European Biogas Association

BIOGENIC CO_2 FROM THE BIOGAS INDUSTRY

A mature business opportunity to enhance sustainable carbon cycles and untap the circularity and climate benefits of biogas production

Table of contents

Executive summary

Considering the need for urgent action to mitigate climate change, a reduction of carbon emissions must be complemented with options for greenhouse gas removal. While displacing fossil fuel utilisation, the biogas and biomethane sector can provide biogenic CO_2 streams that may be used in other sectors or to permanently capture and deliver negative emissions.

This white paper explores the climate impact of biogenic CO_2 use or storage, the main utilisation avenues and perspective markets opportunities. While detailing current CO_2 requirements, the paper underlines current obstacles to and opportunities for the further take-up of BIO-CCS and Bio-CCU solutions, summarises best cases, and concludes with a set of policy recommendations to define a suitable legislative framework for the further deployment of BIO-CCUS solutions, necessary to meeting Europe's mid-century climate neutrality target.

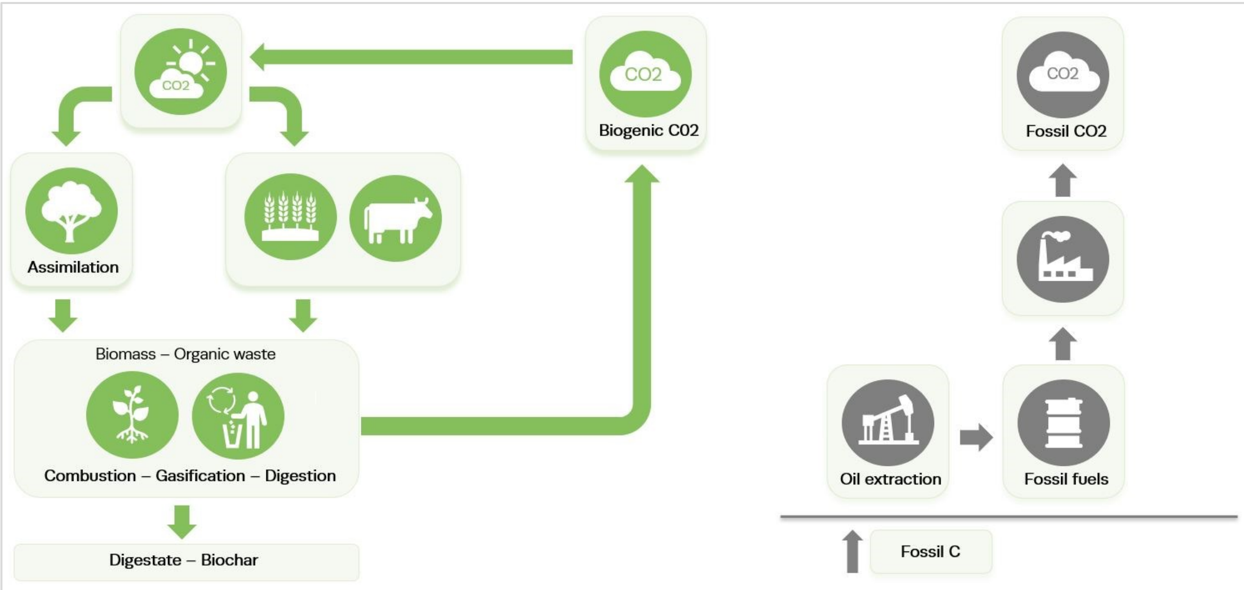
Chapter 1: The biogas sector as a source of biogenic CO_2

1.1. What is biogenic CO_2?

Biogenic CO_2 is the carbon dioxide (CO_2) resulting from the decomposition, digestion or combustion of biomass or biomass-derived products.

Biogenic CO_2 is part of the "**natural short carbon cycle**" (Figure 1). Assimilated by biomass through photosynthesis, atmospheric CO_2 is then returned, as biogenic CO_2, to the atmosphere or to the soil, depending on the conversion type and final use of biomass. In principle, there is no CO_2 accumulation in the atmosphere during the natural short carbon cycle. On the contrary, burning fossil carbon dioxide stored underground and previously not accessible releases additional CO_2 into the atmosphere.

