO_2 which is entirely provided by the pulp mill through residual, low-grade energy (i.e., hot water) that has nil-value and no parasitic impact on the mill's energy balance[88].

Following a six-month demonstration period, Serres Toundra agreed to purchase the captured CO_2 for a period of ten years. CO_2 Solutions expects to realise revenues of approximately $400,000 annually from the sale of captured CO_2 and associated carbon credits.

8.4.6 BECCS Hydrogen – KEW Technology

The timeline below shows the progression of KEW Technology and their development of modular gasification units for hydrogen production and CCUS.

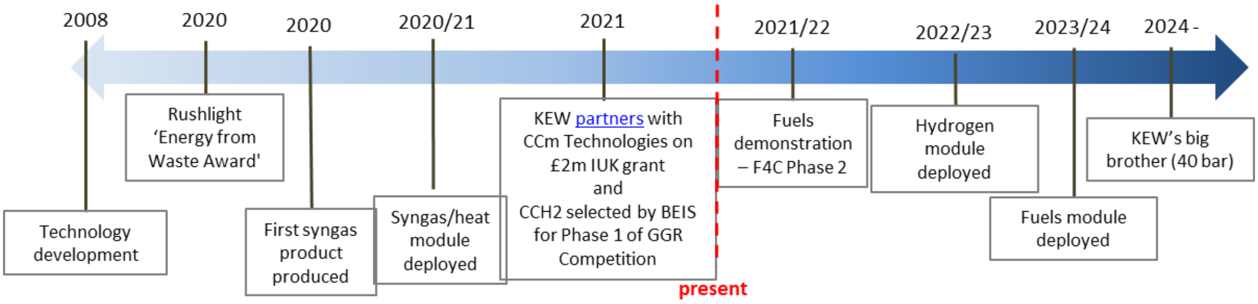

Figure 26: Timeline of KEW Technology development.

KEW Technology has developed a clean, compact, modular process for conversion of biomass to hydrogen-rich gas, with the potential to upgrade the gas into high-purity hydrogen and CO_2 streams. The system's proprietary reformer, the Equilibrium Approach Reactor (EAR) has shown that a wide range of biomass feedstocks can be used, including residual waste from municipal, commercial & industrial sources, and dry agricultural wastes. Importantly, some of these feedstocks would be unsuitable for other EfW schemes[69].

The KEW technology utilises a high efficiency Advanced Thermal Conversion (ATC) technology to maximise the use of end-of-life waste derived fuels, producing a consistent, high-quality hydrogen-rich syngas suitable for fired heating, power generation and fuels production1.

The plant uniquely operates at elevated pressure (7barg) and is more compact than other atmospheric systems.The process works by shredding and densifying the feedstock (either biomass or refuse derived fuels [RDF] blended with biomass). The fuel is then pressurized in a 7 MWt bubbling fluidised bed (BFB) gasifier which thermally converts the feedstock into raw syngas. After filtration to remove any residual solids, the syngas enters the Equilibrium Approach Reformer (EAR – the USP of the technology) to break down the heavy hydrocarbons and methane to H_2, CO, and CO_2. The recovered gas is then cooled (with the heat being used to generate electricity) and scrubbed of R-sulfide components[69].

The syngas then enters the first stage of the Hydrogen Production Module (HPM) where it is first pressurized and further desulphirised. It then enters a 2-stage water gas shift (WGS) where all of the remaining CO is converted into CO_2 and H_2 via steam, leading to a hydrogen syngas purity of 51%. A pre-combustion quench stage is used to remove any remaining water, and a monoethanolamine (MEA) solvent then strips the CO_2 from the syngas with a 98% CO_2 capture rate, which consequently leads to a 98% remaining hydrogen gas purity. The only other 2% gaseous components are residual CO_2 and inert N_2. Developments are being planned to implement pressure-swing absorber (PSA) unit

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[88] CO_2 Solutions Projects page

into the process which would create hydrogen purities of 99.999% should downstream applications of pure hydrogen be identified and commercialised[69].

