EUROPEAN CO_2 AVAILABILITY FROM POINT-SOURCES AND DIRECT AIR CAPTURE

Report for: Transport & Environment

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EXECUTIVE SUMMARY

The European Commission's proposed ReFuelEU mandate places an obligation on fuel suppliers to blend an increasing level of synthetic kerosene (also referred to as e-kerosene) into their fuel mix. The manufacture of e-kerosene requires carbon dioxide (CO_2) and hydrogen (H_2) as feedstocks. Transport & Environment have raised a concern with the proposed ReFuelEU mandate, in that there is no regulation on the sustainability of the CO_2. The utilisation of fossil fuel derived CO_2 is unsustainable, as upon combustion of the kerosene, the CO_2 will be re-emitted to the atmosphere.

The European Union (EU) has set out a legally binding commitment to reach net-zero greenhouse gas emissions by 2050, with an intermediate target of reducing net emissions by 55% compared to a 1990 baseline by 2030. The European CO_2 market, both in terms of its supply and demand, will need to undergo dramatic changes if the decarbonisation objectives are to be achieved. The vast majority of CO_2 supplied as a commodity in this market is served by a single source: the steam reformation of natural gas for the purpose of hydrogen production (also referred to as steam methane reformation, SMR).

This fossil-derived carbon dioxide is unsustainable; therefore, alternative sustainable sources such as biogenic and Direct Air Capture (DAC) CO_2 must take its place. This study has investigated the resource availability of CO_2 in EU-27 members countries plus UK (formerly EU-28) from both unsustainable and sustainable origins. The expected growth of the CO_2 market has been estimated given the expected demand for e-kerosene, as well as other potential future demands, such as other e-fuels, chemicals and plastics, construction materials and horticulture. The growing CO_2 demand outpaces the supply from existing sources and the growing biogenic supply. It has been assumed that DAC CO_2 will fulfil this deficit; the feasibility of scaling-up DAC to meet this required demand has been assessed. Finally, consideration has been paid to what would be the optimal utilisation of CO_2 by origin for the manufacture of e-kerosene.

The primary source of existing CO_2 supply as a commodity is steam methane reforming (SMR) which is unsustainable. To achieve decarbonisation objectives, SMR will have to be displaced by low-carbon hydrogen, thereby reducing CO_2 supply from this source over time

The existing supply of CO_2 is dominated by steam methane reforming (SMR) where CO_2 is a by-product of hydrogen production. It is assumed that low-carbon hydrogen will start to replace SMR, thereby reducing the CO_2 supply from this source. Low carbon hydrogen could be 'green' (electrolysis of water powered by renewable energy) or 'blue' (SMR with carbon capture and storage). Whilst the latter still generates CO_2, for the hydrogen to be considered blue, the CO_2 must be stored permanently, as opposed to being made available for utilisation. New CO_2 supply streams may open up with the advent of carbon capture technologies. The biogenic CO_2 potential in Europe has been estimated and it was found that by 2050 circa 330MtCO_2/yr may be captured. It was assumed that approximately half this CO_2 may be sent to storage to achieve negative emissions, with the other half available for utilisation.

The deployment of carbon capture across Europe is highly uncertain and will depend heavily on future policy and regulation

A literature review of carbon capture deployment on fossil and industrial process CO_2 found that projections are highly uncertain. Though a common theme prevailed in that decarbonisation scenarios assume that captured fossil and industrial process CO_2 will be sent to storage to mitigate emissions, as opposed to utilisation. This makes sense as carbon capture installed on fossil or industrial process CO_2 streams will be deployed to mitigate emissions (likely to meet regulation). This same assumption was used in this work such that no fossil or industrial process CO_2 is made available to the utilisation market.

It was assumed that any future deployment of carbon capture technologies on fossil or industrial process CO_2 will send the CO_2 to storage, as opposed to utilisation in order to mitigate emissions

The CO_2 market is expected to grow; crude oil is the key carbon feedstock for many of the world's products including fuels, plastics and chemicals. Instead, to produce these products sustainably, air-captured carbon dioxide (either biogenic or DAC) can be used, without increasing atmospheric CO_2 concentrations, provided the biomass source is sustainable and DAC is powered by renewables. A literature review of projections of these potential future demands has found that their growth is highly uncertain, though it could be very substantial, potentially outsizing the current CO_2 market demands.

There is high uncertainty in the scale-up of future potential CO_2 demands such as that for fuels, chemicals and plastics, construction materials and horticulture, though the scale-up could be substantial

The CO_2 demand for the manufacture of synthetic kerosene has been estimated. The favoured method of manufacturing e-kerosene is via the Reverse Water Gas Shift Reaction (RWGS) to generate syngas from CO_2 and H_2, then the Fischer-Tropsch (FT) process to generate hydrocarbons from the syngas. The FT process cannot produce kerosene alone, but instead generates a mixture of hydrocarbons often referred to as "e-crude" to represent its chemical similarity to crude oil. From this e-crude, approximately 50% (by energy) may be suitable for e-kerosene and other useful products can be manufactured from the remainder, including synthetic diesel. Under three different scenarios for e-kerosene demand, taking into account the proposed ReFuelEU mandate and T&E's preferred targets, the CO_2 demands for this amount of e-crude manufacture was determined to be between 99 to 313MtCO_2/yr.

A summary of the estimated European CO_2 supplies and demands for every year of the ReFuelEU mandate is shown in the table below (no imports or exports are considered). The full list of demands considered have been detailed in sections 2.1 and 3.1. A deficit between supply and demand begins from 2030, which is assumed to be fulfilled by DAC.

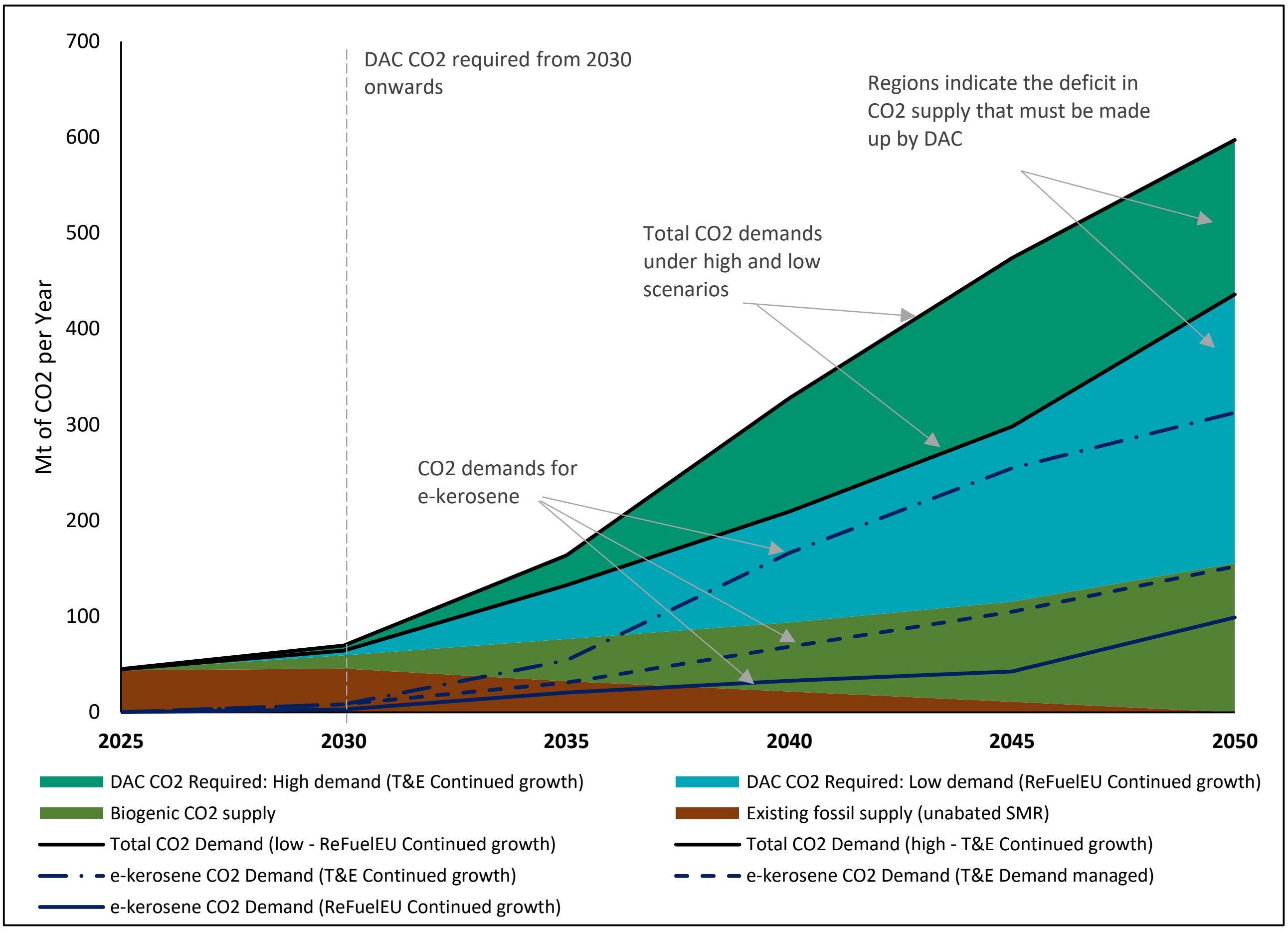
From 2030 onwards, existing fossil CO_2 and biogenic CO_2 supply are not enough to meet the demands of the growing CO_2 market, requiring the development of direct air capture to fulfil the deficit

CO_2 Supply and Demands up to 2050 (MtCO_2)

		2025	2030	2035	2040	2045	2050
CO_2 Demand	e-kerosene CO_2 demand (ReFuelEU Continued growth)	0	3	21	33	43	99
	e-kerosene CO_2 demand (T&E Demand managed)	0.13	8	31	68	105	152
	e-kerosene CO_2 demand (T&E Continued growth)	0.13	8	54	166	255	313
	Whole Market Total CO_2 Demand (low)	**45**	**64**	**133**	**210**	**298**	**436**
	Whole Market Total CO_2 Demand (high)	**45**	**70**	**164**	**328**	**474**	**597**
CO_2 Supply	Existing fossil supply (SMR)	44	46	32	22	11	0
	Utilised biogenic	1	14	44	72	105	156
	Utilised fossil/industrial process	0	0	0	0	0	0
	Total CO_2 Supply:	**45**	**59**	**76**	**94**	**115**	**156**
DAC CO_2 Required	Low (ReFuelEU Continued growth)	0	5	56	116	183	281
	High (T&E Continued growth)	0	10	87	234	359	442

The highest demand for e-kerosene exceeds the supply from SMR and biogenic CO_2 between 2035 and 2040 and therefore will require DAC. The two lower demands for e-kerosene, could, in theory, be supplied completely by biogenic and fossil CO_2 for every year up to 2050, if other competing demands for CO_2 were ignored, but it cannot meet the whole market demand.

CO_2 supply mix to 2050 under low and high demand scenarios



The feasibility of whether DAC can actually scale-up to meet the DAC required capacity has been assessed. There is a good understanding of what capacity DAC may be achieved in the short-term (2025 to 2030) as DAC projects will take several years to build from conception through to commissioning. Given the known DAC projects in planning, the total global capacity of DAC is expected to be in the region of 1.6-2.6 $MtCO_2$/yr by 2026. When including Norway (which could feasibly transport CO_2 to EU-27+UK countries), approximately 1.1-2.1 $MtCO_2$/yr of capacity will be placed in Europe, but most of this capacity is for storage of CO_2, and not for utilisation. There is no major DAC for utilisation capacity planned for EU-27+UK countries; in Norway 0.08$MtCO_2$ is planned for utilisation, with just a further 0.0052$MtCO_2$ planned for the rest of the world, bringing the global utilisation planned capacity to 0.0852$MtCO_2$.

Significant investment will be required in the next few years to introduce more DAC projects to the European pipeline in order to scale up to the potential 2030 demands.

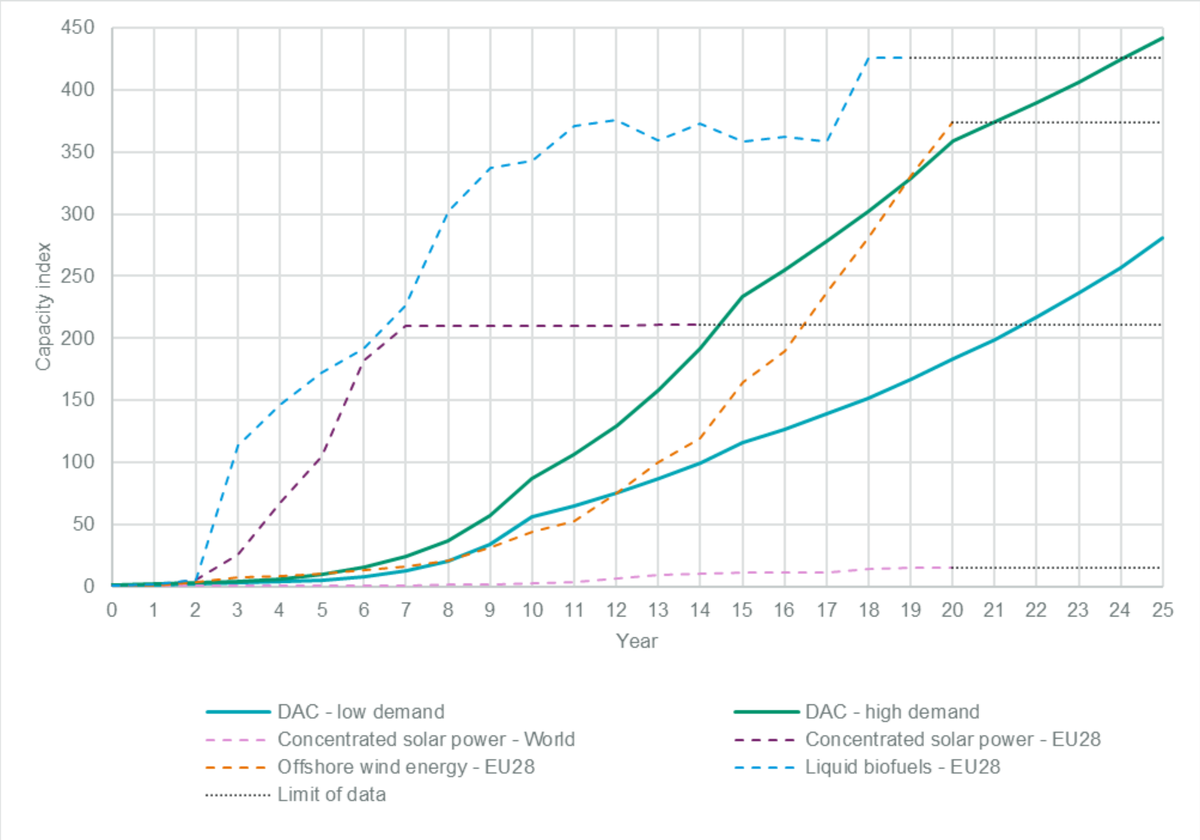
Predicting the long-term scale-up of DAC is highly uncertain. The scale-up that can be achieved by this novel, immature technology is heavily dependent on the policy and regulation landscape of the future. Expert views from literature were sought, and found that the scale-up required might be possible under climate policies consistent with limiting global warming to 2 °C. But, even in a world with aggressive climate policies, factors other than economics can slow the growth of low-carbon technologies. It can be useful to study the growth dynamics of historical technologies as they have been exposed to all the complex interdependencies that arise when attempting to scale in the real world. The DAC required scale-up was compared to the growth achieved by other energy technologies in Europe and it was found that the scale-up might be feasible, though caution must be advised on how comparable these technologies are to DAC.

A high rate of scale-up might be required from DAC, though the rate is not unprecedented in comparison to that achieved by other technologies

In both low and high DAC required scenarios, the highest rates of growth are required in the first 10 years. The scenarios required a growth of 37% and 59% per year from 2025 to 2030, increasing to 63% and 54% per year from 2025 to 2030 for low and high demands respectively. The effect of delaying scale-up of DAC was examined; it was found that delaying scale-up dramatically reduces the likelihood of achieving targets in later years due to the accelerated growth rates required.

Delaying the growth of DAC in early years will dramatically reduce the likelihood of meeting targets in later years

Indexed capacity growth for various energy technologies compared to that required of DAC



The Levelised Cost of Carbon (LCOC) that might be achieved by DAC was estimated by taking a learning curve approach using learning rates of 10% and 20%. Even with the aggressive scale-up stipulated by the DAC required capacities under the high and low demands, the LCOC from DAC fails to reach the cost of captured carbon from other sources.

DAC CO_2 is unlikely to compete economically with other sources of CO_2 without significant policy support

Carbon capture costs against estimated Levelised Cost of Carbon (LCOC) achieved by DAC

CO_2 Source		Cost (€/t_{CO2})	Year Costs Obtained
Power and Heat	Coal	€19-€63	2015 & 2017
	Natural Gas*	€34-€101	2015 & 2017
	Biomass	€54-€101	2015
Chemical Industry	Steam methane reforming (SMR) (Ammonia production)*	€12-€54	2015 & 2017

**Capture costs shown were obtained prior to the natural gas spike in late 2021 which could have increased CO_2 costs from these sources substantially.*

Levelised Cost of Carbon (€$_{2021}$)	2025	2030	2035	2040	2045	2050
Low DAC required (low learning: 10%)	€445	€368	€282	€262	€250	€240
High DAC required (high learning: 20%)	€445	€258	€173	€150	€142	€139

By tapping into a low concentration source of CO_2 – ambient air – DAC is an energy intensive technology. Given the 2050 low and high DAC required estimates of 281 and 442 MtCO2/yr the power capacity and land area requirements for power generation technology were estimated. To supply sustainable power for this quantity of DAC would require a huge scale up of either renewables or nuclear within Europe. The additional capacity required in EU-27+UK represents an increase against 2020 installed capacity of 43-1,272% for solar PV, 17-515% for onshore wind, 79-2,364% for offshore wind or 8-245% for nuclear generation. The required land ranges from an area for this amount of renewables deployment was equivalent to the size of Cyprus (0.23% of EU-27+UK land area) in the lowest scenario, and almost the size of Spain (11.63%) in the highest. Nuclear generation would only occupy a fraction of this land area.

DAC is energy intensive, so consideration needs to be paid to the additional renewable or nuclear electricity generation capacity required to fulfil its power needs

Factors which may influence the end use of CO_2 of certain origins were explored, with a particular focus on if DAC CO_2 may be a suitable candidate for e-kerosene manufacture. An outcome was that there are significant advantages to be gained by siting DAC, electrolysers and Fischer-Tropsch (FT) plants in close proximity to each other. Transport costs and emissions can be negated, or at least reduced, if both the hydrogen and CO_2 feedstocks are generated close to the FT plant. In the case of solid sorbent DAC which requires low-grade heat at circa 100ºC, waste heat from electrolysis and the FT process can be utilised, increasing the overall efficiency of the synthetic fuel manufacture. DAC and electrolysers can be sited almost anywhere, provided that there is access to reliable energy. Whereas FT plants producing large volumes of fuel will want to make best use of the economies of scale gained by existing supply chains for hydrocarbon fuels.

There are significant advantages to be gained by siting DAC, electrolysers and Fischer-Tropsch (FT) plants in close proximity to each other

The collective approach of industrial clusters drives economies of scale and will be key activity regions for all CO_2 origins. Carbon capture technologies (including DAC) are expected to have a high concentration of deployment in these areas. The highest density of Europe's industrial clusters is in the north and the North Sea is also where much of Europe's capacity for geological CO2 storage is. These areas will benefit from the shared use of CO_2 transport infrastructure, though this infrastructure is expected to be developed for the purpose of storage, as opposed to utilisation, in order to mitigate emissions.

CO_2 infrastructure is expected to be developed in industrial clusters, though its purpose will be directed towards storage, as opposed to utilisation, in order to mitigate emissions

Currently there are no sufficient, reliable financial incentives to deploy and operate large-scale engineered negative emission technologies such as bioenergy with carbon capture and DAC. Though there have been some significant voluntary corporate purchases of carbon removals which will help these technologies develop. These purchases have, however, been for the purpose of CO_2 storage to achieve negative emissions and not for CO_2 utilisation such as for manufacturing e-kerosene. The proportion of biogenic and DAC CO2 available for utilisation, whether for e-kerosene or other industries, will depend on country-specific policies as well as EU wide policies. The use of sustainable CO_2 in industrial applications has not yet been credited under the EU ETS (other than to produce precipitated calcium carbonate). Carbon Capture with Storage of CO_2 (CCS) is covered under EU ETS provided there is permanent emissions reduction in the form of geological stores.

1. INTRODUCTION

The European CO_2 market, both in terms of its supply and demand, will need to undergo dramatic changes if decarbonisation objectives are to be achieved. The European Union (EU) has set out a legally binding commitment to reach net-zero greenhouse gas emissions by 2050, with an intermediate target of reducing emissions by net 55% compared to a 1990 baseline by 2030[1].

The vast majority of CO_2 supplied as a commodity in this market is served by a single source: the steam reformation of natural gas (also called steam methane reformation, SMR) for the purpose of hydrogen production. This fossil-derived carbon dioxide is unsustainable; it has been extracted from the ground and its utilisation leads to a net-addition of CO_2 to the atmosphere. The supply of carbon dioxide must therefore switch to a source that does not increase atmospheric CO_2 concentrations.

The demand side of the market is also expected to undergo radical change. Many carbon-containing products such as hydrocarbon fuels and plastics use crude oil as the carbon feedstock. The use of crude oil will lead to net-addition of CO_2 to the atmosphere, and so is considered unsustainable. To produce these products sustainably, we will need to source the carbon from the atmosphere to ensure a carbon-neutral cycle.

A key emerging demand for CO_2, which is a focus of this report, is the manufacture of synthetic kerosene (also referred to as e-kerosene) to be used as aviation fuel. This is in light of the EU's proposed ReFuelEU mandate[2,3], which places an obligation on fuel suppliers to blend increasing levels of Sustainable Aviation Fuel (SAF) within their aviation fuel mix. SAFs are almost chemically identical to their fossil-derived counterpart and are "drop-in" fuels which can be used in existing aviation propulsion systems. There are targets on two different forms of SAF: one for biomass derived SAF (often referred to as bioSAF), and one for synthetically made e-kerosene. The leading method to manufacture e-kerosene is via the Fischer-Tropsch process which requires both CO_2 and hydrogen (H_2) as feedstocks. See Section 3.1.1.2 and Figure 4 for more information on this process.