Figure 1: Natural short carbon cycle (left) and fossil carbon release (right)



Sources of biogenic CO_2 include:

- Solid, liquid and gaseous biomass fuel combustion
- Bioethanol fermentation
- Wine and beer production
- Biogas upgrading process in the biogas industry

1.2. Biogenic CO_2 can be captured and utilised (bio-CCU)

According to the International Panel on Climate Change (IPCC), the world must reach net-zero greenhouse gas emissions by mid-century and net negative emissions shortly thereafter to mitigate the severe consequences of climate warming. **CO_2 recycling helps abate anthropogenic emissions**: CO_2 emitted is captured and converted into valuable chemicals, fuels, or materials. As CO_2 is used as a feedstock in several industries, companies are interested in biogenic CO_2, a climate-friendly source of CO_2.

"**Carbon Capture and Utilisation**" or **CCU** refers to solutions that include the capture of CO2 for its use[1] as a feedstock to produce fuels, chemicals and materials. When these products are made by using biogenic CO2, low-carbon or renewable energy sources, they can displace their fossil-based counterparts and thus reduce net carbon dioxide emissions to the atmosphere. When using biogenic CO2, we will refer to these solutions as "**bio-CCU**".

Bio-CCU embodies sustainable circular carbon economy principles, as it includes CO_2 reduction, reuse, recycling and removal.

1.3. Biogenic CO_2 can be captured and stored permanently to reduce CO_2 in the atmosphere (bio-CCS and bio-CCUS)

When biogenic CO_2 is captured and permanently stored underground in forms of **geological storage** such as depleted gas fields or deep saline aquifers, the process is called "**Bio-Carbon Capture and Storage**" or **bio-CCS**, and it allows CO_2 to be permanently removed from the atmosphere.
Biogenic CO_2 can also be safely stored for a long time in a new product, either construction material or plastics. When long-term storage is combined with the use of biogenic CO_2 to manufacture new materials, we refer to this as "**bio-CCUS**".

Bio-CCS and bio-CCUS are solutions that reduce the absolute quantity of CO_2 in the atmosphere: this absolute reduction is called **carbon dioxide removal** (most often referred to as "carbon removal"). The IPCC 2021 Special report on Climate Change defines carbon dioxide removal as "*anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities*"[2].

Carbon removal enables the issuance of a **carbon credit that can be traded on voluntary carbon markets**. These markets enable public or private players to voluntarily purchase verified emissions reductions in the form of carbon credits. Businesses use carbon credits to neutralise emissions not yet abated when it

[1] (pure CO2 or CO2-containing gas mixtures)
[2] Annex I - Glossary in IPCC, Special Report on Climate Change and Land, 2021. https://www.ipcc.ch/srccl/

is impossible or prohibitively expensive to directly reduce emissions from all activities across their value chains, such as from business travel, shipping or cement production for construction.

1.4. The biogas industry is an "easy-to-access" source of biogenic CO_2

The biogas value chain can **produce biogenic CO_2** along with other co-products in **two different production areas**:

- anaerobic digestion
- gasification

Biogas and biomethane are today produced from fresh organic materials through the **anaerobic digestion process**. The organic matter used as biogas and biomethane feedstock is inherently a source of organic carbon.

Biogenic CO_2 from anaerobic digestion can be captured in various ways:

1. During the process of upgrading biogas into biomethane, biogas is split into CH_4 and CO_2 to get biomethane, which can be used in the same applications as natural gas[3]. The CO2 is captured at relatively low cost due to its high purity.
2. In biogas plants fitted with combined heat and power (CHP), biogenic CO_2 can be captured from the flue gas during biogas combustion.
3. The **production of biohydrogen** from raw biogas, representing a possible third pathway to capture biogenic CO_2[4]. The **biogas upgrading process** is currently the most accessible source of concentrated biogenic CO_2. **This biogenic CO_2 is "ready-to-use"**.

Capture technology is mature, and by 2021 had already been implemented in Europe's 1,000 biomethane production units.

- Most biogas plants range from 50 to 2,000 Nm3/h, and will remain smaller producers of biogenic CO_2 than large biomass power plants[5]. They are geographically widely distributed, anchored in local settings, and represent a local circular economy opportunity in partnership with CO_2 consumers.
- The captured CO_2 from biogas upgrading is highly concentrated and is not diluted like in flue gas (around 10%) or worse, as in air (0.03% to 0.04%). Even though a few pollutants (sulphur, organic compounds) must be removed, it is relatively easy to handle and to process.