Since the technology development in 2008, KEW has entered in the commercialisation phase, and are involved in a variety of different commercial opportunities which reflect the diverse nature of the downstream options for the technology. Some of these projects include: a partnership with CCm Technologies on modular units to be demonstrated at COP26, biomass to hydrogen conversion on contaminated land in the Midlands, Future Fuels for Flight and Freight Competition (F4C), and their larger 'Big Brother' plant with a higher pressure and larger throughput[69].

Phase I funding has been granted from BEIS for the CCH_2 project, which will develop designs for additional modules which will upgrade this gas to produce separate high-purity hydrogen and CO_2 streams. The hydrogen can be sold for industrial / transport applications and the CO_2 sent for sequestration (20,000 tonnes per year per module)[68].

KEW has plans to upscale the technology to 'Big Brother Units' operating at higher pressure with 10 times the throughput (c. 1,300 Kg per hour) for applications such as ammonia production where the existing facilities are of that scale[69].

8.4.7 BECCS Biofuels – ADM corn bioethanol plant in Decatur, Illinois

A timeline of the ADM BECCS projects is given below. Currently ADM do not have plans to extend the IL-ICCS project beyond 2022. No reasons have been publicly given, but injection permitting constraints and energy use/profitability without continuation of public funding are likely factors. Success of these projects has led to the CarbonSAFE feasibility study of CCS in the wider geological region as part of a wider CCS effort across the USA.

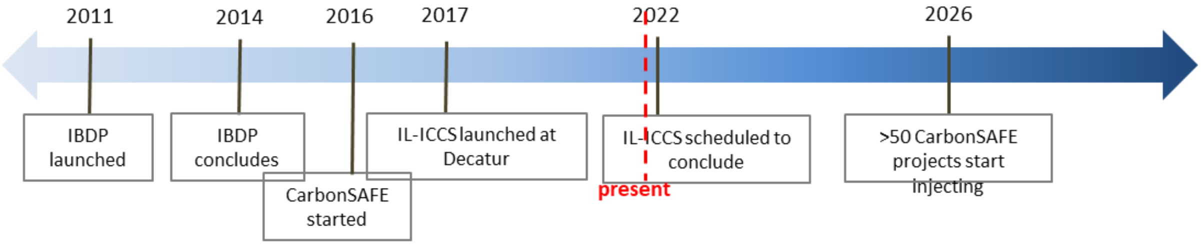

Figure 27: The ADM corn bioethonal plan timeline.

The diagram below illustrates technical process used to capture and store the biogenic CO_2:

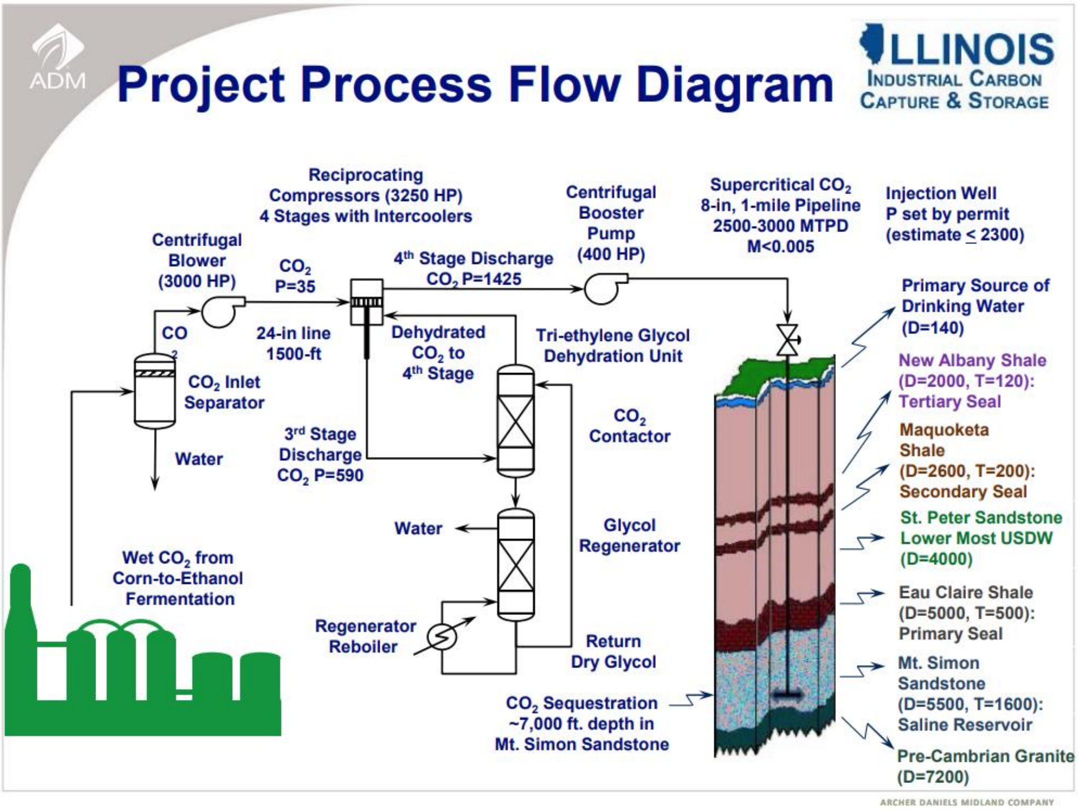

Figure 28: Process flow diagram of ADM BECCS project[89].

CO_2 and water are the main components of the wet gas process stream arising from the corn to ethanol fermentation tanks. A gas-liquid separation step knocks out most of the entrained water. The CO_2 is then further dehydrated and compressed to a super-critical phase, achieving >99% purity (no further gas separation technology is required). The CO_2 is then piped for 1 mile and injected 7,000 ft underground and stored in a saline reservoir within the Mt. Simon sandstone formation, with the CO_2 held in pores within the sandstone.

The individual steps involved in this process; corn ethanol production, gas dewatering, compression and CO_2 injection all operate commercially today, although CCS in saline aquifers is less developed (at around TRL 7-8) than CCS in depleted fields or for enhanced oil recovery. The appraisal, injection, and storage conditions for CO_2 storage in saline formations are somewhat different to the more widely adopted CO_2 injection into depleted fields or for enhanced oil recovery, although there are strong similarities in the technologies used.

8.4.8 BECCS Biomethane – Future Biogas expansion plans in the UK

Future Biogas was founded in 2010 and is currently operating 10 biomethane sites (mostly across Lincolnshire, South Yorkshire, and Norfolk). Investors include Aberdeen City Council, JLEN, Aviva and Bio Capita. The timeline of Future Biogas' BECCS expansion plan is given below. Their first new plant has recently received planning permission in Lincolnshire, UK.

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[89] ADM Project Presentation Link

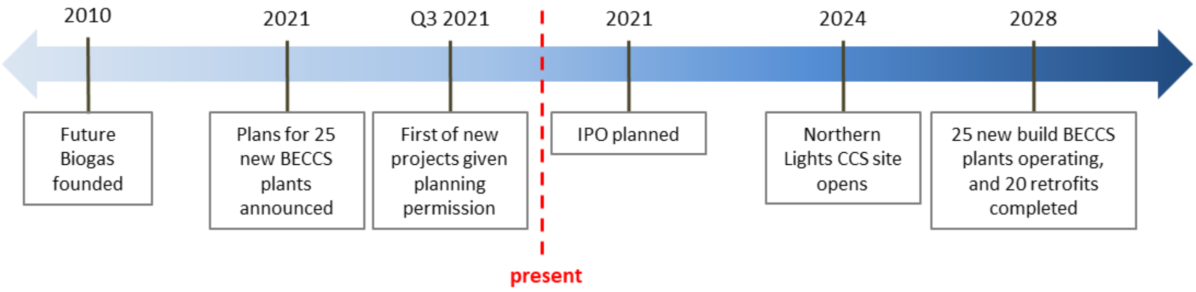

Figure 29: Timeline of Future Biogas expansion plans.