Transport & Environment have raised a concern with the proposed ReFuelEU mandate, in that there is no regulation on the source of CO_2 as a feedstock to manufacture the e-kerosene. Provided the manufacture of e-kerosene is powered by additional renewable sources, the e-kerosene can be sustainable if the carbon feedstock is air-captured carbon dioxide. However, given the existing CO_2 market structure, the most likely candidate to supply the CO_2 in the short-term would be the by-product CO_2 released from the steam reformation of natural gas.

Not only is this unsustainable from an environmental standpoint, but reliance on this resource may be short-sighted from a resource availability perspective. Hydrogen production will have to move away from the unabated steam reformation of natural gas (often referred to as 'grey' hydrogen), and instead be decarbonised either by producing hydrogen via renewably powered electrolysis ('green' or renewable hydrogen), or by capturing the by-product CO_2 from SMR and permanently storing it underground ('blue' or low carbon hydrogen). If hydrogen production is to be decarbonised, then the existing supply stream of 'grey' hydrogen from unabated SMR will have to reduce over time.

The expected proliferation of carbon capture technologies may increase the supply of CO_2 available to the market. Heavy industry, such as the manufacture of cement, is a hard-to-decarbonise sector which will likely rely on carbon capture to mitigate emissions. However, the use of any fossil derived, or industrial process CO_2 is unsustainable, and so should not be relied upon as a future feedstock for the CO_2 market. We must therefore look to methods of sustainable carbon supply which will not be constrained by resource and will not have negative impacts on our environment.

One such method is the use of Carbon Dioxide Removal (CDRs) technologies which capture CO_2 from the atmosphere. Should this CO_2 be utilised and returned to the atmosphere, this would form a CO_2 cycle, keeping atmospheric CO_2 levels constant. If that CO_2 was to be stored underground or trapped permanently within materials throughout their lifecycle, this would reduce the amount of CO_2 in the atmosphere (known as negative emissions). To balance out unavoidable emissions, CDRs are seen as a necessary intervention to keep global

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[1] European Commission, 2019. European Climate Law (ec.europa.eu)

[2] European Commission, 2021. Proposal for a Regulation of the European Parliament and of the Council on Ensuring a Level Playing Field for Sustainable Air Transport (ec.europa.eu)

[3] Transport and Environment, 2021. Fit for 55 ReFuelEU: aviation fuel regulation (www.transportenvironment.org)

temperatures below dangerous levels[4,5]. The IPCC projections require several gigatons of negative emissions technologies in their 1.5°C pathways[4].

Two such CDR mechanisms to capture atmospheric CO_2 include the growth of biomass, in which the natural process of photosynthesis takes in CO_2 to form sugars for plant growth (referred to henceforth as biogenic CO_2), should this biomass be combusted, the CO_2 is released and can be captured. This is known as Biomass with Carbon Capture and Storage (BECCS). The second is via artificial extraction from the atmosphere using Direct Air Capture (DAC) technologies. Both methods can supply CO_2 for utilisation as well as for storage.

A key issue surrounding reliance on biogenic CO_2 is that its supply is limited by land availability. The growth of biomass for the purpose of CO_2 harvesting could directly compete with land for growing food. A body of scientific literature has highlighted the environmental damages caused by biomass crop growth[6]. It can cause significant losses in biodiversity due to habitat loss, can lead to excessive nutrient load, and over-exploitation of land[6].

Direct Air Capture (DAC) is increasingly seen as an attractive option to provide sustainable CO_2 for utilisation. Provided it is powered by sustainable energy sources it has the potential to deliver sustainable CO_2 that will not increase atmospheric levels. The capture plants themselves occupy a small amount of land in comparison to that needed by the growth of biomass (though consideration must be paid to the land required for the additional renewable power generation). And the plants can be sited almost anywhere if there is access to reliable energy supply. However, DAC taps into a relatively low CO_2 concentration source: ambient air. Existing supply sources such as steam reformation and bioethanol fermentation utilise CO_2 streams that can have concentrations as high as 100%, whereas current atmospheric CO_2 levels are approximately 0.041% (often referred to as 410 parts per million (ppm)). Because of this, DAC CO_2 is energy intensive and comparably expensive to existing CO_2 sources and is likely to remain more expensive than fossil and biogenic CO_2 for some time yet. DAC technologies are also immature, with only a few small-scale plants in operation today.

Given the environmental and resource availability concerns surrounding fossil and biogenic CO_2, this work seeks to provide insight on the CO_2 market of the future, and what role Direct Air Capture (DAC) technologies may play in supplying this market. What might be the total European CO_2 demand up to 2050? How much CO_2 might be available from sustainable and unsustainable sources? How much CO_2 might DAC technologies be able to supply?

In light of the ReFuelEU mandate which places targets on e-kerosene uptake for each year from 2025 to 2050 in 5-year intervals, this work has attempted to make projections for each of those years. The scope of this work is the EU-27 member countries plus the United Kingdom (formerly the EU-28).

[4] IPCC, 2018. Global Warming of 1.5°C, Summary for Policymakers (www.ipcc.ch)
[5] CCUS SET-plan, 2021. CCUS Roadmap to 2030 (www.ccus-setplan.eu)
[6] Jeswani et al, 2020. Environmental Sustainability of Biofuels: A Review (pubmed.ncbi.nlm.nih.gov)

2. EXISTING CO_2 MARKET

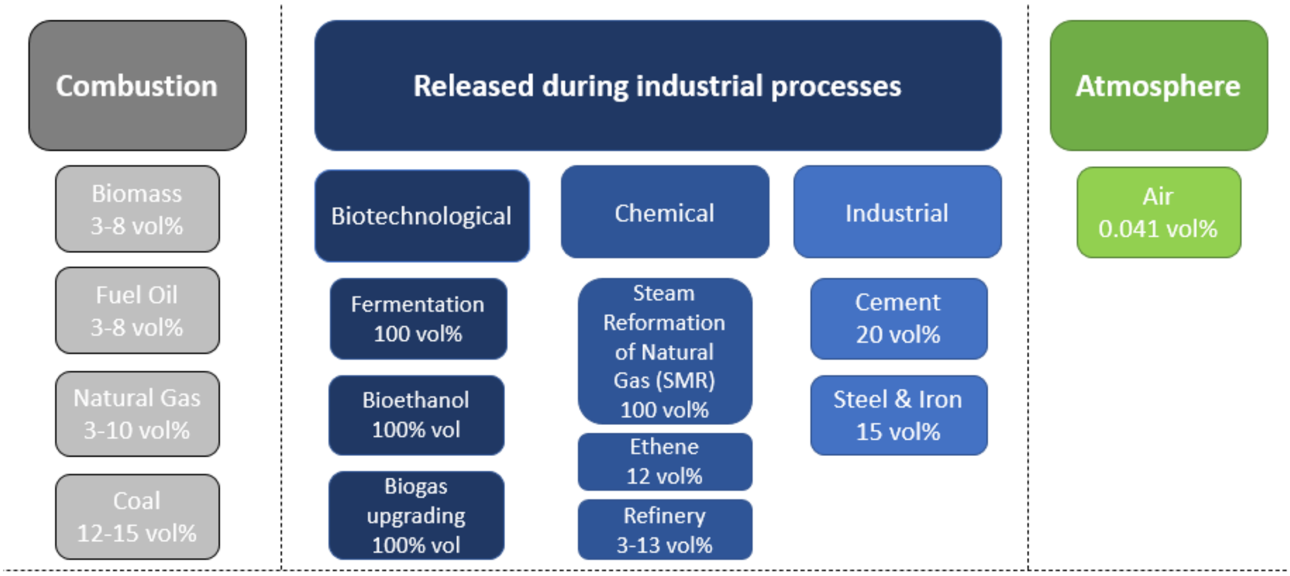
The global market for CO_2 as a commodity is only a fraction of today's global anthropogenic CO_2 emissions. The International Energy Agency (IEA) determined that the global demand for CO_2 in 2015 was 230MtCO_2/yr[7]. In that same year, global CO_2 emissions stood at circa 35,000MtCO_2/yr[8], which is over 150 times greater than the market demand.

However, only a small fraction of emission sources are suitable to supply CO_2 to the market. Firstly, the CO_2 must be captured, but much of our emission sources are dispersed. For example, CO_2 released from combustion in vehicles and in domestic boilers are small-scale sources on which it would be uneconomical to install carbon capture technology. Also, such emission sources are released in relatively low concentrations compared to the existing supply from industrial processes, making carbon capture more difficult and more expensive. As such, today's CO_2 market is mainly supplied either from natural CO_2 sources (as in the US) or from sectors where carbon dioxide is captured from large scale processes and from gas streams with high CO_2 content. Some prevalent examples are the Billingham Manufacturing Plant and Ensus Bioethanol Plant within the UK, which produce 650 ktCO_2/yr[9] (82.3% of the UK's total production), and the Fortum[10] and Brevik[11] plants within Norway which aim to produce 400 ktCO_2/yr each.

The key source of the world's CO_2 supply as a commodity is the steam methane reforming (SMR) which is a process to produce hydrogen. As can be seen in Figure 1 below, the CO_2 available from this process can be released in concentrations of up to 100% by volume, which is much greater than the levels seen in the flue gases on combustion processes (3-15%). This, coupled with the fact that the CO_2 is a by-product from the hydrogen production process, results in the CO_2 being relatively cheap compared to that obtained from carbon capture technologies.

Figure 1: Breakdown of CO_2 supply from combustion, industrial processes, and the atmosphere.

Adapted from Rodin et al[12]



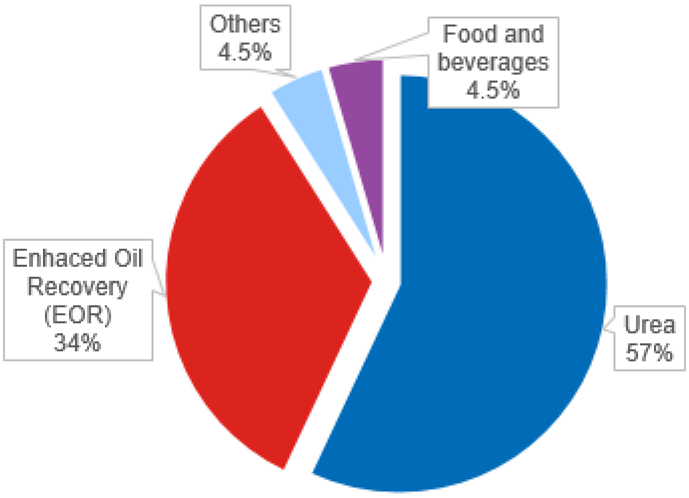
[7] IEA, 2019. Putting CO2 to Use, creating value from emissions (www.iea.org)
[8] Ritchie and Roser, 2020. CO_2 and Greenhouse Gas Emissions (ourworldindata.org)
[9] Global Counsel, 2019. Falling Flat: Lessons on the UK CO2 Market Shortage (www.fdf.org.uk)
[10] Fortum, 2018. A full-scale carbon capture and storage (CCS) project initiated in Norway (www.fortum.com)
[11] HeidelbergCement, 2020. Carbon Capture and Storage (CCS) (www.heidelbergcement.com)
[12] Rodin et al, 2020. Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO2 (www.sciencedirect.com)

2.1 EXISTING DEMANDS

Global demand

The International Energy Agency[7] (IEA) performed a detailed review of the global CO_2 market in 2019, which determined that the global demand in 2015 was 230 Mt/yr, with an expectation to grow to 272 Mt/yr by 2025. The demand is broken down into key categories in Figure 2 below.

Figure 2: Illustrates breakdown of existing CO2 market[7]



Urea is used as a fertiliser, as well as a starting material for the manufacture of plastics and drugs. It is the biggest global demand of CO_2 and its production also requires hydrogen as a feedstock. Because of this, it is typical to have a SMR plant co-located onsite to supply both the hydrogen (which is used to create ammonia as an intermediary feedstock) and CO_2 directly.

EOR utilises CO_2 to improve the extraction of oil and natural gas by compressing the CO_2 to a supercritical fluid with pressures as high as 130 bar and injecting it into depleted reservoirs. The CO_2 will then be permanently stored for millennia underground, but emissions are not necessarily mitigated as the fossil fuel extracted is likely to be combusted, releasing further CO_2 into the atmosphere. Currently, the majority of CO_2 EOR projects are operated within North America[13], who source just 20%-30% of their CO_2 from external sources[7,14], the remaining being sourced from natural CO_2 sources. These natural sources are found in underground wells, where CO_2 is stored within bedrock and aquifers, and extracted using similar techniques to oil and gas extraction. However, this is likely to change as more CCS projects come online in the next decade[13].

In terms of food and beverages, CO_2 is mainly used to carbonate drinks and in packaging to keep food fresh. The 'other category' accounts for industries such as fabricating metal, fire extinguishers, and medicine[7,9].

European Demand

Information on the size of the European CO_2 market and its breakdown of demands is not widely available. The IEA estimated that Europe accounted for 16% of global demand in 2015 (equating to 36.8Mt/yr), however no breakdown was provided in terms of end uses.

The breakdown of demands is expected to differ from the global breakdown provided by the IEA. The key difference is the use of CO_2 for EOR, with only one pilot European plant in operation today within Croatia,

[13] Global CCS Institute, 2021. Global Status of CCS 2021 (www.globalccsinstitute.com)
[14] McGlade, 2019. Can CO2-EOR really provide carbon-negative oil? (energypost.eu)

storing 0.56 Mt/yr[15]. North America seems to be the only region to have adopted CO_2 EOR on a mass scale, with 14 plants in operation today capturing a total of 28.1 – 28.7 Mt/yr[15].

2.1.1 Existing CO_2 demand projection

Using the IEA's estimate of European demand in 2015, an attempt has been made to project European CO_2 demands to 2050. The IEA has used a 1.7% year-on-year growth rate to project demands from 2015 to 2025. A separate report suggested that the UK market has been growing at 2-3% year-on-year[9]. The 2015 estimate by the IEA has been projected forward using an assumed 2% growth rate, the results are shown in Table 1 below.

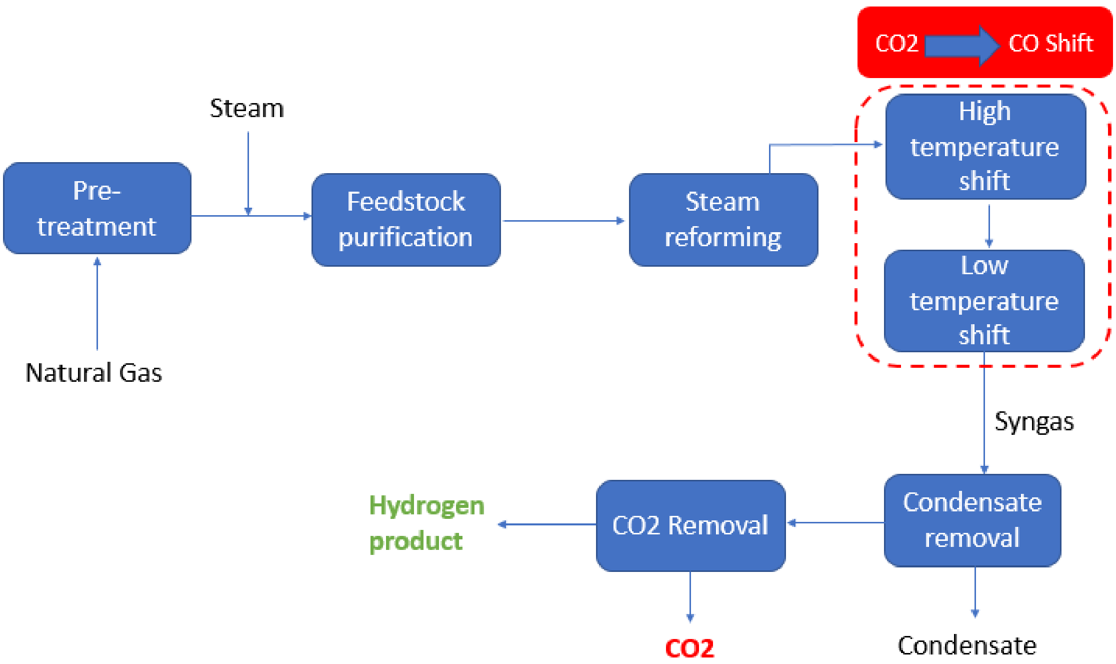
Table 1 Projection of existing CO_2 demands ($MtCO_2$/yr) in the Europe to 2050

2015	2020	2025	2030	2035	2040	2045	2050
36.8	40.6	44.9	49.5	54.7	60.4	66.7	73.6

2.2 Existing Supply

The existing supply of CO_2 is dominated by the steam reformation of natural gas to produce hydrogen, which is subsequently used in ammonia production, which is then in turn used to produce the fertiliser urea[16,17]. This process is split into two main reaction stages, with the gas initially being cracked at high temperatures and pressures using a nickel-based catalyst and steam to form syngas. The syngas (consisting mainly of hydrogen and carbon monoxide) then undergoes a reverse water gas shift reaction to convert carbon monoxide to carbon dioxide, which is separated to produce hydrogen[16] (see Figure 3 below). As mentioned in section 2.1, the separated CO_2 is used onsite to produce urea and any excess CO_2 can be supplied to the market.

Figure 3: Schematic of Steam Reformation (SMR) process



[15] International Association of Oil & Gas Producers, 2020. Global CCUS projects (gasnaturally.eu)
[16] European Fertilizer Manufacturer's Association (EFMA), 2000. Production of Ammonia (productstewardship.eu)
[17] European Fertilizer Manufacturer's Association (EFMA), 2000. Production of Urea and Urea Ammonium Nitrate (productstewardship.eu)

The second most dominant source of CO_2 in Europe is thought to be of bioethanol production[9]. The process uses biomass feedstocks (usually crops such as corn, wheat or waste crops such as straw) in a fermentation process that extracts sugars from the biomass and reacts them with yeast to produce ethanol and CO_2. The CO_2 is a by-product of this process and is released in high concentrations of up to 100%[18]. The demand for bioethanol is expected to follow the demand for conventional road transport fuel, as EU policy mandates that bioethanol forms a percentage of this fuel[19].

2.2.1 Existing CO_2 supply projection

Assuming that SMR and bioethanol fermentation are the dominant sources of CO_2 supplying the existing European market, a projection out to 2050 has been made on the CO_2 supply from these two existing sources. According to ePure, a representative of the European renewable ethanol industry, 0.87MtCO_2/yr was captured from bioethanol fermentation in Europe in 2020[20]. For years 2025 onwards, the amount of CO_2 supply from bioethanol has been determined as per section 3.2.2.2.

It has been assumed that renewable and low-carbon hydrogen (that is either 'green' or 'blue' hydrogen) will start to displace unabated 'grey' hydrogen (starting at 5% of production) from 2030 onwards. From 2030 the low carbon hydrogen uptake is linear to 2050, by which time it accounts for 100% of hydrogen production. The results of this projection are shown in Table 2 below.

'Blue' hydrogen is the production of hydrogen via natural gas SMR but with carbon capture and storage to mitigate the resulting CO_2 emissions. Whilst this process still produces CO_2, much of it is captured, and that fraction which is captured should be sent to permanent storage to mitigate emissions (instead of being utilised). It has therefore been assumed that blue hydrogen production will not supply CO_2 to the market.

Table 2 Projection of existing CO_2 supply (MtCO_2/yr)

Source	2020	2025	2030	2035	2040	2045	2050
CO_2 Demand (Existing Demands)	40.6	44.9	49.5	54.7	60.4	66.7	73.6
CO_2 Supply: Bioethanol	0.9	1.2	1.6	1.3	1.1	0.8	0.5
Low carbon hydrogen uptake	0%	0.0%	5%	29%	53%	76%	100%
CO_2 Supply: Unabated SMR	**39.8**	**43.6**	**45.6**	**32.5**	**21.6**	**10.8**	**0.0**

[18] Busic et al, 2018. Bioethanol Production from Renewable Raw Materials and Its Separation and Purification: A Review (www.ncbi.nlm.nih.gov)
[19] European Commission, 2018. Renewable Energy – Recast to 2030 (RED II) (joint-research-centre.ec.europa.eu)
[20] ePure, 2021. European Renewable Ethanol – key figures 2020 (www.epure.org)

3. POTENTIAL FUTURE CO_2 MARKET

The existing market structure of CO_2 is expected to undergo dramatic change due to the driver of decarbonisation. Existing supply via SMR will decrease as hydrogen production decarbonises, but new supply streams may open up with the advent of carbon capture technologies.

Crude oil is the key carbon feedstock for many of the world's products including plastics and chemicals. To produce these products sustainably, one option is to source carbon dioxide needed for manufacturing these products from the atmosphere.

The key emerging CO_2 supply and demands are discussed in the following sections.

3.1 POTENTIAL FUTURE CO2 DEMANDS

The key emerging demands for CO_2 have been deemed to be e-fuels, chemicals and plastics, construction materials and horticulture. There is a high degree of uncertainty in the expected scale-up of these demands, the IEA for instance has predicted a CO_2 demand of between 200 to 1,000 Mt/yr may be needed globally for emerging demands by 2060[7]. The upper end of that projection is over four times greater than the global demand for CO_2 in 2015. An analysis conducted by University College London (UCL) that examined several EU decarbonisation scenarios found that CO_2 utilisation capacities ranged from 324-2,230 Mt/yr by 2050[21]. The wide range quoted here highlights the uncertainty associated with estimating the CO_2 utilisation market.

3.1.1 E-fuels, chemicals and plastics

Hydrocarbon fuels, carbon-containing chemicals, and plastics rely heavily on the products of crude-oil refining for their manufacture. The process of distilling crude-oil is fundamental to many of the necessities that we depend on today. But this process leads to a net-addition of carbon to the atmosphere, so in order to produce these products sustainably, we must look to alternative methods of manufacturing which can use air-captured CO_2 as the carbon feedstock.

The IEA estimates that global e-fuel and chemical demand has a huge potential to grow, with an expectation that 5 $GtCO_2$/yr may be needed globally if adopted at scale[7]. McKinsey & Co.[22] and Bazanella et al[23] have estimated a CO_2 demand for e-fuels and chemicals of between 667 Mt/yr and 1053 Mt/yr by 2050. The majority of this growth is centred around methanol and synthetic natural gas (SNG) for McKinsey & Co.[22], and Benzene/Toluene/Xylene (BTX), synthetic diesel and olefin production for Bazanella et al[23].