[3] Biomethane is a gaseous mixture containing more than 95% methane from renewable origins and can be injected into existing gas networks and used in end-uses compatible with natural gas.

[4] Two members of the EBA offer biohydrogen production capacities, Bayotech and Rouge H2 Engineering. Rouge H2 Engineering has developed on-site on-demand (OSOD) units of biohydrogen production from biogas. References: https://www.youtube.com/watch?v=HPHpW7xg7VA - OSOD - 1 step process hydrogen generator for highly efficient, safe and cost competitive production and storage of hydrogen | RGH2 OSOD system Project | Fact Sheet | H2020 | CORDIS | European Commission (europa.eu) - High-Purity Hydrogen Obtained Directly From Biogas for First Time | Technology Networks. Reference for Bayotech: https://bayotech.us/resources-2/

[5] Normo cubic metre (Nm^3/) is the common volume unit used for biomethane. 1 Nm^3 of biomethane is one cubic metre of biomethane at atmospheric pressure. An anaerobic digestion plant producing 2,000 Nm^3/h is considered a large-scale plant.

The features and advantages of CO_2 capture from biogas upgrading compared to biomass-fired power generation plants are summed up in table 1 below.

TABLE 1: COMPARISON OF CO_2 CAPTURE FROM BIOMASS COMBUSTION AND BIOGAS UPGRADING		
Features / CO_2 origin	**CO_2 from flue gas (dry) in biomass-fired power generation plants**	**CO_2 from biogas upgrading (dry) in anaerobic digestion plants**
Concentration	< 10 %	99%
Size of plant	Large (50 to 60 MW)	Small size (<400 kW) of many anaerobic digestion plants
Capture conditions:		
• **Equipment**	• Gas cleaning and separation technology required	• No specific equipment apart from adapted desulphurisation upstream of biogas upgrading facility
• **Energy demand**	• High during post combustion using amine scrubber	• CO2 is available after biogas upgrading
• **Cost**	• High	• Comparatively lower costs
• **Maturity**	• Few operational references	• Biogas upgrading is a mature technology (PSA – water or amine scrubbing- membranes-cryogeny, hot potassium carbonate (HPC))

These characteristics of the biogas upgrading process can meet a growing need of a range of industries for climate-friendly CO_2 sourcing options.

Gasification of sustainable biomass can also be an additional source of biogenic CO_2. This process converts dry, organic solid substances like ligno-cellulosic biomass (woody residues and waste) into biochar[6] and "syngas". Syngas is a gaseous mixture containing mainly hydrogen, methane, carbon monoxide and carbon dioxide. While syngas can be further transformed into gaseous or liquid fuels, biogenic CO_2 can also be extracted from it. Gasification combined with direct combustion of syngas to produce energy is a mature technology with more than 2,000 plants worldwide. Gasification combined with processing of syngas into fuels and biogenic CO_2 is in its demonstration phase, with less than 30 facilities currently around the world[7].

[6] Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention of improving soil functions and reducing greenhouse gas (GHG) emissions from biomass that would otherwise decompose rapidly (International Biochar Initiative, 2018).

[7] To find out more: European Biogas Association, *Gasification – A Sustainable Technology for Circular Economies. Scaling up to reach net-zero by 2050*, 2021. Available online at https://www.europeanbiogas.eu/gasification-a-sustainable-technology-for-circular-economies/

Chapter 2: Positive climate impact of biogenic CO_2 use or storage

The reuse and storage of biogenic CO_2 from the biogas industry are among the solutions to mitigate global climate warming.

Emissions of greenhouse gases (GHG) may increase the average global temperature by 1.1 to 6.4°C by the end of the 21st century, according to the Intergovernmental Panel on Climate Change (IPCC)[8]. Global warming of more than 2°C in global average temperatures will lead to serious adverse consequences, and the IPCC has therefore advised that global GHG emissions should be reduced by 50-80% by 2050.