In terms of the technical process involved:

Maize, rye or grass feedstocks will be grown by local farmers and trucked to a local Future Biogas facility. Each new facility is planning to use ~60ktonnes/year of biomass feedstocks[72].

The biomass undergoes anaerobic digestion (AD). AD is an unpressurised, low temperature decomposition process in the absence of air that produces biomethane (50-60% methane and 40-50% CO_2 by volume), plus some impurities[90].

Typically sulphur and water removal occur before the CO_2 is separated out (various separation technologies exist, including membranes, PSA, amine, or water scrubbing – see the main options below), leaving high purity biomethane which can be injected into the gas grid.

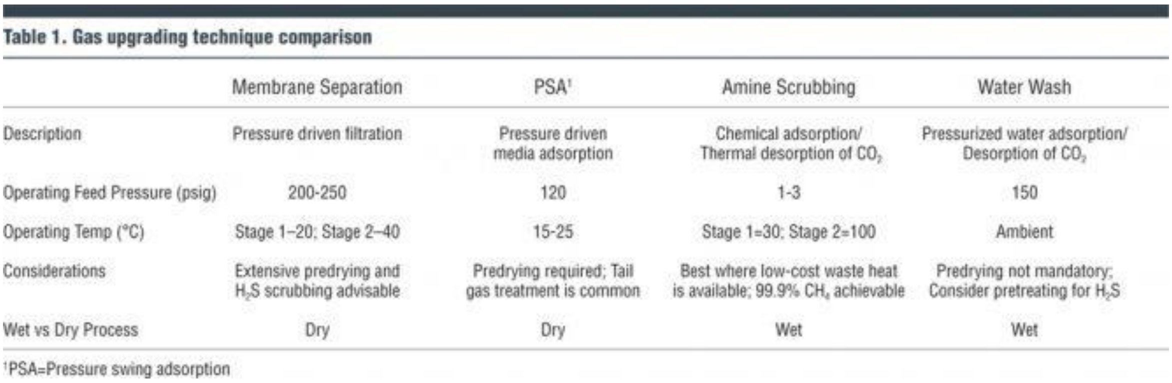

Table 1. Gas upgrading technique comparison

	Membrane Separation	PSA[1]	Amine Scrubbing	Water Wash
Description	Pressure driven filtration	Pressure driven media adsorption	Chemical adsorption/ Thermal desorption of CO_2	Pressurized water adsorption/ Desorption of CO_2
Operating Feed Pressure (psig)	200-250	120	1-3	150
Operating Temp (°C)	Stage 1–20; Stage 2–40	15-25	Stage 1=30; Stage 2=100	Ambient
Considerations	Extensive predrying and H_2S scrubbing advisable	Predrying required; Tail gas treatment is common	Best where low-cost waste heat is available; 99.9% CH_4 achievable	Predrying not mandatory; Consider pretreating for H_2S
Wet vs Dry Process	Dry	Dry	Wet	Wet

[1]PSA=Pressure swing adsorption

Figure 30: Options for biomethane upgrading from biogas[91].

The isolated CO_2 typically has high purity. Future Biogas plan to capture and liquify 15-18 $ktCO_2$/year at each site. The liquid CO_2 is planned to be transported by trucks to the Humber estuary in the UK, where a CO_2 storage facility is being built. From here it is planned to be shipped to an onshore terminal in Norway, before being piped to the Northern Lights CCS facility and stored 2.6 km below the seabed.

AD and biomethane/CO_2 separation are both commercially mature technologies (TRL 9 and TRL 8-9, respectively). CO_2 shipping/piping is also carried out commercially today, although CO_2 trucking is less developed. The Northern Lights CCS facility is yet to be built, but the CCS technology is at TRL 8.

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[90] Biogas Info website - Link

[91] Biocycle (2018) Basics of biogas upgrading https://www.biocycle.net/basics-biogas-upgrading/

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