3.1.1.1 E-fuels

Electro-fuels (often referred to as e-fuels) are an emerging type of fuel which, in the case of hydrocarbon e-fuels, can act as 'drop-in' replacements to conventional fuels. This means they can easily act as a substitute to existing fossil fuels, without the need for significant changes to existing infrastructure. They are made with electricity and have the potential to be carbon-neutral if the electricity is additional and is emission free. Some e-fuels are almost identical to their hydrocarbon counterparts; an example is e-kerosene which could replace fossil kerosene as an aviation fuel. For the e-fuel to be sustainable, both the carbon and hydrogen feedstocks must be sourced by sustainable means. This report has a focus on e-kerosene in light of the EU's proposed ReFuelEU mandate; synthetic kerosene has therefore been discussed in detail in section 3.1.1.2 below.

Other e-fuels include: synthetic diesel, synthetic natural gas (SNG) and methanol. Synthetic diesel has the potential to play a role in heavy road transport and shipping where batteries do not have the required energy density to meet the energy requirements of these transport modes. It has synergy with synthetic kerosene in that both fuels can be co-produced in the same Fischer-Tropsch process (described in more detail in the following section). Synthetic Natural Gas (SNG), often referred to as Power-to-gas or Power-to-Methane, is often discussed as an energy storage option to make best use of intermittent power from renewable sources. SNG is an attractive option as it can be used in existing gas storage and distribution infrastructure. Methanol

[21] Butnar et al, 2020. Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios (zeroemissionsplatform.eu)
[22] McKinsey & Co, 2020. Net-Zero Europe Decarbonization pathways and socioeconomic implications (www.mckinsey.com)
[23] DECHEMA, 2017. Low carbon energy and feedstock for the European chemical industry (dechema.de)

is used as a chemical feedstock as well as a fuel, it is blended with gasoline and ethanol in today's vehicles. In Europe, max 3% by volume of methanol is allowed to be blended in gasoline under the Fuel Quality Directive (2009/30/EC) and CEN standard (EN 228)[24].

3.1.1.2 e-kerosene

Aviation is a particularly hard-to-decarbonise sector. Aircraft require high-density energy storage, both in terms of energy per unit volume and mass. Current battery technology is still way off the energy density of hydrocarbon fuels, therefore, sustainable aviation fuel (SAF) such as e-kerosene is seen as the leading option to decarbonise this sector.

The proposed ReFuelEU mandate places an obligation on fuel suppliers to have a minimum share of SAF, with a sub-quota for e-kerosene in their fuel mix for every 5 years from 2030 to 2050 (see Table 3 below).

Table 3: Proposed ReFuelEU mandate on SAF and synthetic kerosene fuel blend[25]

	2025	2030	2035	2040	2045	2050
Minimum share of SAF	2%	5%	20%	32%	38%	63%
Minimum share of synthetic kerosene	0%	0.7%	5%	8%	11%	28%

The European Confederation for Transport & Environment (T&E) have recommended that the minimum share of SAF and the sub-quota for e-kerosene be more ambitious than the Commission's proposed targets. Increasing the share of SAF will reduce the climate impacts of flying, and T&E believe that the ReFuelEU mandate could be more ambitious, particularly in regard to the sub-quota for e-kerosene.

Further to this, T&E are campaigning that green hydrogen and electricity be considered SAF (currently SAF refers to kerosene jet fuel made in sustainable manner), and that the sub-quota for e-kerosene should be expanded to a synthetic fuels sub-quota which could be fulfilled by the use of green hydrogen and electricity. The SAF definition has not been updated to include for hydrogen and electricity, but in Table 5 below, all three aviation fuel scenarios have assumed that a growing proportion of aviation energy requirements are met by hydrogen and electric aircraft, with 20.9% of the aviation energy requirements met by these technologies by 2050.

Two recommended target options have been proposed by T&E based upon two aviation fuel projections (see Table 4 below). The first assumes continued growth of aviation fuel demands, the second is a demand managed forecast where aviation fuel decreases from 2025 to 2050. Reducing passenger, and therefore fuel demand, will ease the scale-up required by SAF, increasing its ability to take an increasing share of aviation's fuel requirements. The demand managed scenario assumes that in 2050, business travel demands do not exceed 50% of that demanded in 2019, and leisure travel demand does not exceed 100% of 2019's level. The aviation fuel requirements under both projections are provided in Table 5 below.

Table 4: Transport & Environment preferred mandates of SAF and e-kerosene fuel blend[26]

	2025	2030	2035	2040	2045	2050
T&E Continued growth						
SAF fuel demand (Mtoe)	0.8	3.0	12.4	28.9	43.4	56.9
Minimum share of SAF	1.6%	5.7%	22.6%	51.8%	77.4%	100.0%
Minimum share of synthetic kerosene	0.03%	2.0%	13.2%	40.4%	65.8%	88.6%

[24] European Commission, 2009. DIRECTIVE 2009/30/EC, Annex I (eur-lex.europa.eu)

[25] European commission, 2021. Proposal for a Regulation of the European Parliament and of the Council on Ensuring a Level Playing Field for Sustainable Air Transport, Annex I (ec.europa.eu)

[26] Transport & Environment, 2021. ReFuelEU Aviation: T&E's recommendations (www.transportenvironment.org)

	2025	2030	2035	2040	2045	2050
T&E Demand managed						
SAF fuel demand (Mtoe)	0.8	3.0	9.3	15.6	21.7	31.0
Minimum share of SAF	1.9%	7.8%	25.4%	45.2%	66.1%	100.0%
Minimum share of synthetic kerosene	0.04%	2.7%	11.3%	26.8%	46.3%	79.0%

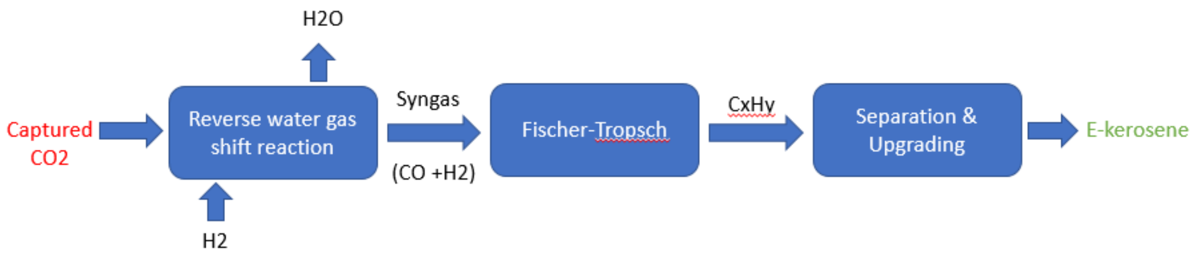
With all sets of targets above, rapid scale-up of e-kerosene manufacture will be needed to meet the quantities required. The favoured production method for the manufacturing of synthetic kerosene is the reverse water gas shift reaction (RWGS) combined with the Fischer-Tropsch process[27,28]. The water gas shift reaction takes in CO_2 and H_2 as feedstocks and generates syngas which is then fed into the Fischer-Tropsch process which generates a mixture of hydrocarbons. Provided that these feedstocks are generated using electricity (for the DAC and electrolysers plants respectively), the resulting product is often referred to as "e-crude", in reference to the electricity used as the power source, and due to its chemical similarity to crude oil.

Alternative methods of producing synthetic kerosene exist; such as via methanol synthesis, from which the methanol can be upgraded into aviation fuel. Although the necessary upgrading processes are used in today's refineries, this conversion step has not been demonstrated yet at scale (TRL 7-8). For this reason, kerosene via this production path has not been approved for use in aviation[29]. By comparison, the FT synthesis is a well-established process which is in use today (TRL 9). Furthermore, Fischer-Tropsch fuels are ideal for locations where existing oil processing sites are in place[28]. However, the RWGS process is at lower stage of development and is currently only shown in demonstration plants (TRL 5-6)[30]. The RWGS is therefore considered a missing part of the overall process to produce fuels from electricity via the FT pathway and needs development to scale to an industrial level.

The reaction scheme is shown below along with a schematic:

1. Reverse Water Gas Shift: $CO_2 + H_2 \rightarrow CO + H_2O$
2. Fischer-Tropsch: $xCO + (0.5y + x)H_2 \rightarrow C_xH_y + xH_2O$

Figure 4: Schematic for e-kerosene production



The molar conversion of carbon monoxide to e-crude products is typically 53%; however, higher conversions of up to 80% are possible if process conditions are optimised[31]. The crude product will contain a mixture of light gases, medium length hydrocarbons, and heavy waxes[32]. Their distribution can be altered by changing the operating conditions, with lower temperatures leading to a 20% kerosene conversion, and higher temperatures producing up to 60% kerosene[33]. Of the remaining hydrocarbons left after the extraction of kerosene, there is potential to produce other valuable fuels such as synthetic diesel, and other valuable

[27] European Commission, 2021. Study supporting the impact assessment of the ReFuelEU Aviation initiative, Annex III (op.europa.eu)
[28] Dieterich et al, 2020. Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review (pubs.rsc.org)
[29] European Commission, 2021. Study supporting the impact assessment of the ReFuelEU Aviation initiative (op.europa.eu)
[30] Schmidt et al, 2016. Power-to-Liquids – Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel (www.umweltbundesamt.de)
[31] Leibbrandt et al, 2013. Process efficiency of biofuel production via gasification and Fischer–Tropsch synthesis (www.sciencedirect.com)
[32] Karaba et al, 2020. Improving the steam-cracking efficiency of naphtha feedstocks by mixed/separate processing (www.sciencedirect.com)
[33] Mark Crocker, ed., *Thermochemical Conversion of Biomass to Fuels and Chemicals*, (2010) Royal Society of Chemistry.

chemical and plastics feedstocks such as benzene, toluene and xylene (BTX), and olefins. The process can be operated in a kerosene mode such that 50% of the products on an energy basis are suitable for kerosene and 25% for diesel[34].

3.1.1.3 Chemicals and plastics

Crude oil is cracked within a refinery using steam at high temperatures (beyond 750 °C) and a silica-alumina catalyst, to produce a range of products such as BTX and light alkenes such as ethylene and propylene (also referred to as Olefins). The lighter compounds, particularly ethylene and propylene, are highly valuable due to their chemical structure enabling the production of plastics[23]. To circumvent the use of crude oil, BTX and Olefins can be manufactured using a methanol synthesis pathway[23], known as Methanol to Aromatics (MTA) and Methanol to Olefins (MTO) respectively. Both pathways require hydrogen and CO_2 to synthesise the methanol which is a feedstock for these processes. There is also potential to manufacture BTX and olefins using the products of the Fischer-Tropsch process, though previous work by DECHEMA has suggested that the methanol synthesis routes are more likely as they are more technologically mature[23].

3.1.2 Construction materials

The adoption of low carbon concrete is a promising utilisation technology, due to its ease of production and ability to improve concrete strength[7,35,36,37]. The process works by injecting CO_2 into the concrete mix during the curing stage, where the clinker reacts with water, aggregates, and the CO_2 to form crystals[37]. The CO_2 is particularly attracted to the calcium oxide within the clinker, where it adsorbs onto the porous structure and is stored for millennia. Furthermore, atmospheric CO_2 will begin to bind to the material once exposed to the atmosphere, encouraging long-term storage of CO_2 that further strengthens the concrete[7,37]. This latter adsorption process is very slow, and hence will not provide the immediate CO_2 capture rates necessary to abate climate change.

Cured concrete is already beginning to grow within the market, with two key start-ups looking to expand their influence worldwide; Carbon Cure[35] and Solida[36], who claim to reduce emissions by 70%-80% compared to traditional Portland cement manufacture. Solida claim that if the global market were to adopt concrete curing rapidly, then between 10 - 1000 Mt/yr of CO_2 could be captured as of today, and grow to 1200 Mt/yr by 2030[37], though manufacturer claims must be taken with caution.

Using the annual 2016 production of concrete blocks in Europe, Patricio et al[38] estimated that if all of those blocks were cured, low carbon concrete, the CO_2 demand would be 22.5MtCO_2/yr.

3.1.3 Horticulture (greenhouses)

Increasing the concentrations of CO_2 within an atmosphere leads to enhanced levels of plant growth[39]. This is an established method of increasing yields within greenhouses. Currently, these facilities will make use of the CO_2 emitted from onsite fossil fuel combustion plants that provide heat to the greenhouses. The flue gases from combustion will be scrubbed to remove any pollutants and be sent into the greenhouse where it will increase the CO_2 concentration levels. This is particularly popular within the Netherlands, which has been estimated to use between 5 – 6.3 MtCO_2/yr[40].

As the CO_2 demand for this purpose is fulfilled by onsite combustion plants, it is not currently common for greenhouses to purchase CO_2 from the commodity market. However, as fossil fuels are phased out within Europe, the CO_2 will need to be sourced by alternative sustainable means. Patricio et al[38] estimated that the total technical potential of all greenhouses in Europe in 2016 was 22MtCO_2/yr.

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[34] Detz, 2019. Fischer-Tropsch fuel production (energy.nl)
[35] CarbonCure. CarbonCure's Sustainable Concrete Solution - Concrete Technology Reducing Carbon Impact (www.carboncure.com)
[36] Solida. Solidia® – Sustainable cement manufacturing and concrete curing technologies (solidiatech.com)
[37] ICEF, 2017. Carbon Dioxide Utilisation (CO¬2U) icef Roadmap 2.0 (www.icef.go.jp)
[38] Patricio et al, 2017. Region prioritization for the development of carbon capture and utilization technologies (www.sciencedirect.com)
[39] Marchi et al, 2018. Industrial Symbiosis for Greener Horticulture Practices: The CO2 Enrichment from Energy Intensive Industrial Processes (www.sciencedirect.com)
[40] Imperial College London and ECOFYS, 2017. Assessing the potential of CO_2 utilisation in the UK (publishing.service.gov.uk)

3.1.4 Emerging demand projections

Three CO_2 demand projections have been developed based on the proposed European Commission (EC) ReFuelEU mandate for e-kerosene, and T&E's preferred targets under the two aviation demand scenarios (see section 3.1.1.2). The aviation fuel requirements have been detailed in Table 5 below. In all demand scenarios below, it has been assumed that hydrogen and electric aircraft meet 20.9% of aviation energy requirements by 2050.

Table 5: e-kerosene demand projections*

	2025	2030	2035	2040	2045	2050
Aviation energy requirements (Mtoe)						
Continued growth forecast	49.4	52.6	54.7	55.8	56.0	56.9
Demand managed forecast	41.5	38.5	36.5	34.6	32.8	31.0
Alternative propulsion uptake (%)						
Hydrogen and electric propulsion uptake**	0.0%	1.0%	4.0%	6.0%	12.0%	20.9%
Kerosene jet fuel aviation energy requirements (Mtoe)						
Continued growth forecast	49.4	52.1	52.5	52.5	49.3	45.0
Demand managed forecast	41.5	38.1	35.0	32.5	28.9	24.5
e-kerosene aviation energy requirements (Mtoe)						
ReFuelEU Continued growth	0	0.4	2.6	4.2	5.4	12.6
T&E Continued growth	0.016	1.0	6.9	21.2	32.5	39.9
T&E Demand managed	0.016	1.0	4.0	8.7	13.4	19.4

**All energy units are net calorific values.*

***Proportion of aviation energy requirements met by hydrogen and battery electric aircraft.*

It has been assumed that all e-kerosene is manufactured via the Fischer-Tropsch process combined with the reverse water gas shift reaction. This process has been assumed to operate in a kerosene mode that will produce e-crude with a composition that allows for 50% of the products (on an energy basis) to be used for kerosene, and 25% of products to be used for the manufacture of synthetic diesel[34]. The remaining 25% will be a mixture of hydrocarbons that have the potential to form other useful products, such as other fuels, chemicals or plastics, which could reduce the CO_2 demands for these emerging areas. The conversion rate of this other 25% into useful products requires further investigation and so has not been considered in the CO_2 calculations.

It has been assumed that 4 tonnes of CO_2 is needed for each tonne of e-crude based on work by Marchese et al[41]. Analysis by Concawe[42] also showed that the mass balance for Fischer-Tropsch fuel production requires

[41] A mass balance table is provided, for a recycle rate of 90%, which details the inputs and outputs of CO_2 feedstock and the following e-crude products: naphtha (C5-11), middle distillate (C11-20), light wax (C20-35), and heavy wax (C35+). An e-crude production rate of 259.6 kg/h - 253.7 kg/h is shown for a CO_2 inlet of 1002.8 kg/h. This leads to a CO_2 requirement of circa 4 tCO_2 per tonne of e-crude:
Marchese et al, 2020. Energy performance of Power-to-Liquid applications integrating biogas upgrading, reverse water gas shift, solid oxide electrolysis and Fischer-Tropsch technologies (www.sciencedirect.com)

[42] A CO_2 requirement of 2.9–3.6 kg CO_2 per litre of fuel is provided. An average was taken and converted to 4.1 tCO_2 per tonne of fuel using a fuel density of 800 kg/m3:
Yugo and Soler, 2019. A look into the role of e-fuels in the transport system in Europe (2030–2050) (www.concawe.eu)

approximately 4.1 tonnes of CO_2 per tonne of e-crude, when assuming a density of 800 kg/m^3 for light liquid crude[43]. This agrees with work by Marchese et al[41].

A demand for synthetic diesel has been taken from a net-zero decarbonisation scenario (1.5TECH) developed by the European Commission[44]. This demand for synthetic diesel is partly fulfilled by the by-product synthetic diesel generated when running the Fischer-Tropsch process in kerosene mode (to meet the kerosene requirements for aviation). Any residual demand for synthetic diesel (which has not been fulfilled by leftover products from e-kerosene manufacture) has been assumed to be met with Fischer-Tropsch production also with a CO_2 requirement of 4 tonnes per tonne of e-crude. The Fischer-Tropsch process can also be operated in a mode to maximise diesel production[34]. For simplicity, it has been assumed that all e-crude from this process can be used for synthetic diesel. In reality, the diesel production will produce e-crude with a proportion of the hydrocarbons only suitable for other products. The hydrocarbons suited for other products could be used to reduce CO_2 demands elsewhere (such as for other fuels, chemicals or plastics), so the CO_2 demand for synthetic diesel has not been increased to reflect the fact that only a proportion of the e-crude is suitable for synthetic diesel.

Table 6: Fischer-Tropsch CO_2 demands for manufacture of e-crude

	2025	2030	2035	2040	2045	2050
e-kerosene demand ($MtCO_2$/yr)*						
ReFuelEU Continued growth	0	3	21	33	43	99
T&E Continued growth	0.13	8	54	166	255	313
T&E Demand managed	0.13	8	31	68	105	152
Synthetic diesel demand (Mtoe)						
All scenarios	0	0	2	6	12	20
By-product of e-kerosene manufacture: synthetic diesel (Mtoe)**						
ReFuelEU Continued growth	0	0	1	2	3	6
T&E Continued growth	0.01	1	4	11	16	20
T&E Demand managed	0.01	1	2	4	7	10
Residual synthetic diesel demand (Mtoe)***						
ReFuelEU Continued growth	0	0	1	4	9	14
T&E Continued growth	0	0	0	0	0	0
T&E Demand managed	0	0	0	2	5	10
Residual synthetic diesel demand ($MtCO_2$/yr)****						
ReFuelEU Continued growth	0	0	3	15	36	54
T&E Continued growth	0	0	0	0	0	1
T&E Demand managed	0	0	1	6	21	40

[43] Speight, 1991. *The Chemistry and Technology of Petroleum*. 2nd Edition, Marcel Dekker, Inc., New York.

[44] European Commission, 2018. [In-depth Analysis in Support of the Commission Communication COM(2018) 773: A Clean Planet for All (ec.europa.eu)]

	2025	2030	2035	2040	2045	2050
Total CO_2 demand for e-kerosene and synthetic diesel ($MtCO_2$/yr)						
ReFuelEU Continued growth	0	3	23	48	79	152
T&E Continued growth	0.13	8	54	166	255	314
T&E Demand managed	0.13	8	31	75	125	193

**The e-kerosene energy requirements in Table 5 (in Mtoe) were converted to mass using a Net Calorific Value (NCV) of 1.0533 Mtoe/Mtonne kerosene. Assumed Fisher-Tropsch production requiring 4 tonnes of CO_2 per tonne of e-crude, assumed 50% of e-crude (by energy) suitable for e-kerosene, 25% suitable for synthetic diesel.*
*** Synthetic diesel produced as a by-product of e-kerosene manufacture using the Fischer-Tropsch process.*
**** Remaining synthetic diesel demand that could not be met with the by-products of e-kerosene manufacture.*
*****Assumed that for every tonne of remaining synthetic diesel demand, 4 tonnes of CO_2 will be required (for the Fischer-Tropsch process. Synthetic diesel energy requirements (in Mtoe) were converted to mass using a Net Calorific Value (NCV) of 1.0318 Mtoe/Mtonne diesel.*

A literature review was conducted of projections for the emerging demands which is detailed in the previous sections. The CO_2 demands for the remaining e-fuels, chemicals and plastics have been taken from the European Commission's 1.5TECH net-zero scenario[44], and DECHEMA's Intermediate scenario projections of low chemical uptake in Europe[23].

The DECHEMA study had a significant demand for a number of the chemical feedstocks in 2025. This was thought to be unreasonable as low-carbon chemical uptake in Europe is currently thought to be small, based on the fact that existing CCU sites in Europe plan to utilise CO_2 on the scale of 0.386 Mt/yr by 2025[45,46,47,48] , which is highly optimistic. Therefore, scale-up over the next few years is thought to be unlikely. The demands for these chemicals have therefore been reduced to zero in 2025, but the following years retain the same demand as per the DECHEMA scenario.

Table 7: Emerging CO_2 demand projections ($MtCO_2$/yr)

	Product	2025	2030	2035	2040	2045	2050	Data source
e-fuels	Synthetic Natural Gas (SNG)	0	0	25	51	76	102	EU Commission 1.5TECH requires approximately 45Mtoe of e-gas by 2050. Assumed linear increase from 2030 onwards.
	Methanol as fuel	0	8	11	11	12	14	Intermediate scenario from DECHEMA low carbon chemical study. 2025 demand artificially reduced to zero.
Chemicals	Methanol as chemical	0	0	0	0	0	1	Intermediate scenario from DECHEMA low carbon chemical study. 2025 demand artificially reduced to zero.
	Benzene, toluene and xylene (BTX)	0	2	3	9	17	27	Intermediate scenario from DECHEMA low carbon chemical study, assumed pathway to production is Methanol-to-Aromatics (MTA). 2025 demand artificially reduced to zero.