Anthropogenic CO_2 emissions are mainly a consequence of fossil fuels being the most important global energy source. Enhanced energy efficiency and increased renewable energy production will reduce CO_2 emissions, but according to the IEA[9], energy efficiency and renewable energy do not have the potential to reduce global CO_2 emissions as much as the IPCC's target, i.e. 50 to 80% by 2050.

A delay in CO_2 emission reductions will have severe consequences. Therefore, it is necessary to include options other than energy efficiency and renewable energy in the strategy to close the gap. In this sense, CCS, CCUS and their biological versions based on biogenic CO_2 have a huge potential to reduce CO_2 emissions. The strategy for reducing global CO_2 emissions should therefore be a combination of:

- Enhanced energy efficiency
- More renewable energy
- Global implementation of (bio)-CCS and (bio)-CCUS

According to the International Panel on Climate Change (IPCC), "*mitigation options are available in every major sector. Mitigation can be more cost-effective if using an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize energy supply, reduce net emissions, and enhance carbon sinks in land-based sectors*"[10].

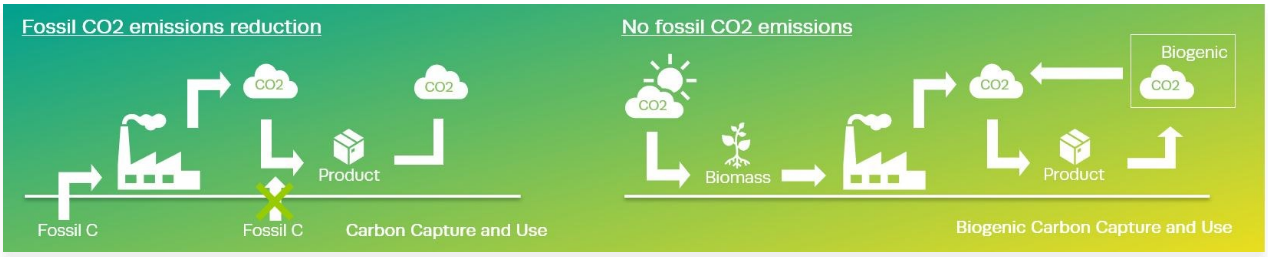
Managing the CO_2 from biogas (through CCU, CCUS or CCS) helps reduce the greenhouse gas intensity of CO_2 consumers and achieve an absolute removal of CO_2 from the atmosphere. It makes any biogas recovery solution much more climate positive, while creating local synergies with CO_2-consuming industries.

[8] Panel on Climate Change (IPCC), *Climate change 2014*, Synthesis Report.
[9] International Energy Agency (IEA), *Putting CO_2 to Use. Creating value from emissions*, September 2019.
[10] International Panel on Climate Change (IPCC), *Climate change 2014*, Synthesis Report.

2.1. Climate benefits of biogenic carbon capture and use (bio-CCU)

Capturing fossil CO_2 and utilising it in industrial applications offers a first level of climate benefit by **avoiding the consumption of further fossil carbon** and the associated CO_2 emissions. However, as seen in Figure 2, CCU with fossil CO_2 is not a CO_2-neutral system, because fossil CO_2 is ultimately released into the atmosphere. Conversely, **bio-CCU is a CO_2-neutral system, which recycles the CO_2** already existing in the atmosphere before eventually releasing it into the air again.

Figure 2: Comparison of CCU with fossil CO2 and CCU with biogenic CO2



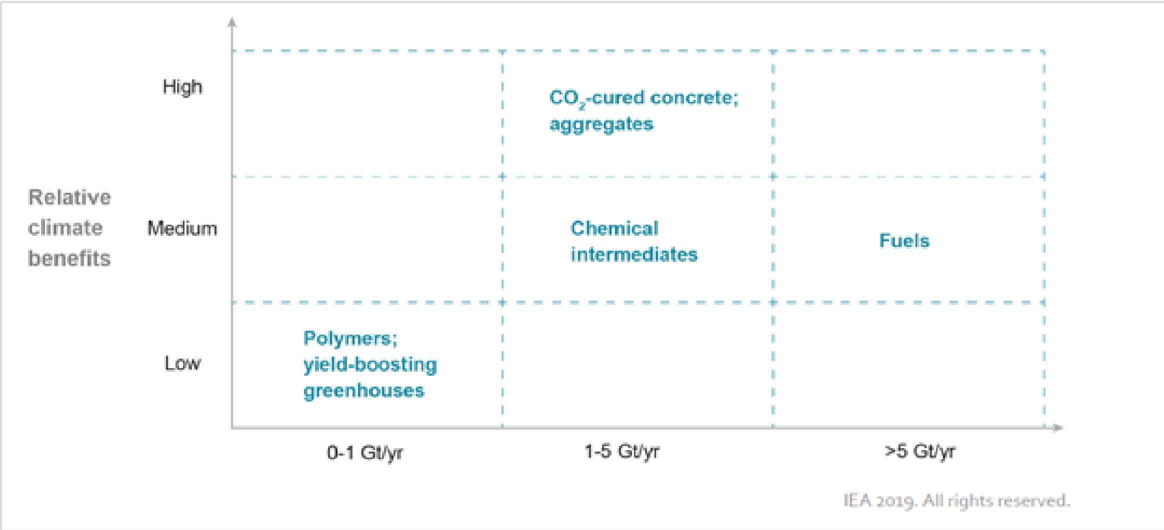
The climate benefits of CO_2 utilisation (bio-CCU) and/or CO_2 storage in new products (bio-CCUS) can be quantified in terms of life-cycle emissions. These may vary and should therefore be assessed according to the following **five key parameters**[11]:

1. the source of CO_2 (fossil vs biogenic)
2. the product or service the CO_2-based product is displacing and the related emissions avoidance enabled by the use of biogenic CO_2
3. the product's carbon storage length (temporary vs permanent)
4. energy efficiency and carbon footprint for the conversion of CO_2 into other molecules
5. the scale of the opportunity for CO_2 use

The International Energy Agency (IEA) assessed the relative climate benefits of five categories of CO_2-derived products and services that could be attractive in the medium term (Figure 3): fuels, CO_2-derived chemicals, building materials, concrete and crop yield boosting. According to the IEA's assessment, fuels have shown the greatest potential for CO_2 used by volume, while building materials have the greatest potential for climate benefits per tonne of CO_2 used.

[11] International Energy Agency, *Putting CO_2 to Use. Creating value from emissions*, September 2019, 83 pages.

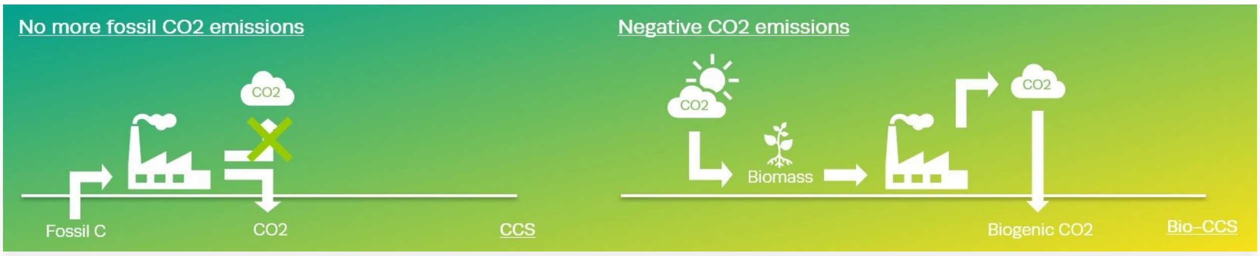
Figure 3: theoretical potential and climate benefits of CO_2-derived outputs (IEA, 2019)



2.2. Climate benefits of biogenic carbon capture and storage (bio-CCS)

As opposed to fossil CCS, which decreases the amount of new CO_2 entering the atmosphere at best, **bio-CCS has the potential to provide net removals of CO_2 from the atmosphere, achieving negative emissions** (Figure 4). By binding atmospheric carbon dioxide during growth of biomass and subsequently capturing CO_2 from the biomass conversion process for permanent storage in geological formations, **CO_2 is extracted from the short carbon cycle**, and **fossil energy use** (and associated emissions) **is avoided at the same time**.

Figure 4: Comparison of CCS with fossil CO2 and CCS with biogenic CO2



2.3. Comparison with other systems

The different impact of the four systems on the fossil fuel phase-out can now be summarised in simple terms in Table 2 below.