45 Carus et al, 2019. Hitchhiker's Guide to Carbon Capture Utilisation (CCU) (renewable-carbon.eu)
46 Carbon Recycling International. Carbon Dioxide to Methanol Since 2012 (www.carbonrecycling.is)
47 Norsk e-fuel. Our Technology | Norsk e-Fuel (norsk-e-fuel.com)
48 Audi. Audi e-gas - Audi Technology Portal (audi-technology-portal.de)

	Product	2025	2030	2035	2040	2045	2050	Data source
Materials	Plastics (ethylene, propylene)	0	1	3	8	14	23	Intermediate scenario from DECHEMA low carbon chemical study, assumed pathway to production is Methanol-to-Olefins/Propylene (MTO/MTP). 2025 demand artificially reduced to zero.
	Concrete Curing	0	1	6	12	17	23	22.5MtCO_2/yr is the estimated total technical potential if all of existing EU-27+UK concrete blocks were cured with CO_2. 2030 demand has arbitrarily been set at 0.5MtCO_2/yr.
Horticulture	Greenhouse enrichment	0	1	6	11	17	22	22MtCO_2/yr is the estimated total technical potential if all of EU-27+UK greenhouses enriched their atmospheres with CO_2. 2030 demand has arbitrarily been set at 0.5MtCO_2/yr
Total potential future CO_2 demands including e-kerosene and synthetic diesel (MtCO_2/yr)								
ReFuelEU Continued growth		0	15	78	149	231	363	
T&E Continued growth		0	20	109	267	407	523	
T&E Demand managed		0	20	86	176	278	403	

3.2 POTENTIAL FUTURE SOURCES OF CO2

Over the coming decades, it is thought that more CO_2 will be captured and permanently stored to reduce anthropogenic emissions. Carbon capture is seen as a necessary technology alongside renewables and energy efficiency to achieve decarbonisation objectives. Despite best efforts to reduce the use of fossil-fuels, there will likely be some unavoidable residual emissions in 2050. To balance out the warming effect of these unavoidable emissions and truly achieve net-zero, air-captured carbon will have to be stored underground to achieve negative emissions.

The proliferation of carbon capture may also open new supply streams of CO_2 to the market for utilisation. Due to the large, industrial size nature of carbon capture technologies, it is thought that they will only be deployed on what is termed as “point-sources” or “stationary” sources of emissions. These include large scale emitters such as power stations and industrial facilities. Distributed sources of emissions, such as the combustion of fuels in road vehicles and domestic properties are not suited for carbon capture. Alternatively, CO_2 can be extracted directly from the atmosphere with DAC technologies, however, CO_2 is in relatively low concentrations in the air, and so this comes with a large energy penalty.

The origin of the carbon determines the sustainability of the use of captured CO_2. In the following sections the emerging supply streams have been split out fossil and industrial process CO_2, which is unsustainable, biogenic CO_2 which has the potential to be sustainable, and by DAC CO_2 which has the potential to be sustainable if powered by a sustainable source.

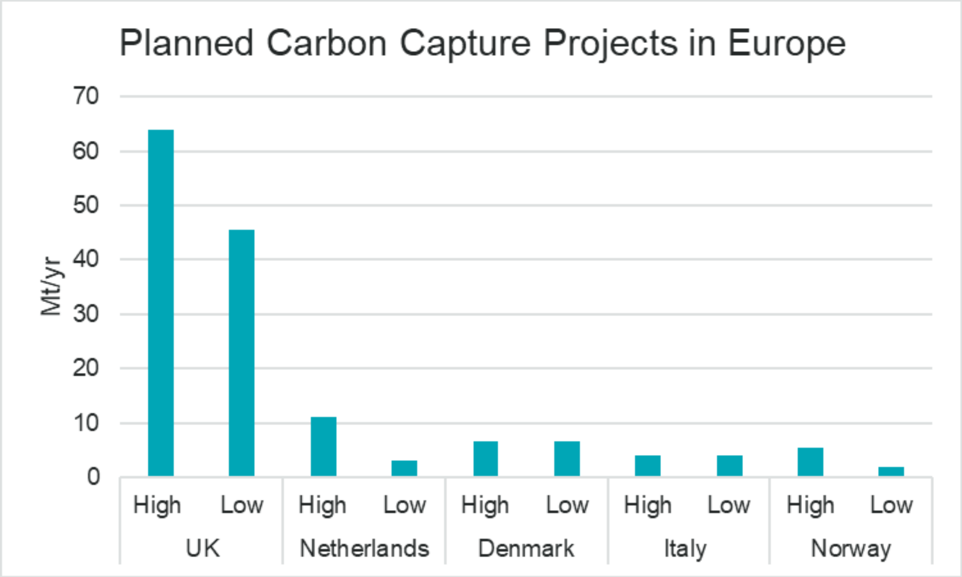
3.2.1 Point-source: Fossil and industrial process

Both fossil derived and industrial process CO_2 are unsustainable sources as their utilisation leads to a net-addition to the atmosphere. Fossil CO_2 is that derived from the use of fossil-fuels; typically, when a fuel is combusted for power or heat generation. Whereas industrial process CO_2, such as that arising from cement production, is not derived from fossil-fuel combustion, but rather there is a chemical process using other substrates that release CO_2. For instance, CO_2 is a by-product of the chemical conversion process used in the production of clinker, a component of cement, in which limestone ($CaCO_3$) is heated to convert to lime (CaO), releasing CO_2 in the process.

Fossil-fuel use for power and heat generation is hoped to decline in the coming decades, as viable low-carbon alternatives exist, such as solar PV, wind, electric heat pumps and hydrogen. Industrial process emissions are much harder to decarbonise, as the very chemical process itself would need to change. Also, fossil fuel use in industry is expected to continue for some time. Many industrial processes require high temperatures suited to the combustion of a fuel, and so electrification is not seen as a viable alternative. Carbon capture is therefore seen as a vital solution to mitigate emissions in the industrial sector.

It is expected that carbon capture across power and industrial sectors will grow significantly in the coming decades. Within Europe the Global CCS institute estimates that there is a total of 61-91 $MtCO_2$/yr carbon capture capacity in planning which will be operational by 2035[13]. The majority of these planned carbon capture projects are located within the UK's industrial cluster, which account for 70-75% of future European carbon capture (Figure 5). This captured carbon could be utilised; however, as of now, all planned projects aim to store carbon in depleted oil and gas reservoirs[13].

Figure 5: Carbon capture projects planned within Europe[13]



Projections on the scale-up of carbon capture in Europe are highly uncertain, a meta-analysis by University College London (UCL) gathered several CCS projections for 1.5°C European decarbonisation scenarios and saw a range of between 324 to 2,230 $MtCO_2$/yr captured and stored underground by 2050[21]. However, these included projections included a mixture of captured biogenic and fossil CO_2. A separate review of decarbonisation scenarios of the fossil and industrial process CO_2 was conducted for this work. To align with the European Commission's legally binding target of achieving net zero by 2050, this research attempted to focus on projections that achieved this target. In all the projections reviewed below, the captured carbon values were provided for 2050 only, and all of the captured carbon was to be sent for underground storage.

Table 8: Fossil and industrial process carbon capture capacity projections ($MtCO_2$/yr)

Scenario	2050 Carbon Capture Capacity	Scope	Comments
EU-Comm: Clean Planet for All: 1.5TECH[44]	120	EU-27+UK	Power sector negative emissions via BECCS by 2050.
EU-Comm: Clean Planet for All: 1.5LIFE[44]	74	EU-27+UK	Power nearly decarbonised by 2050.
EU-Comm: Clean Planet for All: 1.5LIFE-LB[44]	77	EU-27+UK	Power nearly decarbonised by 2050.

Scenario	2050 Carbon Capture Capacity	Scope	Comments
ICF Industrial Pathways: Mix95[49]	46	EU-27+UK	Industry only (no power sector), may include some biogenic CO_2. Achieves 95% reduction in emissions against 1990.
ICF Industrial Pathways: CCS[49]	294	EU-27+UK	Industry only (no power sector), may include some biogenic CO_2. Achieves 87% reduction in emissions against 1990.
McKinsey 2019[50]	150	EU-27	Does not include UK.

3.2.2 Biogenic

Biogenic resources are derived from living (as opposed to fossilised) plant material either directly, used as solid biomass fuel or processed into liquid or gaseous fuel. Or indirectly following ingestion by animals and humans, or prior use as materials. Through photosynthesis they consume carbon dioxide from the atmosphere when living, therefore providing an opportunity to capture and sequester carbon during the process of conversion to fuel and eventually when combusted.

The following sections detail the results of an analysis of the biogenic CO_2 resource within the EU-27+UK, along with an estimate of the amount captured. The methodology used to determine the biogenic resource has been explained in further detail in Appendix 2.

3.2.2.1 Sustainable and Unsustainable sources

Whilst generally viewed as a renewable and low-carbon alternative to fossil fuels, the growth of energy from biogenic sources is not without contention. Production of biofuels from food crops (cereal, sugar, starch and oil crops) has given rise to concerns of using viable arable land for the production of fuel, rather than food. This risks increasing greenhouse-gas emissions via indirect land-use changes, by driving food production onto areas with high-carbon stock, such as forests, wetlands and peatland[51]. In response, a revision to the renewable energy directive (REDII) has sought to promote the use of “advanced” biofuels. Firstly, by restricting the allowable portion of conventional biofuels to 7% of road and rail final energy consumption in 2030. Secondly, by introduction of targets to increase advanced biofuels to 3.5% of final energy consumption[19].

Annex IX of the directive lists biogenic materials accepted as feedstocks for advanced biofuels. These materials can generally be termed “residues and wastes”, being by-products of other activities. An exception to this is specific lignocellulosic energy crops, including perennial crops (such as miscanthus), coppicing and short-rotation forestry. Even so, several of the sources included under Annex IX also give rise to some sustainability concerns with unrestricted use. Palm oil mill effluent and empty palm fruit bunches arise from the growing oil palms, causing clearing of primary rainforest and disturbance of peatland[52]. Saw logs and veneer logs from traditional forestry are specifically excluded. However, this leaves a large amount of tree biomass not suited for timber. Stumps should not be extracted, to avoid disturbing the ground. Leaves and needles should also be left in-situ to preserve soil fertility, and acceptable removal rates for brash are site specific[53]. Many of the remaining forestry resources have competing uses such as, fencing, paper and pulp, and panel board production. Similarly primary agricultural residues (such as cereal straws) are subject to restrictions on removal to preserve soil condition, and competing uses from animal bedding and horticulture[54].

[49] ICF, 2019. Industrial Innovation: Pathways to deep decarbonisation of Industry (ec.europa.eu)
[50] McKinsey & Co, 2020. Net-Zero Europe Decarbonization pathways and socioeconomic implications (www.mckinsey.com)
[51] Journal of the European Union, 2018. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (eur-lex.europa.eu)
[52] WWF. Palm Oil (wwf.panda.org)
[53] Forest Research, 2009. Guidance on site selection for brash removal (cdn.forestresearch.gov.uk)
[54] Searle and Malins, 2016. Waste and residue availability for advanced biofuel production in EU Member States (www.sciencedirect.com)

This report places additional restrictions on which biogenic sources are considered "sustainable" and "unsustainable", beyond the inclusion of the resource in annex IX of the directive. As such, resources arising from problematic production practices and those that risk displacing competing uses of material or land (increasing the potential for indirect land use changes) are deemed unsustainable. Additionally, wastes where the principle of reducing, reusing and recycling are given precedence over energy recovery, are also categorised as unsustainable. See Appendix 1 Feedstock Sustainability for the full list of feedstock sustainability categorisation.

3.2.2.2 Biogenic CO_2 Availability

This section presents the results of determining the theoretical CO_2 supply from all biogenic sources. This is before any carbon capture technology is applied, so the amounts shown here are equivalent to the amount of CO_2 which could be sent to permanent storage or for utilisation.

The CO_2 resource is categorised by distributed sources (residential and commercial) and point-source (energy and industry). Then further split by sustainable and unsustainable feedstock, following discussion in 3.2.2.1. Emissions from combustion of biofuels for transport (as discussed in Appendix 2) have been excluded due to lack of any potential for capture.

Table 9: Theoretical biogenic CO_2 resource ($MtCO_2$/yr). Categorised by source type and feedstock sustainability.

Source		Type	2025	2030	2035	2040	2045	2050
Distributed	Sustainable	Small-scale solid biomass facilities	18	23	22	17	16	14
	Unsustainable	Small-scale solid biomass facilities	270	312	288	226	207	184
	Sustainable	Biomethane combustion	4	6	7	8	6	7
	Unsustainable	Biomethane combustion	3	4	6	7	8	9
Point source	Sustainable	Large-scale solid biomass facilities	30	43	48	47	50	52
	Unsustainable	Large-scale solid biomass facilities	437	576	632	623	650	677
	Unsustainable	Bioethanol fermentation	5	5	4	3	2	1
	Sustainable	Biogas upgrading	3	4	5	6	4	4
	Unsustainable	Biogas upgrading	2	3	4	4	5	6
	Sustainable	Biogas combustion	43	70	75	90	66	73
	Unsustainable	Biogas combustion	37	43	63	73	90	101
Total point-source biogenic CO_2 resource			**557**	**744**	**831**	**847**	**866**	**915**
Sustainable fraction of point-source biogenic CO_2 resource			**76**	**117**	**128**	**143**	**120**	**130**

3.2.2.3 Captured biogenic CO_2 Supply

Of the resources shown in Table 9, the portion available for storage or utilisation depends on the deployment of capture technology and the capture rates that can be achieved. For distributed source, these are considered to be too small for deployment of capture technology to be viable before 2050. Therefore, the availability from the total resource is zero. Similarly, although counted as point sources, biogas combustion is predominantly CHP generators which are also assumed to be too small in scale for CCS deployment. For large-scale solid biomass facilities and biomethane upgrading, deployment in 2025 is assumed to be zero. By 2030, 5% of capacity has carbon capture, this then rises steadily to 50% by 2050. Capturing CO_2 is already practiced at some bioethanol plants, deployment in 2025 is 28% of capacity rising steadily to 50% in 2050. See Appendix 3 for the full list of uptake rates for each year.

Capture rates define how much of the produced CO_2 capture facilities are capable of capturing. For large-scale solid biomass and bioethanol fermentation, this is assumed to be 90%. For biogas upgrading this is 95%[55].

Table 10: Captured CO_2 from sources where deployment of carbon capture is deemed viable ($MtCO_2$/yr).

Source		Type	2025	2030	2035	2040	2045	2050
Point source	Sustainable	Large-scale solid biomass facilities	0	2	6	11	16	23
	Unsustainable	Large-scale solid biomass facilities	0	26	85	140	205	305
	Unsustainable	Bioethanol fermentation	1	2	1	1	1	0
	Sustainable	Biogas upgrading	0	0	1	1	1	2
	Unsustainable	Biogas upgrading	0	0	1	1	2	3
Total biogenic CO_2 captured			**1**	**30**	**94**	**154**	**224**	**334**
Sustainable fraction of biogenic CO_2 captured			**0**	**2**	**7**	**12**	**17**	**26**

The total of 334 $MtCO_2$/yr is in relative agreement with the UCL analysis of several BECCS projections which found a range of between 105 to 795 $MtCO_2$/yr, with the median projection being 400 $MtCO_2$/yr. The sustainable fraction of this work (26$MtCO_2$/yr) is just a small fraction (8%) of the total captured biogenic CO_2.

3.2.3 Direct Air Capture (DAC)

Direct Air Capture (DAC) technologies extract CO_2 from ambient air, where the CO_2 concentration is relatively low (0.04% or 410ppm). Because of the low concentration of CO_2, DAC technologies have a very high energy requirement compared with other carbon capture techniques that tap into sources of CO_2 with greater concentrations. For example, the thermodynamic minimum energy required to extract CO_2 from ambient air is about 250 kWh/tonne CO_2, which is much higher than the theoretical values of about 100 and 65 kWh/tonne CO_2 to capture and concentrate CO_2 from natural gas and coal power plants respectively[56].

DAC has some significant advantages over other Carbon Dioxide Removal (CDR) technologies. It can be located in most land terrain and the capture plants have significantly lower land requirements compared to the biomass cultivation land area for BECCS[57]. However, it must be considered that large amounts of land may be needed to power DAC plants with additional renewable electricity (discussed in more detail in section 6.2.3.). DAC plants also have potential sustainability benefits compared to BECCS, such as reducing acidification and eutrophication compared to biomass growth[6].

[55] Rodin et al, 2020. Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO2 (www.sciencedirect.com)
[56] Science Advice for Policy by European Academies, 2018. Novel carbon capture and utilisation technologies (www.sapea.info)
[57] Creutzig et al, 2019. The mutual dependence of negative emission technologies and energy systems (pubs.rsc.org)

DAC has the potential to provide sustainable CO_2 that will not lead to an increase in atmospheric CO_2 levels, however, this is only possible if it is powered by an emission free energy source. For example, in a study by Terlouw et al, a lifecycle emissions analysis found that if the DAC was powered with grid electricity that has the carbon intensity of the global average, only a carbon removal efficiency of 9% being achieved[58]. This means that for every tonne of CO_2 extracted from the air, approximately 0.91 tonnes were emitted, resulting in a net extraction of only 0.09 tonnes of CO_2. If this is substituted for 100% wind power, then the lifecycle carbon removal efficiency increases to 97%[58]. An efficiency of 100% wasn't achieved due to upstream emissions associated with wind turbine manufacture and transportation of materials to the site. The carbon removal efficiency of DAC is discussed more in section 6.2.

The leading technologies use either a solid or liquid sorbent to extract CO_2 from the air, with the CO_2 in the air attaching to this substance. This modified sorbent will then either be heated directly (like Climework's process) or undergo further processing before being heated (like Carbon Engineering's process), to assist with breaking the bonds they have formed with the CO_2, releasing a pure stream of carbon dioxide for storage or utilisation. This technology is pioneered by three companies: Climeworks, Carbon Engineering, and Global Thermostat. Carbon engineering utilises a liquid alkaline solvent to capture the CO_2, whilst Climeworks and Global Thermostat use a solid sorbent[59,60,61]. As of present day, there are 19 DAC plants in operation, capturing just ~0.01 $MtCO_2$/yr[62]. The largest of which is Climework's Orca plant, which captures a total of 0.004 $MtCO_2$/yr. The two technology types are discussed in more detail in the following section.

3.2.3.1 Liquid vs Solid Sorbent DAC Technologies

Both technologies utilise sorbents, which can either be liquid solvents or solid adsorbents. For the liquid sorbent technology, large fans are used to draw air over a potassium hydroxide solvent. This forms potassium carbonate, which is subsequently converted to calcium carbonate and heated to high temperatures of 900°C to release the CO_2[59,60]. For solid sorbent processes, the air is drawn into modular contactor units, the CO_2 then adsorbs onto the solid adsorbent surface (typically amine based). The CO_2 can then be released by heating the adsorbent to temperatures of circa 100°C[63].

The use of a solid adsorbent requires much lower temperatures[61,63], which adds the advantage that a greater variety of heat sources can be used compared to the higher temperature liquid technology. Such examples include using geothermal heat and waste heat from waste incineration plants Climeworks' Orca[64] and Swiss pilot plants[65] respectively. Carbon Engineering's systems requires higher temperatures of 900°C. This is typically provided by the combustion of natural gas; however, Carbon Engineering has considered substituting this with green hydrogen to help decarbonise their operations. Climeworks' capture units are built from modular contactor units which can be stacked together to achieve a range of plant sizes. Whereas Carbon Engineering has focussed on building larger scale plants at the mega-ton scale.

Carbon Engineering claim capture costs of between \$94-232/tCO_2[59] which are significantly lower than Climeworks' \$600/tCO_2 (€85-€209 and €540 respectively with USD/EU exchange rate of 0.9€/\$). Though caution must be used in assessing manufacturer claimed costs which may be overly optimistic. The Carbon Engineering upper bound cost relates to their baseline scenario, where natural gas is used to heat their existing pilot plant. The lower bound refers to an optimised configuration to provide CO_2 for fuel synthesis, which assumes natural gas is substituted with hydrogen from electrolysis. This removes air separation and CO_2 combustion capture costs[59]. The liquid sorbent lifetime is also significantly greater[63], which helps save on feedstock costs.

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[58] Terlouw et al, 2021. Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources (www.dora.lib4ri.ch)

[59] Keith et al, 2018. A Process for Capturing CO2 from the Atmosphere (www.cell.com)

[60] Socolow et al, 2011. Direct Air Capture of CO2 with Chemicals (www.aps.org)

[61] Ishimoto et al, 2017. Putting Costs of Direct Air Capture in Context (www.american.edu)

[62] IEA, 2021. Direct Air Capture (www.iea.org)

[63] McQueen et al, 2021. A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future (iopscience.iop.org)

[64] Climeworks. Orca: the first large-scale plant (climeworks.com)

[65] Climeworks, 2015. Climeworks builds first commercial-scale direct air capture plant (climeworks.com)

Table 11: Comparison of solid and liquid DAC

Category	Solid DAC	Liquid DAC
Electricity Requirement (kWh)[66]	153-306	206-472
Thermal Energy Requirement (kWh/tCO_2)[66]	944-1,333	2,139-2972
Regeneration Temperature (°C)	80-130	900
Capture Cost (€/tCO_2)*	€540[63]	€85-€209[59]
Modularity	Modular contactor units which can be stacked together to achieve a range of plant sizes	Larger scale plants at the mega-ton scale
Sorbent/Solvent Lifetime	0.5 – 1 years	Entire plant lifetime ~20-30 years

**Claimed costs by manufacturers. Converted from USD/Euros with exchange rate of 0.9€/$.*

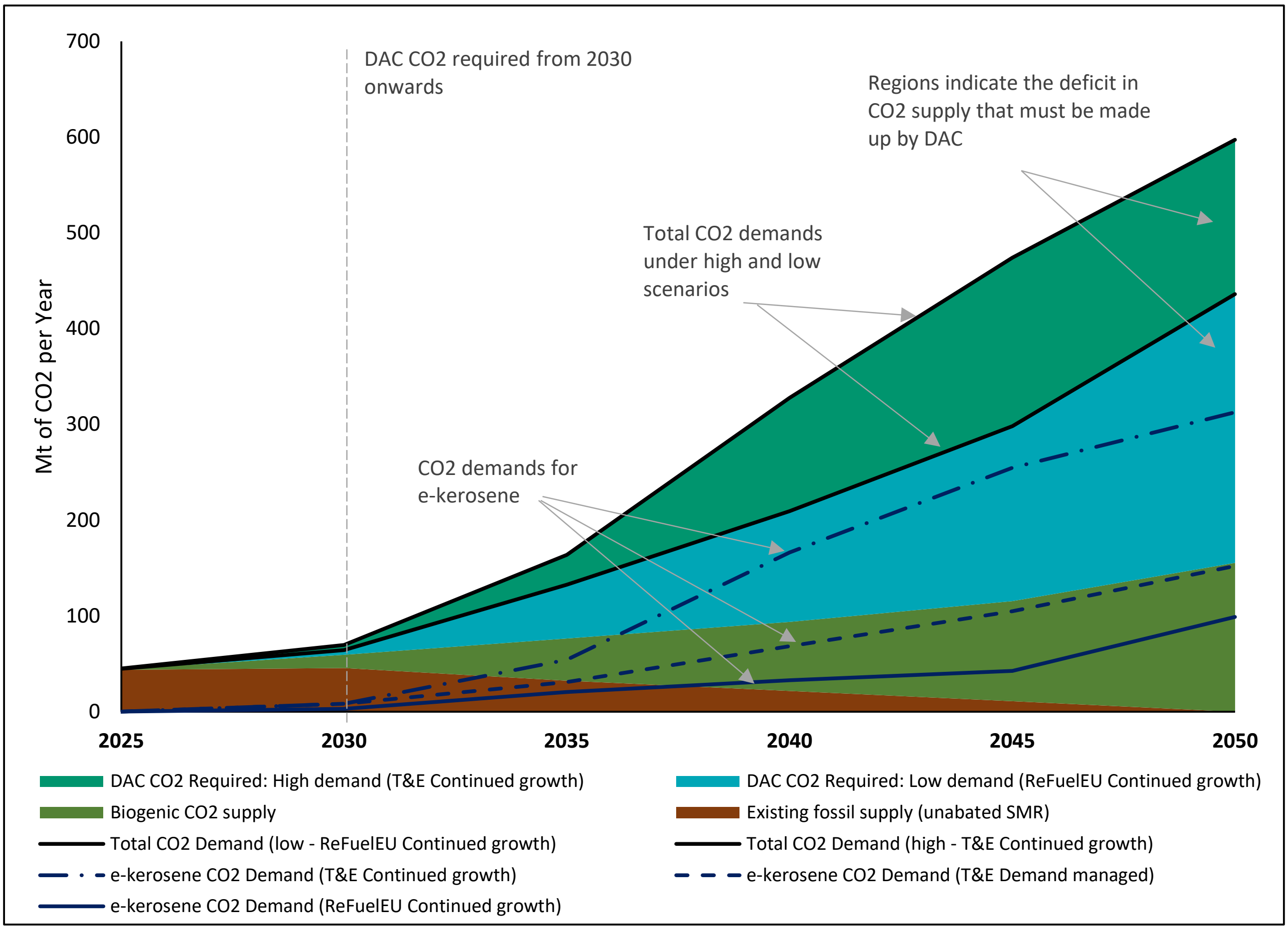
[66] The National Academies Press, 2018. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (www.ctc-n.org)

4. CO_2 BALANCE

Figure 6 and Table 12 summarise the results from the previous sections; both the CO_2 supply and demand projections have been included, from both existing and potential future sources of carbon dioxide. No imports or exports of CO_2 have been considered. From 2030 onwards there is a CO_2 deficit which has been assumed to be fulfilled by DAC CO_2. The DAC required numbers determined here feed into the latter sections of the report.

The three different e-kerosene demand projections result in three CO_2 demands and consequently three total CO_2 demands. The total CO_2 demands, including both the existing and emerging, amount to between 463 to 597 $MtCO_2$/yr by 2050. The existing supply (unabated SMR) reduces to zero by 2050, requiring that the emerging supply options meet the demand. The analysis below shows that between 281 and 442 $MtCO_2$/yr is required from DAC in 2050 to satisfy the increasing carbon dioxide utilisation market. This requires an aggressive scale-up of DAC in Europe, the feasibility of this being achieved is discussed in section 5. The scale-up of DAC is unlikely to happen unless the right incentives are in place to support this.

Figure 6: CO_2 supply mix to 2050 under low and high demand scenarios



In the European Commission's 1.5TECH scenario, the percentage of CO_2 captured that is sent to storage in 2050 from fossil/industrial process, biogenic and DAC is 100%, 54% and 0% respectively. These percentages were used in determining the amount of CO_2 available for utilisation. None of the DAC CO_2 here is sent to storage, though it must be considered that Europe may require further scale-up of DAC beyond that required in these projections for the purpose of storage to achieve negative emissions.

In order to achieve net zero targets, the IPCC highlighted that significant amounts of CO_2 need to be permanently stored. Our assumption is that all CO_2 generated in Europe from fossil fuels is sent to permanent storage in the North Sea where there is sufficient CO_2 storage capacity. This will be facilitated by recent developments such as the Northern Lights project. In addition, in the latest Taxonomy legislation, Europe is expected to phase out fossil fuel power generation and place restrictions on existing and new gas power plants to capture carbon dioxide. Furthermore, a life cycle emission threshold of 100 gCO2/kWh means that gas power generation needs to permanently store carbon dioxide in order to ensure they continue to operate.

The case for storage vs utilisation will depend on the business case for any given project and needs to be considered on a case-by-case basis. This makes the mapping of CO_2 supply to specific demand applications an impossible task and so high-level assumptions are made to simplify the analysis. The factors influencing whether CO_2 is sent to storage or utilised has been discussed in more detail in section 6.3.3.

4.1 DAC CO_2 REQUIRED QUANTITIES VS E-KEROSENE DEMAND

Whether a certain CO_2 source is used for the manufacture of e-kerosene will depend on several factors, many of which are discussed in more detail in section 0. But the results shown here allow us to make an assessment from a resource availability perspective.

The e-kerosene demands amount to between 99 and 313 $MtCO_2$/yr by 2050. The highest demand begins to exceed the combined CO_2 supply from existing fossil and biogenic supply between 2035 to 2040 (see Figure 6). By 2050, this projection of e-kerosene demand will require at least 157 $MtCO_2$/yr from DAC. The two lower demands for e-kerosene could, in theory, be supplied completely by biogenic and fossil CO_2 for every year up to 2050, if other competing demands for CO_2 were ignored.

Due to the growing future potential demands for CO_2, DAC is required from 2030 onwards. The DAC required continues to grow up until 2050 where 281 and 442 $MtCO_2$/yr are required in the low and high demand scenarios respectively. This is greater than the CO_2 demand for e-kerosene, and this is the case for every year up until 2050. Should these DAC required numbers be achieved (assessed in section 5), and ignoring competing uses for CO_2, DAC may supply all of the CO_2 demands for e-kerosene.

Figure 7: DAC CO_2 required quantities vs e-kerosene demand

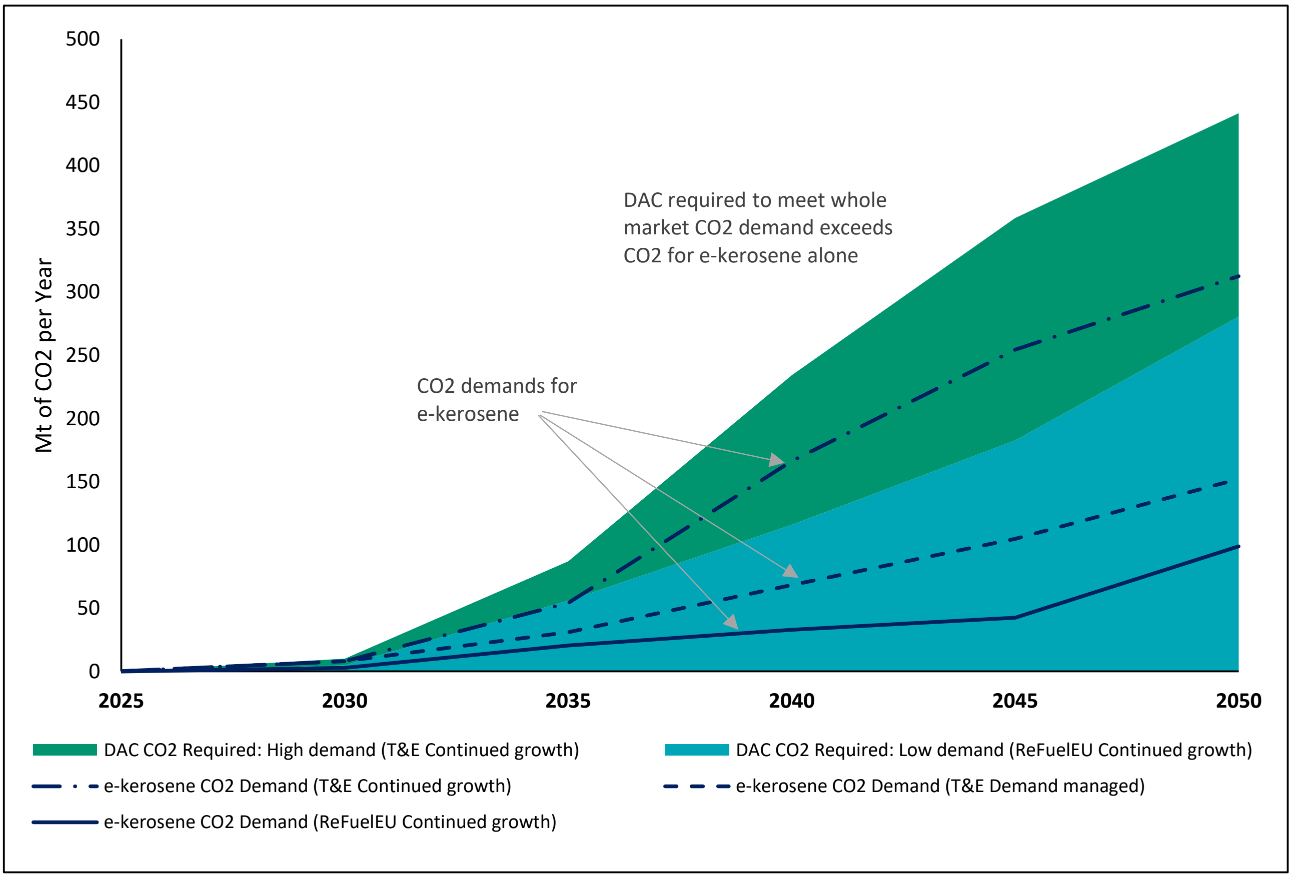


Table 12: CO_2 balance sheet ($MtCO_2$/yr)

		2025	2030	2035	2040	2045	2050	Notes
CO_2 Demand	Existing Demands	45	50	55	60	67	74	
	Emerging: T&E Continued growth	0	20	109	267	407	523	
	Emerging: T&E Demand managed	0	20	86	176	278	403	
	Emerging: ReFuelEU Continued growth	0	15	78	149	231	363	
	Total CO_2 Demand (low - ReFuelEU Continued growth)	**45**	**64**	**133**	**210**	**298**	**436**	
	Total CO_2 Demand (high – T&E Continued growth)	**45**	**70**	**164**	**328**	**474**	**597**	
CO_2 Captured	Existing fossil supply	44	46	32	22	11	0	Assumed supply of CO_2 from unabated SMR operations in the hydrogen production sector. Assumes decline of CO2 from "grey hydrogen" after 2030 as a result of increasing deployment and production of "green or blue hydrogen".
	Captured biogenic	1	30	94	154	224	334	
	Captured sustainable biogenic	0	2	7	12	17	26	
	Captured fossil/process	0	24	48	72	96	120	Uses the 2050 captured value from 1.5TECH scenario. Assumed linear trajectory from 2030 onwards.
CO_2 Stored	Biogenic storage	1	16	50	82	120	178	2050 figure based on 1.5TECH scenario. Assumed % of captured biogenic CO_2 sent to storage stays consistent with % in 2050 (54%).
	Fossil storage	0	24	48	72	96	120	As per 1.5TECH scenario, all fossil CO_2 is sent to geological storage. Discussed further in section 7.
	DAC storage	0	0	0	0	0	0	Assumed zero DAC CO_2 stored as per 1.5TECH scenario.
CO_2 Supply	Existing fossil supply	44	46	32	22	11	0	
	Utilised biogenic	1	14	44	72	105	156	
	Utilised fossil/process	0	0	0	0	0	0	As per 1.5TECH scenario, all fossil CO_2 is sent to geological storage. Discussed further in section 7.
	Total CO_2 Supply:	**45**	**59**	**76**	**94**	**115**	**156**	
DAC CO_2 Required	Low (ReFuelEU Continued growth)	0	5	56	116	183	281	DAC CO_2 balances out the deficit between CO_2 supply and demand.
	High (T&E Continued growth)	0	10	87	234	359	442	

5. DIRECT AIR CAPTURE SCALE-UP

As per the results in the previous section, to fulfil the CO_2 deficit between whole market CO_2 supply and demands, the ReFuelEU Continued growth scenario requires 281 $MtCO_2$/yr of DAC CO_2 and T&E Continued growth requires 442 $MtCO_2$/yr (hence force referred to as low and high demands respectively). This section provides insight into the feasibility of this scale-up being achieved within Europe.

In the short-term, the scale-up of DAC capacity can be determined with a reasonable degree of confidence. The development of DAC plants takes several years from conception through to commissioning. Therefore, with an understanding of the DAC projects which are active today, and those which are in planning to be built, one can make a reasonable estimate of the DAC capacity that will be available over the next several years.

However, predicting the long-term growth of this novel, immature technology cannot be achieved with any high degree of confidence. Its scale-up will be highly reliant on the policy and regulation landscape of the future. Insight can still be drawn from the latest views of industry, and parallels can be drawn against the scale-up rates that have been historically achieved by other, similar technologies.

This section has therefore been split between short-term scale-up, where there is a reasonable degree of confidence that these capacities will be achieved, and long-term scale-up where the picture is more uncertain.

5.1 SHORT-TERM: 2025 AND 2030

There are three key DAC manufacturers: Climeworks, Carbon Engineering and Global Thermostat. In Table 13 below, the major projects from these manufacturers (both currently operational and those in planning) have been detailed. Further DAC plants exist, but their capacity is small in comparison and so have not been listed here.

The total global capacity of DAC is expected to be in the region of 1.6-2.6 $MtCO_2$/yr by 2026. When including Norway (which could feasibly transport CO_2 to EU-27+UK countries), approximately 1.1-2.1 $MtCO_2$/yr of capacity will be placed in Europe.

Considering only EU-27+UK countries, just one major DAC plant is in planning: Storegga and Carbon Engineering's plant in Scotland is expected to have a capacity of between 0.5 and 1 $MtCO_2$/yr. This single plant will be used for storage of CO_2, meaning that there is no planned major utilisation capacity in EU-27+UK countries. Several small DAC utilisation demonstration plants exist in EU-27+UK countries, but their combined capacity is less than 0.001$MtCO_2$/yr[67], and so will not have a substantial impact on meeting the DAC required demands set out in Table 12.

The planned Norwegian plant constructed by Climeworks should have a capacity of 0.08$MtCO_2$ for utilisation, some of which could be transported to the EU27+UK. This is the biggest DAC utilisation project, the combined capacity of all other utilisation plants amounts to 0.0052 $MtCO_2$/yr, bringing the global capacity to 0.0852 $MtCO_2$/yr.

As detailed in section 4.1, the amount of DAC required in 2030 is between 5 to 10 $MtCO_2$/yr, therefore significant investment will be required in the next few years to introduce more DAC projects to the European pipeline to scale-up to the potential 2030 demands.

[67] Gordon, 2022. The birth of the carbon removal market (www.energymonitor.ai)

Table 13: Major DAC projects in operation and in planning

Company	Project	Location	Year of operation	Capacity (MtCO2/yr)	Utilisation or Storage
Climeworks	Pilot plants	Switzerland[65,68]	2017	0.0009	Utilisation
		Switzerland[69]	2018	0.0006	Utilisation
		Italy[70]	2018	0.00015	Utilisation
		Iceland[64]	2021	0.004	Storage
	Producing e-fuel for Norsk e-fuel[47]	Norway	2026	0.08*	Utilisation
Carbon Engineering	Pilot Facility to produce e-fuel[59]	Canada	2015	0.000365	Utilisation
	Innovation Centre to produce e-fuels[71]	Canada	2021	0.001	Utilisation
	DAC1[72]	USA	2024	0.5**	Storage
	Storegga[13].	UK	2026	0.5-1	
	Carbon Removal[73]	Norway	N/A	0.5-1	
Global Thermostat	Research and Development[69]	United States	2010	0.0005	N/A
	Research and Development[69]	United States	2013	0.001	N/A
	HIF Haru Oni e-fuels[74]	Chile	2022	0.00219	Utilisation

**Producing 12.5 Ml/yr of e-fuel by 2024 and 25 Ml/yr by 2026. Converted to CO_2 utilisation by assuming a fuel density of 800 kgm^{-3} and 100% conversion of CO_2 to fuel.*

***Expected to expand to 1 Mt/yr in the near future.*

5.2 LONG-TERM: 2035 TO 2050

Studies exist providing estimates for the required scale-up of negative emissions technologies (NET) to achieve climate targets[75], and recently have provided modelling approaches to assessing the potential role for DAC among other NET technologies[76]. Uncertainty remains regarding the scale-up of DAC within the current policy environment and the contribution that can realistically be achieved by a relatively novel technology. This work has attempted to assess the feasibility of DAC from four angles: to compare the DAC requirements with

[68] Climeworks. Capricorn (climeworks.com)
[69] IEA, 2022. Direct Air Capture 2022 (www.iea.org)
[70] Climeworks, 2018. Climeworks launches direct air capture plant in Italy (climeworks.com)
[71] Carbon Engineering, 2021. Carbon Engineering Innovation Centre Update (carbonengineering.com)
[72] IEA. CCUS around the world – DAC 1 (www.iea.org)
[73] Carbon Engineering, 2021. New partnership to deploy large-scale Direct Air Capture in Norway (carbonengineering.com)
[74] Global Thermostat, 2021. Global Thermostat to Supply Equipment Needed to Remove Atmospheric CO2 for HIF's Haru Oni eFuels Pilot Plant (globalthermostat.com)
[75] IPCC, 2018. Global Warming of 1.5°C, Summary for Policymakers (www.ipcc.ch)
[76] Realmont et al, 2019. An inter-model assessment of the role of direct air capture in deep mitigation pathways (www.nature.com)

the views of experts[77]; to compare the required scale-up rate with that historically achieved by other technologies; to determine the future cost of DAC CO_2 to see if it can ever compete with other sources of CO_2; and finally to assess whether the energy requirements for DAC are realistic.

5.2.1 Expert views

Table 14 shows a range of expert views gathered by Shayegh et al (2021). The table shows estimates of DAC capacity in Europe under two scenarios: Policy as usual (PAU) and climate policies consistent with limiting global warming to 2°C (2DC), requiring deployment of negative emissions technologies from 2030 onwards. Eighteen experts participated in the study, selecting which technology (solid sorbent or liquid solvent) they thought would be dominant. They provided a low, medium and high (10th, 50th, and 90th percentiles) assessment of capacity by 2050, for either solid sorbent or liquid solvent, the estimates were aggregated, and the median capacity taken. The experts gave estimates of global capacity, of which 16% is expected to be located in Europe.

Table 14: Comparison of demand with expert assessment of European DAC capacity ($MtCO_2$/yr) in 2050.

Source	Scenario	Low	Medium	High
Expert assessment	PAU	8	38	214
	2DC	30	271	938
Ricardo DAC required	Low demand	281		
	High demand	442		

Under the current policy assumptions, even the median high estimate for DAC capacity falls short of our low demand DAC requirement. This suggests that it is unlikely that the DAC requirements can be achieved without a change in policy towards DAC. Our low demand DAC requirement estimate is comparable to the medium estimate under the 2DC scenario. The DAC capacity required under the high demand scenario is exceeded only by the high estimate for the 2DC scenario.

5.2.2 Growth rates

Even in a world with aggressive climate policies, factors other than economics can slow the growth of low-carbon technologies. The speed at which technologies scale is a function of institutional, behavioural, and social factors which can be difficult to model and to predict[78].

The scaling of new technologies will be inhibited by lack of experience and uncertainties surrounding policies and regulation. Public perception, political support and media coverage will also affect the pace of growth. CCS for instance, may experience public opposition due to the perceived risks associated with transportation and storage of CO_2.

It can be useful to study the dynamics of historical technologies as they were exposed to all the complex interdependencies that arise when attempting to scale in the real world. It is important to note that historical technological growth is not a confident predictor of future evolution of new technologies, though it can provide a useful reference point.

The growth rate (or sometimes referred to as a diffusion rate) is the average annual percentage that the total installed capacity of a technology has grown over a set period. In this case, the total installed CO_2 capture capacity of DAC for every year under the DAC required projections (detailed in Table 12: CO_2 balance sheet ($MtCO_2$/yr) has been assessed. Comparison has been made to other technologies such as the growth of wind power, where the total installed electrical capacity (in MW) has been used to determine growth rate.

[77] Shayegh et al, 2021. Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey (www.frontiersin.org)

[78] Lyer et al, 2015. Diffusion of low-carbon technologies and the feasibility of long-term climate targets (www.sciencedirect.com)

Significant growth in capacity will be required to achieve the DAC demand requirements in the low and high demand scenarios set out in Table 12. Table 15 shows the annual capacity growth rates required to meet the demand in 2030, 2035, 2045 and 2050. This assumes a starting capacity in the EU-27+UK of 1MtCO$_2$/yr in 2025, and growth from that year onwards.

Table 15: Annual growth rates required in each 5-year period to meet target.

Scenario	2025 - 2030	2030 - 2035	2035 - 2040	2040 - 2045	2045 - 2050
Low DAC required	37%	63%	16%	10%	9%
High DAC required	59%	54%	22%	9%	4%

In both scenarios, the highest rates of growth are required in the first 10 years. The low scenario requires a growth of 37% per year from 2025 to 2030, increasing to 63% per year from 2030 to 2035. The high demand scenario increases capacity at a higher rate initially but falls from then on. High growth, which requires a greater rate of scale-up in the initial years, reduces the required growth rates required in the final 10 years leading to 2050.

Table 16 below shows the capacity of new DAC plants that will on average have to be built every year in order to meet the 5-year targets. The low DAC required projection (for the ReFuelEU Continued growth scenario) has a steady increase in average new capacity up to 2050, whereas the high DAC required (for the T&E Continued growth scenario) requires the greatest new capacity building in the 2035 to 2040 interval. This is shown graphically in Figure 8 and Figure 9.

Table 16: Average newly installed capacity required each year for each 5-year interval to meet target (MtCO$_2$/yr)

Scenario	2025 - 2030	2030 - 2035	2035 - 2040	2040 - 2045	2045 - 2050
Low DAC required	1	10	12	13	20
High DAC required	2	15	29	25	17

Table 17 shows the effect of delaying capacity growth, on the average annual growth rates required to achieve the DAC capacity requirements by 2050. Delaying scale up until 2030, increases the required annual growth rate by around 30%. Delaying by 10 years increases the required annual growth rate by around 80%. Each 5-year delay in growth also decreases the likelihood of achieving the target in the next 5 years. For example, achieving the 2035 target, starting from 2030, requires an annual growth rate of 124% in the low and 145% in the high demand scenarios respectively. Delaying growth until 2035, increases the required growth rates further.

Table 17: Average annual growth rates to achieve DAC required demands. Assuming growth from various start years.

Scenario	2050 target - 2025 start	2050 target - 2030 start	2050 target - 2035 start	2035 target – 2030 start	2040 target – 2035 start
Low DAC required	25%	33%	46%	124%	159%
High DAC required	28%	36%	50%	144%	198%

Figure 8 and Figure 9 further demonstrate the rate of growth required by DAC under the two scenarios. The left-hand side chart shows the total installed capacity of DAC required each year to meet the 5-yearly DAC requirements in Table 12 (solid lines), with steady annual growth trajectories that the meet 2050 target (coloured dashed lines), and a steady annual growth of 20% (black dashed line) that fails to meet the 2050 target. Total cumulative installed capacity refers to the total amount of DAC capacity that has been built since

2025 (both new and old plants). This has not accounted for replacing plants that have exceeded their economic life before 2050. Average new capacity refers to the capacity of new plants which need to be built each year to meet the 5-year intervals (detailed in Table 16). All steady annual growth projections fail to achieve the 5-year intervals DAC demand targets until 2050. Each delay of 5 years to the starting year, significantly increases the steady growth rate required.

Figure 8: Cumulative total installed capacity (left) and average newly installed capacity per year (right) for low demand scenario.

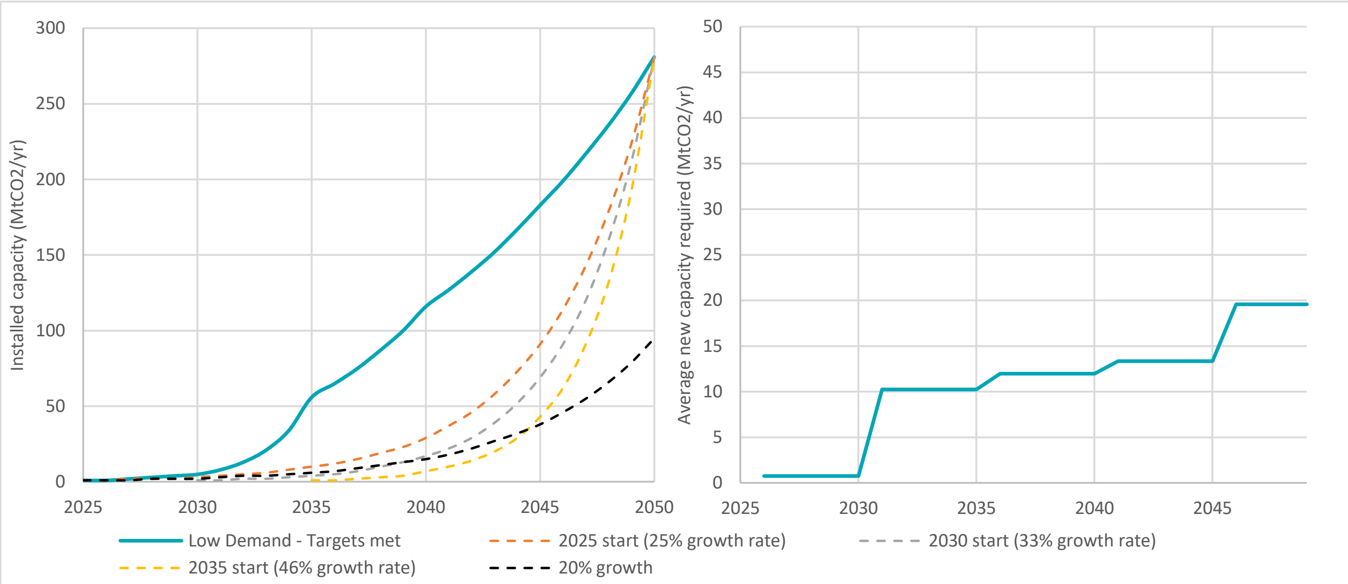


Figure 9: Cumulative total installed capacity (left) and average newly installed capacity per year (right) for high demand scenario.

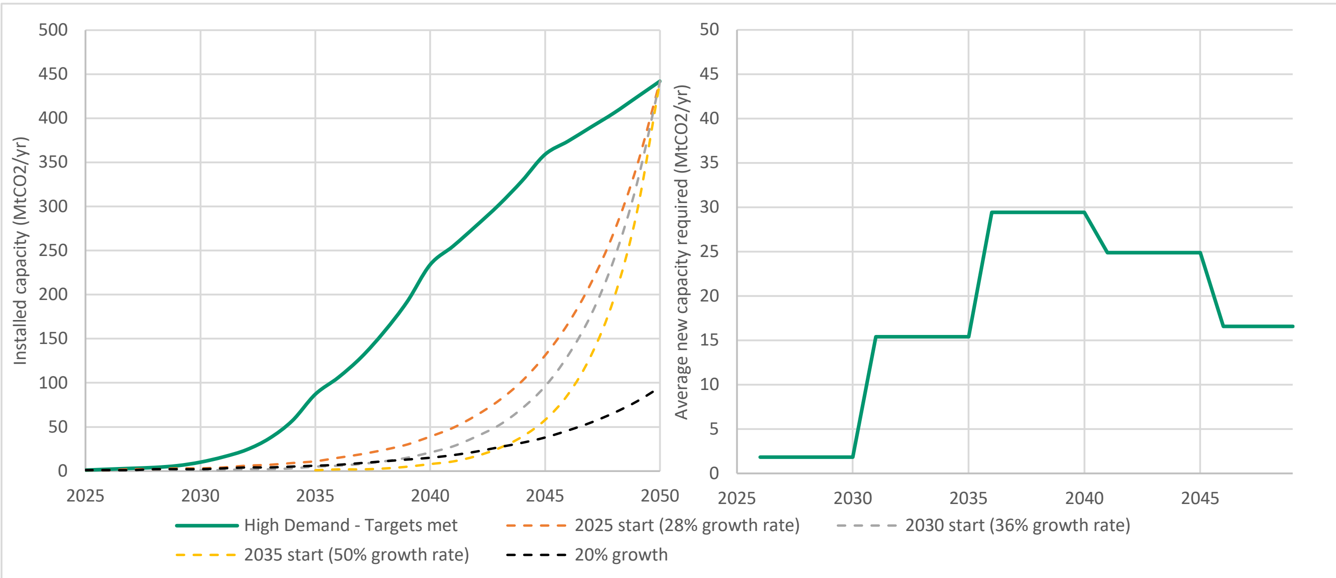
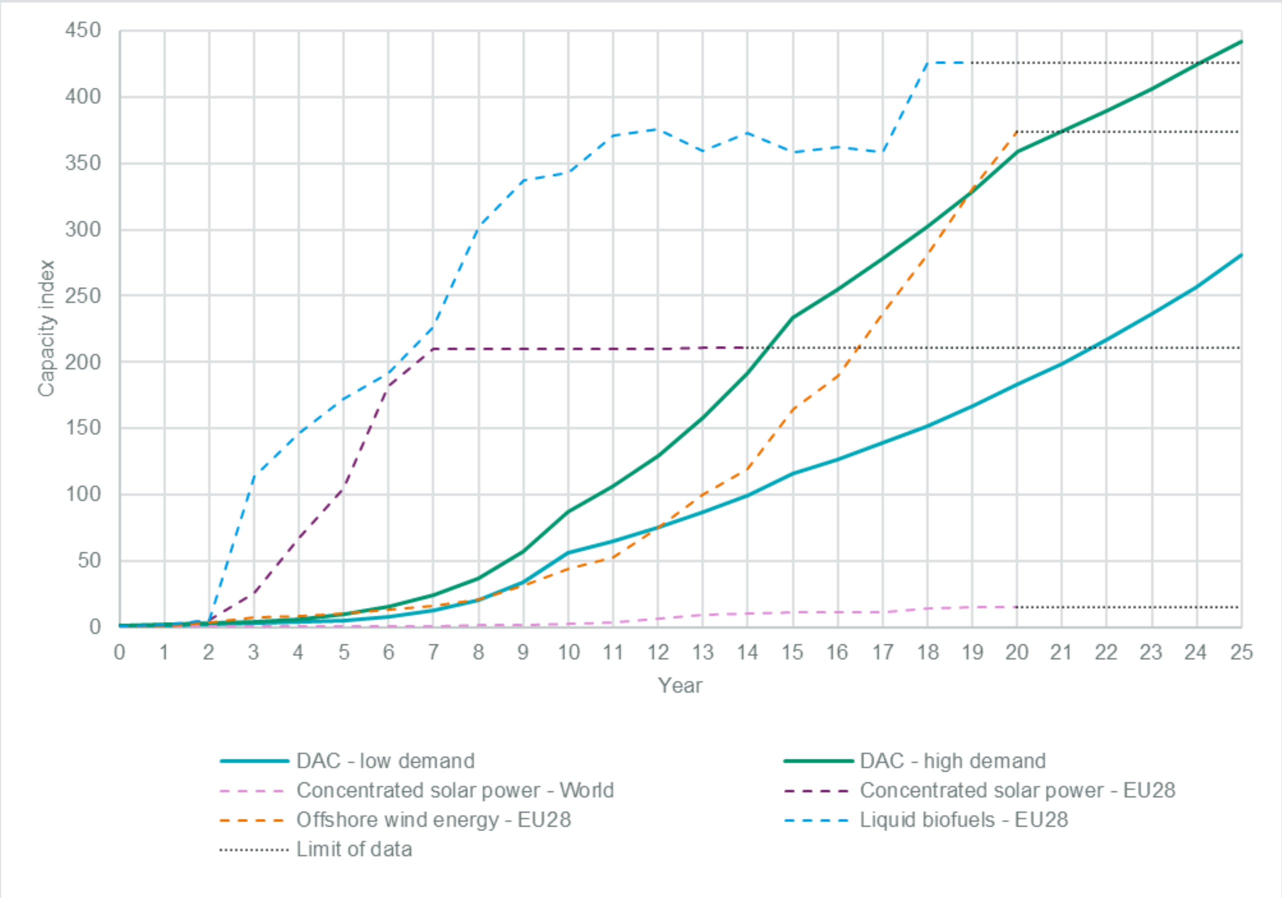


Figure 10 shows a comparison of capacity growth for various renewable technologies (based on available capacity data from 2000 to 2020), and DAC in the low and high demand scenarios. Capacities have been normalised, such that at year 0 all technologies regardless of their total installed deployment have a capacity of 1. Comparator technologies were selected on the basis of having relatively low or zero deployment at the time of the earliest available data, in 2000. Technologies with significant capacity in 2000 generally had lower growth rates. Taking wind energy as an example, onshore wind capacity in EU-27+UK in the year 2000 was 12.6 GW, compared to only 67 MW for offshore wind, so offshore was chosen as the technology to use for comparison. The average annual growth rate over the next 20 years for these two wind technologies was 14%

for onshore wind and 34% for offshore wind. An exception to this is grid-scale solar PV, which had a global capacity of 759 MW in 2000 but nevertheless grew at an average of 41% per year for the next 20 years.

Figure 10: Indexed capacity growth for various technologies and required of DAC to meet targets. Renewables data from IRENA[79].



Year 0 represents various start years. For DAC, this is 2025. For the remaining technologies, year 0 is the first year any significant capacity exists. For offshore wind and CSP (world), some capacity existed in 2000. For CSP in EU-27+UK, there was no existing capacity until 2006. Year 0 for liquid biofuels is 2001.

Growth of onshore wind and liquid biofuels in EU-27+UK is representative of growth seen throughout the world over the same time period. By the time significant CSP capacity was present in the EU, around 300 MW had been installed elsewhere. Therefore, there is a significant difference between the growth rate of CSP within EU-27+UK and in the world as a whole.

Liquid biofuels show the highest growth in capacity of all technologies through all years. By year 5 capacity has increased by 172 times and by year 10 capacity has increased by 343 times. CSP in the EU shows a similar level of growth initially but plateaus at year 7 (2013). Offshore wind grows at a similar rate to that required of DAC in both the low and high demand scenarios, until year 6. At which point, DAC capacity under the high demand scenario increases at a greater rate. Offshore wind growth follows DAC under the low demand scenario until year 12 but grows at a higher rate thereafter, exceeding DAC growth under the high demand scenario by year 20 (the latest available year for offshore wind capacity data, 2020).

Table 15 gives a further comparison of capacity growth rates for each technology in Figure 10. Growth rates shown are the average annual growth rates over the first three 5-yearly periods. Also shown is the plant capacity at year 0 (start capacity) and year 15 (end capacity), and the average annual growth rate over the whole 15-year period.

[79] IRENA, 2022. Installed electricity capacity (MW) by Country/area, Grid connection, Technology and Year (pxweb.irena.org)

Table 18: Comparison of average annual growth rates in 5-yearly periods.

Technology	Start capacity (MW or $MtCO_2$/yr)	1st period	2nd period	3rd period	End capacity (MW or $MtCO_2$/yr)	Average annual growth
CSP – EU-27+UK	11	154%	15%	0%	2,321	47%
Offshore wind	67	59%	34%	30%	10,994	41%
Liquid biofuels	5	180%	15%	1%	1,792	48%
DAC - low demand	1	37%	63%	16%	116	37%
DAC - high demand	1	59%	54%	22%	234	44%

Liquid biofuels and CSP experienced the highest growth rates in the first 5-year period, both more than doubling in capacity each year. Offshore wind and DAC under the high demand scenario experience equal growth. The lowest growth of any technology is DAC under the low demand scenario.

In the second 5-year period. Capacity growth for liquid biofuels and CSP has reduced significantly, and is now exceeded by offshore wind and DAC under both the low and high demand scenarios. The growth rate for offshore wind has reduced, as has the growth rate for DAC under the high demand scenario, to a lesser extent. As opposed to all other technologies, the growth rate for DAC under the low demand scenario must increase in order to meet the demand in year 10.

By the third 5-year period, CSP and liquid biofuel capacity has plateaued. Growth rates for offshore wind, and DAC under both scenarios have fallen. Offshore wind experiences the most sustained growth, whereas DAC growth falls more significantly. Over the whole 15-year period, average annual growth rates for the technologies are comparable. CSP and liquid biofuels experience the highest growth over the period, albeit taking place almost entirely in the first 10 years. DAC under the high demand scenario has higher overall growth than offshore wind over the 15 years, however, offshore wind growth is more sustained and (as shown in Figure 10) will exceed DAC by year 20. DAC under the low demand scenario experiences the lowest growth of all the compared technologies, but is unique in increasing the rate of growth in the second 5-year period. Giving this pathway additional time to increase the rate of capacity growth through the first growth period.

The comparison of growth rates between technologies shows that the previous technologies have achieved the growth rates required of DAC in both the low and high demand scenarios. The pattern of growth for offshore wind most closely resembles both scenarios. In the event of DAC growth being delayed, CSP and liquid biofuels show that high-capacity growth has been demonstrated over a relatively short period of time. Some judgement is required regarding how comparable these technologies are to DAC. Solar PV was excluded from the comparison, due to the modular nature of the technology. This was judged to be incomparable to DAC plants where each installation is expected to be 'monolithic' in the case of liquid solvent technology type, though the solid sorbent technology developed by Climeworks is claimed to be modular. CSP is more comparable, however, but 400MW of capacity already existed outside of the EU in year 0 of the comparison in Figure 10.

5.2.3 Levelised cost of capturing carbon dioxide[80]

The current cost of capturing CO_2 via DAC is relatively high, when compared to EU ETS prices and the current cost of jet kerosene. Climeworks claim the current cost of DAC CO_2 to be 445-535 €/tCO_2[63]. In comparison, EU ETS carbon permit prices have peaked at €98.49 per tonne[81]. The current price of Jet-A1 in the UK is €776 per tonne[82]. Four tonnes of CO_2 are required for every tonne of e-crude, of which approximately 50% may be

[80] All costs expressed in 2021 values, where required. OECD, 2022. Exchange rates (data.oecd.org). The World Bank, 2022. Inflation, GDP deflator (annual %) - European Union (data.worldbank.org).

[81] Trading Economics, 2022. EU carbon permit prices (tradingeconomics.com)

[82] Jet-A1-fuel, 2022. Jet A1 price United Kingdom (jet-a1-fuel.com, accessed 08/03/2022)

suitable for e-kerosene. Therefore, the cost of DAC CO_2 feedstock alone required for e-kerosene manufacture exceeds the price of conventional fossil kerosene.

Falling prices are common with the introduction and increased learning of new technologies and products. A notable example is the fall in levelised cost of energy (LCOE) for solar PV, from €344/MWh in 2010 to €51.5/MWh in 2020[83]. Cost reductions are expressed in learning rates, giving the percentage fall in cost for every doubling in capacity. Table 19 shows learning rates for a range of technologies (other than renewable generators). Typical rates range between 11% and 30%.

Table 19: Learning rates for technologies, excluding renewable generators[63].

Technology	Learning rates
Lithium-ion batteries (electronics)	30%
LED A lamps	18%
Hydraulic fracturing	13%
Flue gas desulfurization systems	11%
Natural gas turbines	15%

Amongst renewable power generators, the effect of improving capacity factors for generators can be seen by a comparison of learning rates for total installed cost and levelized cost of energy. From 2010 to 2020 CSP and onshore wind experienced the greatest increase in capacity factor, increasing by 40% and 31% respectively. Accordingly, there is a larger difference between learning rates for total installed cost and LCOE. The smaller difference for Solar PV shows that the reduction in LCOE was largely driven by the fall in installation costs.

Table 20: Learning rates for total installed cost and LCOE of renewable generators[83].

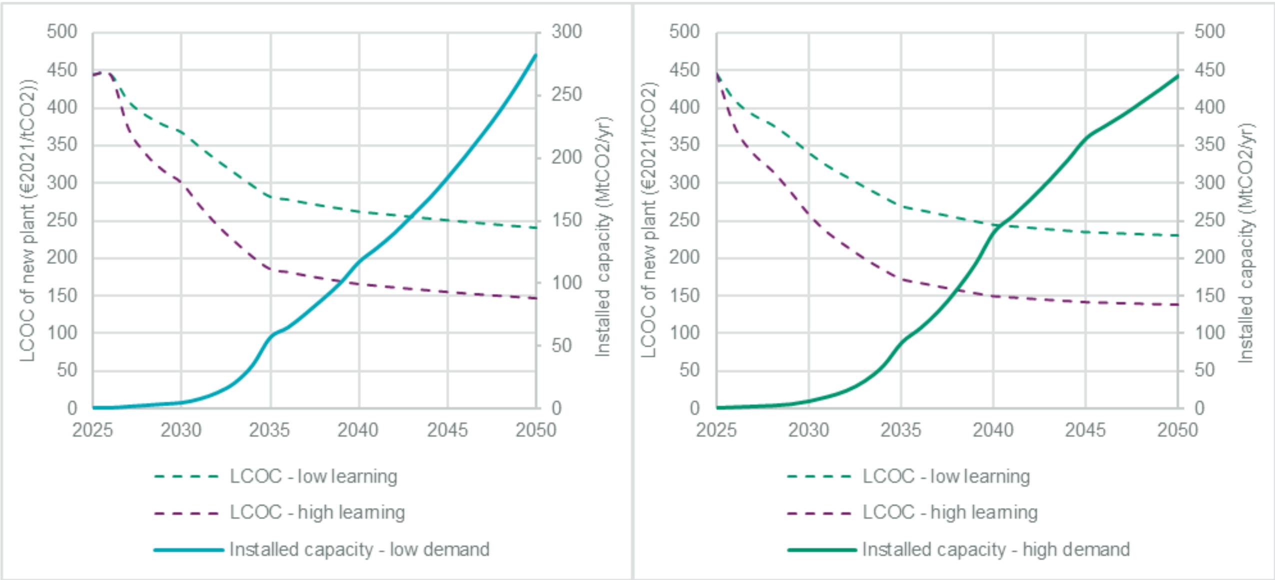
Technology	Total installed cost	LCOE
Utility-scale solar PV	34%	39%
CSP	22%	36%
Onshore wind	17%	32%
Offshore wind	9%	15%

Applying learning rates to the DAC demand scenarios for this report, it is possible to estimate the levelized cost of capturing carbon dioxide (LCOC) under these scenarios, using a simple model. Following the method set out by McQueen et al[63], the LCOC in year 0 is \$500/tCO_2 comprising \$400/tCO_2 for total installed cost (CAPEX) and \$100/tCO_2 for operational expenditure (OPEX). Respectively, this equates to €355.79/tCO_2 and €88.95/tCO_2 for installed cost and OPEX. Learning is applied to total installed cost only, OPEX remains constant throughout the model. All reduction in LCOC is therefore assumed to be as a result of reducing total installed cost. Learning rates are 10% (low learning) and 20% (high learning), comparable to learning rates for the total installed cost of renewable generators (other than solar PV).

Figure 11 shows the results of the model, both scenarios show the greatest reductions in LCOC occur in the first 10 years of growth. During this period capacity doubles 6 times in the low demand scenario and 7 times in the high demand scenario. Onwards, reduction in cost declines as growth slows. By 2050, there is little difference in LCOC between the low demand and high demand scenario. Costs for new plant in 2050, following a low rate of learning are €240/tCO_2 in the low demand scenario and €230/tCO_2 in the high demand scenario. Following a high rate of learning, costs are €147/tCO_2 and €138/tCO_2.

[83] IRENA, 2021. Renewable Power Generation Costs in 2020 (www.irena.org)

Figure 11: Levelised cost of capturing carbon dioxide (LCOC) from newly installed DAC plant in each year. Using Ricardo DAC required estimate scenarios.



The results in Figure 11 give the LCOC of DAC plants newly installed in that year. The average cost of carbon dioxide captured in each year will be higher than the LCOC, accounting for the contribution of older, more expensive, DAC plants. In a scenario where there is no need to replace plant (economic life equals or exceeds 25 years), the average cost for capturing carbon dioxide in 2050 is €270/tCO_2 and €258/tCO_2 for the low and high demand scenarios, following low learning rates. Following high learning rates, the average LCOC in 2050 is €177/tCO_2 and €165/tCO_2.

Table 21 gives a comparison of LCOC provided during a survey of experts[77], and the results from modelling shown in Figure 11. Expert views were given on the basis of net carbon dioxide removal (carbon captured less carbon emitted during the capturing process), resulting in higher costs than gross carbon dioxide removal. The ratio of gross to net carbon captured is dependent on the source of electric and thermal energy required for the process. For a mix of low carbon and natural gas sources, the ratio ranges from 0.63 (solid sorbent DAC, with natural gas electricity and heat) to 0.99 (liquid solvent DAC, with solar power and hydrogen heating)[66]. To convert estimates of net LCOC to gross LCOC, an averaged ratio of 0.84 was used. The table also shows the results of applying 10% and 20% learning rates to the median global DAC capacity from the expert assessments, following the method in McQueen et al[63].

Table 21: Comparison of expert assessment of levelized cost of capturing carbon dioxide (LCOC) with results of Ricardo estimate, for new plant in 2050. Costs in €$_{2021}$ per gross tonne of CO_2 captured.

Source	Scenario	Low	Medium	High
Expert assessment	PAU - Liquid	101	206	861
	PAU - Solid	118	252	473
	2DC - Liquid	93	160	333
	2DC - Solid	58	155	518

Source	Scenario	High learning	Low learning
Expert assessment	2DC – Global capacity	130	217
Ricardo estimate	Low demand	147	240
	High demand	139	230

5.2.4 Energy requirements

The largest energy requirement for DAC is heat. Power is required to drive fans and pumps, but a significantly larger amount of energy, as heat, is required to regenerate the material used for capture. For liquid solvent technologies, temperatures up to 900°C are required to convert $CaCO_3$ to high-purity CO_2. This is achieved by burning natural gas (or possibly hydrogen) for direct heating or to raise steam. Solid sorbent technologies require much lower temperatures, regeneration can be achieved at only 100°C. Consequently, overall energy demands are lower for solid-sorbent DAC plants than liquid solvent plants. Solid sorbent also has the advantage of potentially making use of low-grade waste heat sources.

Table 22 shows the power and heat requirements for the two DAC options, based on estimates of current energy demands. The thermodynamic minimum energy requirement for separating CO_2 from the ambient air is 250kWh/tCO_2[56]. The current energy demands for DAC are closer to 10 times this theoretical minimum. Achieving an energy efficiency close to this minimum is very unlikely, however, there could still be space for process efficiency improvements as DAC technology advances.

Table 22: Energy requirements for liquid solvent and solid sorbent DAC options[66].

DAC type	Power required (kWh/tCO_2)		Heat required (kWh/tCO_2)	
	Low	High	Low	High
Liquid solvent	206	472	2,139	2,972
Solid sorbent	153	306	944	1,333

The net carbon removal from DAC (carbon captured less carbon emitted during capture) is dependent on the energy sources. Power requirements would ideally be provided by low carbon generators. Heat for solid sorbent DAC plants could conceivably also be provided by low carbon electricity. The high temperature requirements for liquid solvent DAC plants favours combustion of a fuel, which could be natural gas or hydrogen.

Given the 2050 low and high DAC required estimates of 281 and 442 MtCO2/yr determined in section 4, the power capacity and land area requirements for power generation technology have been estimated below. Table 23 shows generation capacities required to supply DAC plants with power only or power and heat. Results are provided for fulfilling the DAC power requirements only, or power and heat by electricity. The power and heat requirements for calculation, are the average of the low and high demands in Table 22. Electricity based heat is either resistance heating (assuming near 100% efficiency) for solid sorbent, or H_2 via electrolysis for liquid solvent. Calculations assume DAC requirement is fulfilled by one type of DAC plant and one type of power generator. Capacities are determined by EU-27+UK average load factors in 2019 for each generator[84]. As per previous sections, the low and high DAC required demands correspond to that generated by ReFuelEU Continued growth and T&E Continued growth aviation fuel scenarios respectively. The power and land area requirements for the T&E Demand managed scenario have been provided in Appendix 4 T&E Demand managed scenario DAC power and land area requirements.

Table 23: Generation capacity (GW) required for DAC. Heat for liquid solvent provided by H_2 from electrolysis.

GW	Scenario	Solar PV	Onshore wind	Offshore wind	Nuclear
Power only	Liquid solvent - low demand	94	45	29	14
	Solid sorbent - low demand	64	30	20	9
	Liquid solvent - high demand	148	71	46	22
	Solid sorbent - high demand	100	48	31	15

[84] IRENA, 2022. Electricity generation (GWh) by Country/area, Technology, Grid connection and Year (pxweb.irena.org)

GW	Scenario	Solar PV	Onshore wind	Offshore wind	Nuclear
Power and heat	Liquid solvent - low demand	1,211	577	374	178
	Solid sorbent - low demand	380	181	117	56
	Liquid solvent - high demand	1,906	908	589	279
	Solid sorbent - high demand	598	285	185	88

Due to lower load factors, solar PV requires greater capacity than any other power generator type. The greatest power demand is liquid solvent DAC under the high demand scenario. Therefore, of all the scenarios in Table 23, the greatest capacity requirement is liquid solvent DAC (with heat provided by electrolysis H2) under the high demand scenario, with power provided by solar PV. The lowest power demand is solid sorbent under the low demand scenario, with heating provided by natural gas. Although "power only" scenarios result in lower power and capacity demands, use of natural gas for heating could reduce the net carbon dioxide removals of the plant if the CO_2 from the natural gas combustion is not captured. The additional capacity required in EU-27+UK represents a growth of 43-1272% for solar PV, 17-515% for onshore wind, 79-2364% for offshore wind or 8-245% for nuclear generation.

Solar PV and onshore wind have significant land area requirements. For the purposes of calculation, solar PV has a higher power density than onshore wind (6.63 W/m^2 for solar PV and 1.84 W/m^2 for onshore wind)[85]. However, it should be noted that the onshore wind area is the nominal land area over which the wind farm is spread. The presence of the wind turbines does not necessarily render the entire area unavailable for other uses. Table 24 shows the land area required for solar PV or onshore wind in each, in square kilometres and as a percentage of the total EU-27+UK land area. Although solar PV requires a larger installed capacity, the higher power density reduces the land required for installation of solar PV systems. Therefore, onshore wind has the greater land area requirement. The required land ranges from an area the size of Cyprus (0.23% of EU-27+UK land area) to almost the size of Spain (11.63%). In comparison, the highest land requirement for nuclear generation would be 279 km^2 [86], only 3% of the smallest land area requirement for the renewable generation options.

[85] Zalk and Behrens, 2018. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. (www.sciencedirect.com)

[86] Mackay, 2008. Sustainable Energy — without the hot air (www.inference.org.uk)

Table 24: Land requirements in 2050 for solar PV and onshore wind providing energy for DAC.

	Scenario	Land area (km^2)		% of EU-27+UK land area	
		Solar PV	Onshore wind	Solar PV	Onshore wind
Power only	Liquid solvent - low demand	14,199	24,369	0.33%	0.57%
	Solid sorbent - low demand	9,602	16,479	0.23%	0.39%
	Liquid solvent - high demand	22,335	38,331	0.53%	0.90%
	Solid sorbent - high demand	15,103	25,921	0.36%	0.61%
Power and heat	Liquid solvent - low demand	182,726	313,601	4.31%	7.39%
	Solid sorbent - low demand	57,320	98,375	1.35%	2.32%
	Liquid solvent - high demand	287,420	493,280	6.78%	11.63%
	Solid sorbent - high demand	90,162	154,739	2.13%	3.65%

6. CO2 UTILISATION BY ORIGIN

Under the proposed ReFuelEU mandate, there is no regulation on the origin of CO_2 used as a feedstock in the manufacture of synthetic kerosene. Should that CO_2 have an unsustainable origin, such as fossil fuel derived or industrial process CO_2, the combustion of that kerosene will lead to a net-addition of CO_2 to the atmosphere. To achieve the EU's ambition of net-zero emissions by 2050, e-kerosene must be manufactured with air-captured (biogenic or DAC) CO_2, or else negative emissions would be required to balance out its utilisation.

Whilst the environmental credentials of e-kerosene must be considered, the sustainable supply of CO_2 may be limited as BECCS and DAC need time to scale-up. Stalling the deployment of synthetic kerosene infrastructure in the short-term may impede its ability to meet long-term demands. Instead, e-kerosene could be manufactured in an unsustainable manner in the short-term, with a view that in the long-term this would become more sustainable over time. This does, however, risk lock-in to unsustainable methods, particularly given that current unsustainable supplies of CO_2 are much cheaper than the sustainable alternatives.

The following sections provide qualitative insight on factors that will impact how differing origins of CO_2 may be utilised, with a particular focus on what CO_2 may be directed towards e-kerosene manufacture.

6.1 OPTIMAL CO_2 ORIGIN BASED ON CAPTURE COST

In Table 25 below, a range of carbon capture costs have been provided for a variety of CO_2 origins[12]. The costs are highly dependent on how concentrated the source of CO_2 is. For example, bioethanol processes produce gas streams with high CO_2 concentrations (almost 100%) which results in costs below €50/tCO_2, whereas more diluted sources, such as the flue gases from natural gas or biomass combustion produce diluted CO_2 concentrations (3-14%) and so have costs in the region of €50-100/tCO_2. By tapping into the lowest concentration source - ambient air - DAC is the most expensive, with manufacturers currently claiming between €210-€540/tCO2 (see section 3.2.3). It must be noted that current natural gas costs are extraordinarily high due to the price spike which began in in late 2021. The costs could return to their pre-spike level, but if the price remains high, this could in turn increase the cost of natural gas derived CO_2.

Table 25: Range of carbon capture costs by origin of CO_2[12]

CO_2 Source		Cost (€/t_{CO2})	Year Costs Obtained
Power and Heat	Coal	19-63	2015 & 2017
	Natural Gas*	34-101	2015 & 2017
	Biomass	54-101	2015
Chemical Industry	Steam methane reforming (SMR) (Ammonia production)*	12-54	2015 & 2017
Heavy Industry	Iron and steel production	19-41	2015 & 2017
	Cement, clinker and lime production	22-69	2015 & 2017
Biogenic	Biogas upgrading	5-9	2015
	Bioethanol fermentation	5-12	2015 & 2017

**Capture costs shown were obtained prior to the natural gas spike in late 2021 which could have increased CO_2 costs from these sources substantially.*

In Table 26 below, the levelised cost of DAC CO_2 as determined by the methodology set out in section 5.2.3 has been detailed for each year of the ReFuelEU mandate. Even under the high learning assumption (20% reduction in cost for every doubling of capacity), and the high deployment of DAC, the cost of the CO_2 by 2050 is €139. Assuming constant cost from other sources, DAC will require policy support in order to compete, even as far ahead as 2050. Optimal use of CO_2 in terms of cost would therefore seek to avoid DAC and make use of more concentrated origins such as SMR, bioethanol fermentation and biogas upgrading.

Table 26: Range of levelised cost of carbon projections using DAC required estimates

	2025	2030	2035	2040	2045	2050
Low DAC required (low learning: 10%)	€445	€368	€282	€262	€250	€240
High DAC required (high learning: 20%)	€445	€258	€173	€150	€142	€139

6.2 OPTIMAL CO_2 ORIGIN BASED ON GHG EMISSIONS

For every tonne of CO2 from fossil or industrial process used to manufacture e-kerosene, at least one tonne of CO_2 will be emitted to the atmosphere on combustion of the fuel. The use of biogenic and DAC CO_2 has the potential to form a CO_2 neutral cycle, though the lifecycle emissions arising from biomass cultivation and the energy source for DAC must be considered.

Previous work by the National Academy of Sciences[87] has investigated the effective net CO_2 captured by DAC powered by a variety of energy sources (the results are shown in Table 27 below). In the case of the solid sorbent type, should the electricity and heat energy requirements be met by natural gas, for every tonne of CO_2 captured and returned to atmosphere via utilisation, a net 0.365 tonnes of CO_2 would be emitted (equivalent to a carbon removal efficiency of 63.5%). The use of low-carbon energy sources such as solar and nuclear dramatically reduces the net CO_2 emitted, though a small amount of lifecycle emissions remain.

It should be noted that it is possible to employ carbon capture on fossil energy sources to reduce carbon emissions, though it would come at the expense of additional capital and operating costs. This is an inherent part of Carbon Engineering's design, as they favour the use of natural gas as the heat source for their liquid solvent technology type[88]. Since liquid DAC requires heat at high temperatures (circa 900ºC), the use of a fuel is favoured over direct electric heating, and given the relative cheapness of fossil fuels over low carbon alternatives, the use of fossil fuels for DAC's thermal requirements may continue. The carbon removal efficiencies of these systems appears to differ across literature, with the National Academy of Sciences determining that 0.735 tonnes of CO_2 would be emitted for every tonne captured[87], the National Energy Technology Laboratory determining a figure of 0.61[89] and Carbon Engineering (the most prominent liquid DAC manufacturer) claiming 0.1 (equivalent to carbon removal efficiencies of 27.5%, 39% and 90% respectively).

Table 27: Net CO_2 emitted per tonne of CO_2 captured and utilised

Direct Air Capture System	Energy Source		Net CO_2 emitted per tonne CO_2 utilised (tCO_2)*
	Electricity	Heat	
Solid Sorbent	Natural Gas	Natural Gas	0.365[87]
	Wind	Natural Gas	0.260[87]
	Solar	Solar	0.058[87]
	Nuclear	Nuclear	0.048[87]
Liquid Solvent	Solar	Hydrogen**	0.010[87]
	Natural Gas	Natural Gas	0.735[87]
	Not stated	Natural Gas	0.61[89]

[87] The National Academies Press, 2018. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (www.ctc-n.org)

[88] Joule, A Process for Capturing CO_2 from the Atmosphere: A Process for Capturing CO2 from the Atmosphere: Joule (cell.com)

[89] National Energy Technology Laboratory, 2021. Life Cycle Greenhouse Gas Analysis of Direct Air Capture Systems (netl.doe.gov)

Direct Air Capture System	Energy Source		Net CO_2 emitted per tonne CO_2 utilised (tCO_2)*
	Electricity	Heat	
Liquid Solvent (with carbon capture on heating fuel emissions)	Not stated	Natural Gas	0.1[88]

**The mid-range has been taken from National Academy of Sciences high and low estimates.*

***Assumes 'green' hydrogen made via electrolysis using near zero-carbon power.*

The net emissions from the use of captured biogenic CO_2 will be dependent on the biomass cultivation conditions. The Renewable Energy Directive II (RED II) sets out GHG savings thresholds for biomass fuels for the purpose of electricity, heating and cooling. The current threshold set is to save at least 70% lifecycle emissions against a fossil-fuel comparator, with this rising to 80% by 2026.

From a GHG savings perspective, it is clear that the use of fossil and industrial CO_2 should be avoided, though careful consideration must also be paid to the sustainability credentials of both biogenic and DAC CO_2. The use of biogenic CO_2 from biomass feedstocks that meet the RED II criteria will offer substantial emissions savings over the use of fossil derived CO_2. The use of DAC CO_2 for e-kerosene should not act as a free pass to be claimed as sustainable, instead the CO_2 should be subject to a lifecycle analysis to assess the degree of net CO_2 emitted. Also, a standardisation of the lifecycle analysis approach, particularly in regard to determining the carbon removal efficiency of liquid DAC systems with carbon capture, should be developed so DAC systems can be compared on a level playing field.

6.3 GEOGRAPHIC, ECONOMIC AND REGULATORY CONSIDERATIONS ON CO_2 UTILISATION BY ORIGIN

The optimal utilisation of CO_2 by its origin for an e-kerosene manufacturer will depend on several factors beyond capture cost and lifecycle GHG emissions. There are geographic, economic, regulatory drivers that may sway the direction of CO_2 towards particular end uses. Some of the key factors are discussed in the following sections.

6.3.1 Co-location of DAC, Electrolysers and Fischer-Tropsch Plants

There are significant advantages to be gained by siting DAC, electrolysers and Fischer-Tropsch (FT) plants in close proximity to each other. Transport costs and emissions can be negated, or at least reduced, if both the hydrogen and CO_2 feedstocks are generated close to the FT plant.

Solid sorbent DAC technology (such as that developed by Climeworks) can utilise low-grade waste heat (80-120°C). There is potential to use the waste heat from electrolysis of water to produce 'green' hydrogen[90], and from the Fischer-Tropsch process as it is exothermic[91,92]. The utilisation of this waste heat increases the efficiency of the overall system, thereby reducing the cost of the kerosene product.

DAC and electrolysers can be sited almost anywhere, provided that there is access to reliable energy. In particular, access to affordable, sustainable and continuous electricity supply. The cost of both the CO_2 and H_2 feedstocks will be a function of the cost of electricity used to power the DAC and electrolyser plants respectively. Should future regulation impose that the lifecycle impact of the origin of CO_2 and H_2 used in the manufacture of e-kerosene be assessed, access to low or zero carbon electricity will be vital to fuel's sustainability characteristics. Reliance on renewable power alone will likely lead to intermittency issues as both DAC and electrolysers favour a continuous and steady power supply. To provide reliable power, connection to the grid, energy storage such as batteries, or connection to a continuous power source such as nuclear will be required.

[90] Beuttler et al, 2019. The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions (www.frontiersin.org)

[91] Marchese et al, 2020. Energy performance of Power-to-Liquid applications integrating biogas upgrading, reverse water gas shift, solid oxide electrolysis and Fischer-Tropsch technologies (www.sciencedirect.com)

[92] Institute for Applied Ecology, 2019. The significance of electricity-based materials for climate protection in Germany (www.oeko.de)

Another consideration on location is the access to fuel export infrastructure. FT plants producing large volumes of fuel will want to make best use of the economies of scale gained by existing supply chains for hydrocarbon fuels. Such infrastructure will include road and rail networks, storage terminals, ports and pipelines. The same infrastructure could benefit the DAC and electrolyser plants, should any excess CO_2 or H_2 be generated for export to other end uses.

6.3.2 Industrial Clusters

The collective approach of industrial clusters drives economies of scale and will be key activity regions for all CO_2 origins. Heavy industry is a hard to decarbonise sector; it will rely heavily on carbon capture for mitigation of emissions. Captured fossil and industrial process CO_2 is therefore likely to be sourced from these regions. Also, biogenic CO_2 from large scale solid biomass combustion (which accounts for 98% of captured biogenic CO_2 in 2050 – see section 3.2.2) will also have a tendency to fall within these regions, as biomass is an alternative fuel for high-temperature processes. The highest density of Europe's industrial clusters is in the north. The North Sea is also where much of Europe's capacity for geological CO_2 storage is.

Having several producers of CO_2 in concentrated regions will benefit shared CO_2 infrastructure through economies of scale. There are examples of industrial cluster projects that are exploring shared use of pipeline and shipping infrastructure. These include the Teesside Collective in the North-East of England which is proposing the use of a pipeline to send CO_2 to offshore storage[93]. Another is the Northern Lights project in Norway, which is developing a facility to accept CO_2 via ship from across Europe, with a pipeline to send the CO_2 to offshore storage. Both of these projects are focussed on building CO_2 infrastructure for the purpose of storage, as opposed to utilisation, as the objective is to mitigate fossil and industrial process emissions. Whilst DAC is a location-independent technology, any DAC deployed for the purpose of storage may also want to make use of this shared CO_2 infrastructure.

CO_2 utilisation activities, such as the production of FT fuels and low carbon chemicals, will also benefit from the facilities available in industrial clusters. Such clusters are often located on the shore, providing the means to ship large volumes of fuels and chemicals.

6.3.3 Storage vs Utilisation for Unsustainable CO_2

The amount of CO_2 available for utilisation from all origins is highly sensitive to the amount that is sent to storage. In European Commission's 1.5TECH scenario, the percentage of CO_2 captured that is sent to storage in 2050 from fossil/industrial process, biogenic and DAC is 100%, 54% and 0% respectively. These percentages were used in determining the amount of CO_2 available for utilisation in Table 12.

It is difficult to predict with any high degree of confidence the split of utilisation vs storage in the long-term, however, it could be argued that lower the sustainability characteristics of the CO_2, the greater the likelihood of it being directed away from utilisation and towards storage. It is hoped that future policy and regulation will be designed to encourage or enforce this behaviour.

For example, Directive 2009/31/EC on the geological storage of carbon dioxide encourages fossil fuel power plants and in industry to be capture-ready and to permanently store CO_2. The latest taxonomy rules means that fossil fuel power generation will be gradually phased out. Old gas power plants will be unlikely to meet the 270 g/kWh taxonomy threshold for direct CO_2 emissions without carbon capture or conversion to a lower carbon fuel. New natural gas power plants need to meet a threshold of 100g CO_2/kWh lifecycle emissions; this will require blending with a lower carbon fuel or capture and permanent storage of CO_2.

However, as shown in section 6.1, fossil CO_2 may remain cheaper than DAC CO_2 for some time, therefore manufacture of e-kerosene may favour the unsustainable feedstock. Also, there could be pragmatic and geographic drivers behind the use of fossil CO_2. Fischer-Tropsch plants will benefit from location in industrial clusters, putting them in close proximity to captured fossil and industrial process CO_2.

However, any site that installs carbon capture will likely be seeking to reduce their emissions either to: meet regulation, to avoid taxation, or to make use of a policy incentive for storage. If this site was to divert their unsustainable captured CO_2 away from storage, and sell it on as a commodity for utilisation, it is hoped that in a future Europe this would either: violate regulation, be subject to a carbon tax, or negate any policy incentive for storage.

[93] Net Zero Teesside. Delivering a Net Zero Teesside (www.netzeroteesside.co.uk)

To achieve net zero, any utilisation of fossil CO_2 would have to be balanced out by negative emissions elsewhere (such as BECCS or DAC with storage). If the outright use of fossil CO_2 is not banned by 2050, it may be subject to taxation, or the supplier may be required to pay the cost of CO_2 removal to balance it out to net zero. These disincentives may drive the direction of unsustainable CO_2 away from utilisation and towards storage. Our assumption is thus that all fossil fuel-derived and industrial process CO_2 is permanently stored and so no carbon dioxide will be available for utilisation from fossil fuel power generation and from industry.

6.3.4 Policy and Market Mechanisms

The current discussion around DAC and BECCS is mainly around these technologies providing negative emissions (through storage of CO_2 as opposed to utilisation) which are seen as necessary for net zero targets to be achieved. Currently there are no sufficient, reliable financial incentives to deploy and operate large-scale engineered NETs.

There are, however, some voluntary corporate purchases through bilateral agreements which driving the sector forward. For example, in 2021, Microsoft purchased a total of 1.3 $MtCO_2$ of carbon removal from 15 organisations, including 1.4kt tCO_2 from Climeworks and 2ktCO2 from Charm Industrial (a BECCS plant)[94]. Shopify, another advocator of corporate carbon removal purchases, bought 15.6 $ktCO_2$ removal via DAC from both Carbon Engineering and Climeworks and 1 ktCO2 via BECCS from Charm Industrial in 2020. In 2020, Stripe added three DAC projects to their portfolio of promising carbon removal providers. Furthermore, Climeworks is offering monthly subscriptions publicly for DAC removal for €100 per 100kg every month (equivalent to €1000 per tonne CO_2)[95].

These examples show high profile negative emissions purchases which will help the negative emission market develop and may lead to encouraging the permanent storage of CO_2 from DAC. It is expected that selling GHG removal credits from DAC by DAC and BECCS operators will continue and grow in the coming years. This is seen as a key competitive market for the utilisation of DAC CO_2 in the manufacture of e-kerosene.

The proportion of biogenic and DAC CO_2 available for utilisation, whether for e-kerosene or other industries, will depend on country-specific policies as well as EU wide policies. Some of these policies and factors which will influence the split of CO_2 between permanent storage and industrial utilisation are discussed below.

First, it is noteworthy that the total CO_2 storage capacity in the North Sea far exceeds the projected CO_2 production in 2050. Several EU countries have ruled out the storage of CO_2 in their boundaries and so transboundary CO_2 transport will be needed. Projects such as the Northern Lights in Norway are aimed at encouraging the receipt and storage of carbon dioxide in the North Sea. If this is to be undertaken at large scale in the future, legislation to address transboundary-transport of CO_2 (for example, the London Protocol, only ratified by 6 countries, inhibits cross-border transport of CO_2), ownership and rights of access issues and liability related to the stored CO_2 need to be addressed. The European CCS Directive for Geological Storage aims to address some of these issues, but further work is still needed by member states. The discussion here shows that, based on the current status, it is unlikely for permanent storage to advance significantly in the next decade until regulatory and legal issues are sorted and transposed into legislation and large and complex CCS infrastructure (i.e., transport and injection) is developed.

The major competitor for CO_2 available (from DAC and biogenic sources) for e-kerosene is expected to be permanent storage of CO_2 in the North Sea. The split between the two markets for CO_2 will depend on how fast legislation and incentives are developed to support each of the applications (negative emissions vs. CO2 utilisation in synthetic fuels).

In Europe so far there is no clear timetable for any adaptation or modification of the existing EU ETS that would allow integration of NETs. Carbon capture with utilisation (CCU) of CO2 in industrial applications has not been credited under the ETS Directive yet (other than to produce precipitated calcium carbonate). For instance, users of e-fuels manufactured with sustainable air-captured CO_2 will have to surrender one ETS allowance per tonne of CO_2 just in the same way than if fossil fuels were used. Carbon capture with storage of CO_2 (CCS) is covered under EU ETS provided there is permanent emissions reduction in the form of geological stores. A coalition of countries (Netherlands, Norway, Sweden and Denmark) calls for incentives to promote BECCS and DAC as part of EU climate policy.

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[94] Charm Industrial produces bio-oil through pyrolysis and stores it permanently in geologic formations.

[95] Climeworks, subscriptions accessed on 25/04/2022: https://climeworks.com/subscriptions

APPENDICES

APPENDIX 1 FEEDSTOCK SUSTAINABILITY

Categorisation of fuels and feedstocks, as "sustainable" and "unsustainable" for the purposes of this report. Inclusion in this table does not necessarily indicate that the material has been included in any of the biogenic CO_2 resource estimates.

* Denotes biogenic material deemed unsustainable but not specifically mentioned in the included estimates for biogenic resources. These may be aggregated into other categories.

** Material has been categorised as "unsustainable", except where specified as arising from gardens, verges and parks.

Fuel / feedstock	Sustainable	Unsustainable
Cereal, sugar, starch and oil crops		✓
Annex IX fuel / feedstock	**Sustainable**	**Unsustainable**
Part A:		
(b) Biomass fraction of mixed municipal waste		✓
(c) Biowaste from private households	✓	
(d) Biomass fraction of industrial waste not fit for use in the food or feed chain	✓	
e) Straw		✓
(f) Animal manure and sewage sludge	✓	
(g) Palm oil mill effluent and empty palm fruit bunche*		✓
(h) Tall oil pitch*		✓
(i) Crude glycerine*		✓
(j) Bagasse*		✓
(k) Grape marcs and wine lees	✓	
(l) Nut shells	✓	
(m) Husks	✓	
(n) Cobs cleaned of kernels of corn	✓	
(o) Biomass fraction of wastes and residues from forestry and forest-based industries		✓
(p) Other non-food cellulosic material**		✓
• Other non-food cellulosic material sourced from gardens, verges and parks	✓	
(q) Other ligno-cellulosic material except saw logs and veneer logs**		✓
• Other ligno-cellulosic material sourced from gardens, verges and parks	✓	
Part B:		
a) Used cooking oil	✓	
b) Animal fats classified as categories 1 and 2		✓

APPENDIX 2 BIOGENIC SUPPLY METHODOLOGY

This appendix details the methodology used to determine the theoretical biogenic CO_2 resource from both sustainable and unsustainable feedstocks.

Bioethanol production via fermentation

Bioethanol production represents an existing source of captured carbon dioxide. Current production of bioethanol is almost entirely dominated by 1st generation (1G) bioethanol, from food crops, whereas bioethanol from lignocellulosic material comprises less than 1% of production[96]. Bioethanol production from food crops takes place via fermentation of the plant material, releasing between 0.75 and 0.8 kg of CO_2 per litre of bioethanol produced[97]. Fermentation produces a relatively pure carbon dioxide off-gas with few impurities. Making the process of capturing CO_2 from fermentation less costly than capturing CO_2 from combustion gases. Current (2020) production of 1G bioethanol in the EU is 5,443 million litres, the potential CO_2 source is therefore around 4.25 million tonnes per year[96].

Transport fuel is the primary use for bioethanol, with 86% of bioethanol produced in the EU used for transport fuel in 2020. Projections for EU bioethanol production have therefore been based on projections of liquid biofuel demand in the road transport sector, scenarios leading to a goal of net zero emissions by 2050[98]. A medium demand scenario was taken. In which, demand for liquid fuels amongst road transport reduces from 2040 as ICE vehicles are displaced by EVs. From 2030 to 2040, production of advanced liquid biofuels increases, reducing production of 1G biofuels. The current ratio of 1G bioethanol to biodiesel is 20:80, this split was assumed throughout to calculate bioethanol demand in each year. No assumptions for import and export of bioethanol were made, nor for bioethanol demand in other sectors. Therefore, 1G bioethanol production in the EU is equal to road transport demand.

Table 28 shows the result of estimating 1G bioethanol production and resulting CO_2 emissions from fermentation. Demand projections were available for 2030, 2035, 2040 and 2050. Interim years were calculated assuming linear change. The results show growth until 2030, followed by decline to 2050 as advanced biofuels and electric vehicles become more prevalent. The availability of CO_2 is lower from 2035 onwards, than the current availability.

Table 28: Estimate of fermentation CO_2 from current (2020) bioethanol production[96] and projected bioethanol demand.

	2020	2025	2030	2035	2040	2045	2050
1G bioethanol production (Million litres)	5,443	6,163	6,882	5,162	3,871	2,581	1,290
CO_2 available ($MtCO_2$/yr)	4.25	4.81	5.37	4.03	3.02	2.01	1.01

Solid biomass

Within IPCC 1.5°C scenarios, all projections limiting global warming to 1.5°C include negative emissions technologies[75]. Amongst these, increasing bioenergy with carbon capture and storage (BECCS) capacity is expected to achieve net zero targets. The supply of solid biomass is therefore a key means of sequestering carbon and providing fuel to BECCS plants. Solid biomass suitable for direct combustion can be sourced from agriculture (crop residues and potentially perennial energy crops), forestry (traditional and emerging short-rotation practices) and waste streams.

Current EU-27+UK combustion of solid biomass (including renewable municipal waste) for energy uses amounted to 4.8 EJ, in 2019[99]. Resulting in emissions of 527 $MtCO_2$/yr when combusted[100]. Whilst the majority of solid biomass was used in point-source plants, a significant minority (42% of all solid biomass combusted)

[96] USDA, 2021 European Union: Biofuels Annual (www.fas.usda.gov)
[97] Kheshgi and Prince, 2005. Sequestration of fermentation CO2 from ethanol production (www.sciencedirect.com)
[98] Concawe, 2021. Transition towards Low Carbon Fuels by 2050: Scenario analysis for the European refining sector (www.concawe.eu)
[99] European Commission, 2021. EUROSTAT Energy balances 2021 edition (ec.europa.eu)
[100] IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Stationary Combustion (ipcc-nggip.iges.or.jp)

was used in the residential, commercial and public sector and of this primarily in households. Showing that a large amount of the current CO_2 emissions from solid biomass is distributed and unlikely to be captured in the future.

Projections of future solid biomass resource in the EU were gathered from 3 studies[101,102,103]. The included studies provide what can be described as the "sustainable resource". That generally being the technically available resource (accounting for harvest losses), less the resource required for competing uses and required to be left in-situ to maintain soil health.

Each study provided 3 scenarios for multiple years, resulting in 9 projections for 2030, 3 for 2040 and 6 for 2050. Interim years were scaled linearly. 2020 estimates for minor sources (secondary agricultural residues and arboricultural arisings) were included to reflect that such small-scale sources of solid fuel are less likely to be included in statistics. The estimated size of the resource was taken as the mean average of projections.

Table 29: Estimates of sustainable and unsustainable solid biomass energy resource. CO_2 emissions assume direct combustion of fuel.

PJ	2020	2025	2030	2035	2040	2045	2050
Sustainable resource	463	479	665	733	743	754	764
Unsustainable resource	4,757	6,800	8,844	9,570	9,649	9,737	9,825
$MtCO_2$/yr	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Sustainable resource	47	49	68	74	75	77	78
Unsustainable resource	527	721	914	986	994	1,004	1,014

In order to determine the likelihood of CO_2 emissions being captured, the resource is divided between point-source and distributed uses. Projections of biomass derived power and heat, and biomass final energy demand for industry, and residential and commercial sectors were taken from POLES modelling of a net zero scenario[104]. The growth in demand for these sectors was indexed and then applied to the current biomass energy use for each of the sectors according to EUROSTAT. For example, if POLES modelling expects biomass power generation to double from 2020 to 2040, the solid biofuel demand of that sector will also double by 2040.

An emerging demand for solid biomass, not included in POLES modelling, is production of advanced liquid biofuels from lignocellulosic b (2G biofuels). As discussed below, current production of 2G biofuels covers less than 1% of biofuel production in the EU. The same scenario used to project 1G bioethanol production is used to project 2G biofuel production. Demand for 2G biofuels peaks in 2040 for road transport, with greater use of EVs, but continues to rise through to 2050 for aviation and maritime transport. Resulting in overall growth from 2030 to 2050.

Table 30: Projections for 2G biofuel demand and solid biomass requirement. Assumes 2.46 PJ of biomass per PJ of biofuel[96]

PJ	2020	2025	2030	2035	2040	2045	2050
2G biofuel demand	1	84	167	502	1,591	1,844	2,097
Solid biomass demand	1	207	413	1,238	3,921	4,544	5,167

As shown in Table 30, the solid biomass demand from 2G biofuels alone is almost half of the projected available resource in 2050. Adding fuel demand from biomass power and heat production, and industry,

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[101] European Commission, 2006. Outlook of spatial biomass value chains in EU-27+UK: Deliverable 2.3 of the Biomass Policies project

[102] Ruiz et al, 2015. The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries (publications.jrc.ec.europa.eu)

[103] Imperial College London, 2021. Sustainable biomass availability in the EU, to 2050 (www.concawe.eu)

[104] CD-LINKS Scenario Explorer, POLES CD-LINKS NPi2020_400 model, accessed 01/02/2022: https://data.ene.iiasa.ac.at/cd-links/#/workspaces/1

commercial and residential sectors. Total demand for solid biomass fuel in 2050 is 16,337 PJ, 54% greater than the estimated solid biomass supply. Therefore, the available supply was apportioned between the sectors according to their % of total demand (e.g. power generation is 33% of the demand, so receives 33% of the available supply). By this method, the solid biomass produced in the EU provides only 65% of each sector's solid biomass demand. Table 31 shows the distribution of EU-27+UK domestic resources between the sectors.

Table 31: Distribution of projected EU-27+UK solid biomass resources by sector.

PJ	2020	2025	2030	2035	2040	2045	2050
Electricity generation	1,704	2,443	3,374	3,371	2,781	3,126	3,438
Centralised heat generation	268	394	491	433	322	292	272
Industry	1,038	1,441	1,823	2,050	1,730	1,679	1,608
2G biofuel production	1	274	578	1,441	3,196	3,229	3,349
Residential and commercial	2,209	2,727	3,243	3,007	2,363	2,165	1,922

For calculation of CO_2 emissions from each sector, solid biomass used for electricity and centralised heat generation, in industry, and in residential and commercial sectors is assumed to be combusted. IPCC default emissions factors have been used to convert fuel energy to flue gas CO_2 emissions (no account for lifecycle emissions is made)[100].

CO_2 emissions arising from conversion of solid biomass to biofuel can vary greatly depending on the process. Bioethanol production via dilute acid and enzymic processes with fermentation, result in emissions as low as 0.9 kgCO_2 per litre of bioethanol, or 10-13 ktCO_2per PJ of biomass input (depending on biofuel demand per litre of bioethanol)[105]. Alternatively, biofuel production via gasification and Fischer-Tropsch (FT) can result in substantially higher CO_2 emissions of 4.5 kgCO_2 per litre of biofuel, albeit with greater demand for solid biomass per litre of biofuel, or 96 ktCO_2 per PJ of biomass input[106]. A mixed case scenario has been assumed, whereby each PJ of biomass input to 2G biofuel production results in emissions of 54 ktCO_2.

Table 32 shows the results of converting the available solid biomass energy for each sector to CO_2 emissions. In determining potential to capture this CO_2 output, residential and commercial sectors emissions were deemed to be distributed sources, which have no potential for capture. Electricity and heat generation, industry and 2G biofuel are judged to be potential areas for deployment of carbon capture.

Table 32: CO_2 emissions from solid biomass use in each sector. Assumes combustion of biomass for sectors other than 2G biofuel production. Assumes multiple conversion pathways for 2G biofuel with average emissions of 52 ktCO_2 per PJ of solid biomass input.

MtCO_2/yr	2020	2025	2030	2035	2040	2045	2050
Electricity generation	188	258	348	347	286	322	354
Centralised heat generation	29	42	51	45	33	30	28
Industry	114	152	188	211	178	173	166
2G biofuel production	0	15	31	78	173	174	181
Residential and commercial	243	288	335	309	243	223	198

[105] Slade et al, 2009. The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe (biotechnologyforbiofuels.biomedcentral.com)

[106] Energy and Environmental Solutions, 2001. Life-Cycle Greenhouse-Gas Emissions Inventory For Fischer-Tropsch Fuels (www.eesi.org)

Biogas upgrading from Anaerobic Digestion

Many of the biogenic resources deemed sustainable by T&E are those most suited to anaerobic digestion for biogas. These include manures, sewage sludge and wastewater, biowaste (food/green waste), and food and drink industry wastes. AD biogas can also be produced from food energy crops (similar to those used in 1G bioethanol production), sequential crops and some other agricultural residues not considered sustainable sources. Biogas from AD plants is a mix of primarily methane and CO_2, with a typical ratio of 60% methane and 40% CO_2, although this varies according to feedstock[107]. Biogas can be combusted without upgrading but, in order to be injected into the gas grid, the CO_2 content must be removed to produce biomethane. This upgrading process is a potential source for capturing CO_2.

Estimates of biomethane production were sourced from a review of biomethane projections[108]. The review covered 12 projections across various years (2030, 2040 and 2050). Most reviewed papers included both sustainable and unsustainable biogenic feedstocks, and biomethane production by AD and gasification. In order to separate AD and gasification biomethane, and sustainable and unsustainable resources, only the projections that provided disaggregated estimates were used. To avoid double-counting the potential CO_2 resource from solid biomass, only CO_2 from AD was considered.

Current (2019) production of biogas in the EU is 704 PJ[99]. Information on feedstock type is not common. Of the total biogas production of 625 PJ in 2014, 51% is estimated to have been produced from energy crops, 18% from landfill gas and the remainder from other non-food feedstocks (organic waste, sewage sludge and manure)[109]. The 2014 breakdown of feedstock was applied to 2019 total production, to provide an estimate of current biogas resource from each source. Biogas production from thermal processes comprised less than 1% of biogas in 2019[110].

Table 33: Projections of biogas production from sustainable and unsustainable feedstocks. CO_2 emissions from upgrading of biogas to biomethane for grid injection.

PJ	2020	2025	2030	2035	2040	2045	2050
Sustainable feedstock	346	547	883	951	1,140	832	925
Unsustainable feedstock	358	463	542	789	924	1,132	1,280
$MtCO_2$/yr	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CO_2 from upgrading	3.4	4.9	6.9	8.4	10.0	9.5	10.6

Data for current production and projections for 2030, 2040 and 2050 were amalgamated. Where estimates for interim years were not available, linear change was assumed. This method resulted in 6 projections to 2030, 4 to 2040 and 3 to 2050. The estimated production was the mean average of the available projections. Table 33 shows the results of projection biogas production, 2020 is assumed to be equal to 2019 data.

Nearly 83% of biogas production is currently used for electricity and heat production. The remaining uses are industry (4%), transport (1%) and residential and commercial (12%)[99]. Biogas used within the energy and industry sectors is assumed to be combusted without upgrading. Therefore, only 13% of the production (that going to transport, and residential and commercial) is upgraded, for transport fuel or gas grid injection. This sector split was maintained throughout the modelled years. Of the biogas produced, 40% of the volume is assumed to be CO_2. The capture potential is therefore 36.67 $ktCO_2$ per PJ of biogas upgraded.

Emissions from combustion of liquid biofuels, biomethane and biogas

The final source of biogenic CO_2 is combustion of biofuels. Current consumption of liquid biofuels is almost entirely within the transport sector. Exceptions are construction, and agriculture and forestry although these are assumed to be construction plants and farm machinery[99]. Capturing CO_2 from liquid biofuel combustion is

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[107] The Official Information Portal on Anaerobic Digestion. Biogas (www.biogas-info.co.uk)
[108] Guidehouse, 2021. The future role of biomethane (www.europeanbiogas.eu)
[109] European Commission, 2016. Optimal use of biogas from waste streams (ec.europa.eu)
[110] EurObserv'ER, 2020. Biogas Barometer 2020 (www.eurobserv-er.org)

therefore not considered viable by 2050. Similarly, all production of biomethane is assumed to be consumed by small-scale distributed users (such as households, commercial and public sector).

As discussed above, the vast majority of biogas production is consumed for power generation. 47% of biogas produced was consumed by CHP units and 28% for electricity only production. The next largest consumer is industry at only 4% of biogas production, main industry sector users are food, beverages & tobacco, and paper, pulp & printing[99]. Unlike transport, and residential and commercial users, biogas consumed by the energy and industry sectors is assumed to be combusted without upgrading. Therefore, the CO_2 emissions are those that arise from combustion of the methane element of biogas (producing 54.6 kt CO_2 per PJ of biogas) plus the CO_2 already present in the biogas (36.7 kt CO_2 per PJ of biogas). As these consumers are larger and more centralised, these were considered viable for introduction of carbon capture in the next 30 years. Table 34 shows the biogas energy use by these sectors, and the resulting CO_2 emissions.

Table 34: Biogas consumption and resulting CO_2 emissions in the energy sector and industry.

PJ	2020	2025	2030	2035	2040	2045	2050
Energy sector	584	838	1,181	1,442	1,710	1,628	1,828
Industry	28	40	56	69	81	77	87
$MtCO_2$/yr	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Energy sector	53	76	108	132	156	149	167
Industry	3	4	5	6	7	7	8

APPENDIX 3 BIOGENIC CARBON CAPTURE UPTAKE RATES

Table 35: Biogenic carbon capture uptake rates

Source	Type	2025	2030	2035	2040	2045	2050
Distributed	Small-scale solid biomass facilities	0%	0%	0%	0%	0%	0%
	Biomethane combustion	0%	0%	0%	0%	0%	0%
Point-source	Large-scale solid biomass facilities	0%	5%	15%	25%	35%	50%
	Bioethanol fermentation	28%	32%	37%	41%	46%	50%
	Biogas upgrading	0%	5%	15%	25%	35%	50%
	Biogas combustion	0%	0%	0%	0%	0%	0%

APPENDIX 4 T&E DEMAND MANAGED SCENARIO DAC POWER AND LAND AREA REQUIREMENTS

Table 36: Whole market CO2 supply and demand under the T&E demand managed scenario (MtCO2/yr)

Source	Type	2025	2030	2035	2040	2045	2050
CO_2 Demand	Existing Demands	45	50	55	60	67	74
	Emerging: T&E Demand managed	0	20	86	176	278	403
	Total CO_2 Demand	**45**	**70**	**141**	**236**	**345**	**477**
CO_2 Supply	**Total CO_2 Supply**	**45**	**59**	**76**	**94**	**115**	**156**
DAC CO_2 Required	T&E Demand managed DAC required*	0	11	65	142	230	321

**DAC assumed to fulfil the deficit between CO_2 supply and demand.*

Table 37: 2050 Installed generation capacity requirements under T&E demand managed scenario (GW)

GW	Scenario	Solar PV	Onshore wind	Offshore wind	Nuclear
Power only	Liquid solvent - T&E demand managed	108	51	33	16
	Solid sorbent - T&E demand managed	73	35	22	11
Power and heat	Liquid solvent - T&E demand managed	1,384	659	428	203
	Solid sorbent - T&E demand managed	434	207	134	64

Table 38: 2050 Land Area for DAC Power Generation Requirements under T&E Demand managed scenario

	Scenario	Land area (km^2)		% of EU-27+UK land area	
		Solar PV	Onshore wind	Solar PV	Onshore wind
Power only	Liquid solvent - T&E demand managed	16,220	27,838	0.38%	0.66%
	Solid sorbent - T&E demand managed	10,969	18,825	0.26%	0.44%
Power and heat	Liquid solvent - T&E demand managed	208,737	358,242	4.92%	8.45%
	Solid sorbent - T&E demand managed	65,480	112,378	1.54%	2.65%

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