Table 2: IMPACT OF THE DIFFERENT CARBON CAPTURE SYSTEMS ON FOSSIL-FUEL			
Systems	CO2 emissions "avoidance"	CO2 emissions "neutral"	CO2 emissions "negative"
CCU	Yes	No	No
Bio-CCU	Yes	Yes	No
CCS	Yes	Yes	No (yes in specific cases)*
Bio-CCS	Yes	Yes	Yes

* In case the captured biogenic CO2 is used to produce building materials or long-term plastics (bio-CCUS), negative emissions can be considered.

Bio-CCS and bio-CCUS from the biogas industry are reliable pathways for reducing historic CO_2 compared to other alternatives. Other **"Negative Emissions Technologies"** (NET) can deliver carbon removals, but many are still in their infancy and suffer from technical or economic limitations.

TABLE 3: NEGATIVE EMISSIONS TECHNOLOGIES				
Negative Emission Solution	Carbon dioxide source	Technological Readiness Level	Additional benefits	Sequestration permanency
Afforestation[12] and Reforestation[13]	Atmosphere	Medium	Wood exploitation	Limited
Carbon farming practices	Biomass	Medium	Food/feed exploitation	Limited
Enhanced weathering[14]	Atmosphere	Low	-	> 1,000 years
Biochar production	Biomass	High	Renewable energy[15], soil fertility & water resilience	100-1000 years

[12] Conversion to forest of land that historically has not contained forests from "Annex I - Glossary" in IPCC, *Special Report on Climate Change and Land*, 2021. https://www.ipcc.ch/srccl/

[13] Conversion to forest of land that historically has not contained forests from *ibidem*.

[14] Enhancing the removal of carbon dioxide (CO2) from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans from *ibidem*.

[15] When the production of the biochar also includes production of energy from renewable sources in compliance with sustainability requirements of the law. This is the case with sustainable gasification of biomass. For more information, see: European Biogas Association, "Gasification – A Sustainable Technology for Circular Economies. Scaling up to reach net-zero by 2050", 2021. Available online at https://www.europeanbiogas.eu/gasification-a-sustainable-technology-for-circular-economies/

Compatible with bio-CO2 from biogas	Mineralisation	Atmosphere / Biomass	Medium	Natural rock saving	> 1,000 years
	Geological storage combined with Direct Air Capture or bio-CCS	Atmosphere / Biomass	High[16]	Renewable energy[17]	> 1,000 years

2.4. Mitigation potential of the biogas and biomethane industry

The biogas and biomethane sector is an increasingly significant contributor to the achievement of the mid-century climate neutrality target. As calculated by the World Biogas Association, the sector has the potential to reduce global greenhouse gas (GHG) emissions by 10-13%[18]. The biogas and biomethane industries reduce emissions in several ways, including avoiding emissions by replacing fossil fuels; avoiding methane emissions from manure; producing green fertiliser, which replaces carbon-intensive chemical fertilisers.

According to the EBA[19], biogas and biomethane production in Europe[20] accounted for **18 billion cubic metres (bcm) in 2020**. While the sector is growing dramatically, it is estimated that biogas and biomethane potential can increase to **35 bcm in 2030**, the equivalent of 10% of the EU's natural gas consumption. The potential is assessed to be at least **95 bcm by 2050**, which may be enough to meet 30-40% of gas demand in an environment of a substantial decrease in consumption.

Assuming that all biogas is upgraded to biomethane and that all resulting biogenic CO_2 is stored permanently, **the theoretical potential of biogenic CO_2 production** in 2020, 2030 and 2050 are the following:

TABLE 4: THEORETICAL POTENTIAL OF BIOGENIC CO2 FROM BIOGAS

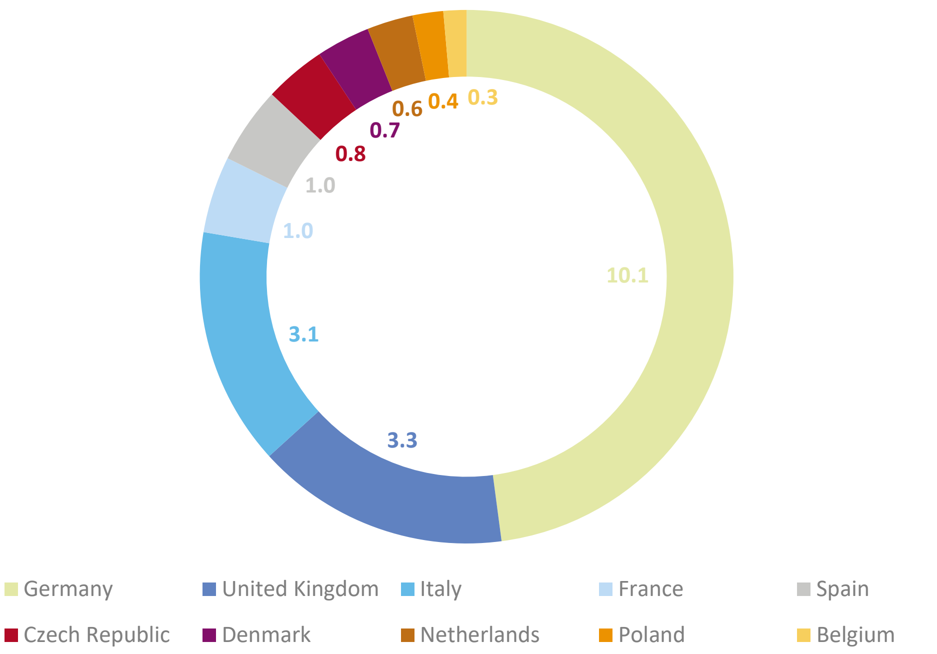
	Biogas and biomethane production in Europe	Theoretical potential of biogenic CO2 from biogas	Equivalence[21]
2020	18 bcm	24 Mton	Equivalent of the GHG emissions of Croatia in 2020
2030	35 bcm	46 Mton	Equivalent of the GHG emissions of Sweden in 2020
2050	95 bcm	124 Mton	3% of EU-27 GHG emissions in 2020

[16] Refers it to the safe injection and storage of CO2 in geological underground formations.
[17] In compliance with sustainability requirements of the law.
[18] World Biogas Association 2019, *Global Potential of Biogas*, World Biogas Summit, July 2019.
[19] EBA 2021, *Statistical Report of the European Biogas Association 2021*, Brussels, Belgium, November 2021.
[20] The geographical scope is the European Union, EFTA countries, Serbia and Ukraine.
[21] European Environment Agency, *Annual European Union greenhouse gas inventory 1990–2020 and inventory report 2022*, 2022. That report is the official inventory submission of the European Union for 2022 under the United Nations Framework Convention on Climate Change (UNFCCC).

Following the same hypothetical reasoning, country-wise, Germany, the UK and Italy would be the European leaders of biogenic CO_2 production in 2020. The ten biggest European biogas and biomethane producers could have theoretically produced **21.3 Mton/year of biogenic CO_2** in 2020 (Figure 5).

According to biomethane production in Europe **in 2020** (3 bcm/year)[23], approximately **3.9 Mt biogenic CO_2/year were already separated during biogas upgrading**.

Figure 5: Biogenic CO2 production potential per country (Mton/year) if AD plants would upgrade to biomethane, based on the actual combined biogas and biomethane production in 2020



2.5. The requirement of sustainability

For bio-CCS or bio-CCUS to provide carbon removal, biogas production must be environmentally sustainable. The potential of 35 bcm in 2030 and 95 bcm in 2050 **can be achieved sustainably**, i.e. by sourcing only sustainable feedstocks according to the evolving requirements of the Renewable Energy Directive.[22]

The Renewable Energy Directive's sustainability criteria must be applied by biogas facilities beyond 2 MW of total rated thermal input (or 200 Nm^3/h of installed capacity), and they include **substantial GHG emissions savings calculated along the supply chain and the guarantee that biomass sourcing has a minimum impact on biodiversity and soil quality. Compliance with such criteria is necessary** to qualify

[22] Renewable Energy Directive, EU 2001/2018 article 29 *et al.*

as renewable, to be eligible for financial support and to be zero-rated under the EU emissions trading system.

To demonstrate compliance with such criteria, biogas and biomethane producers must certify their production with one of the European Commission's recognised voluntary schemes.

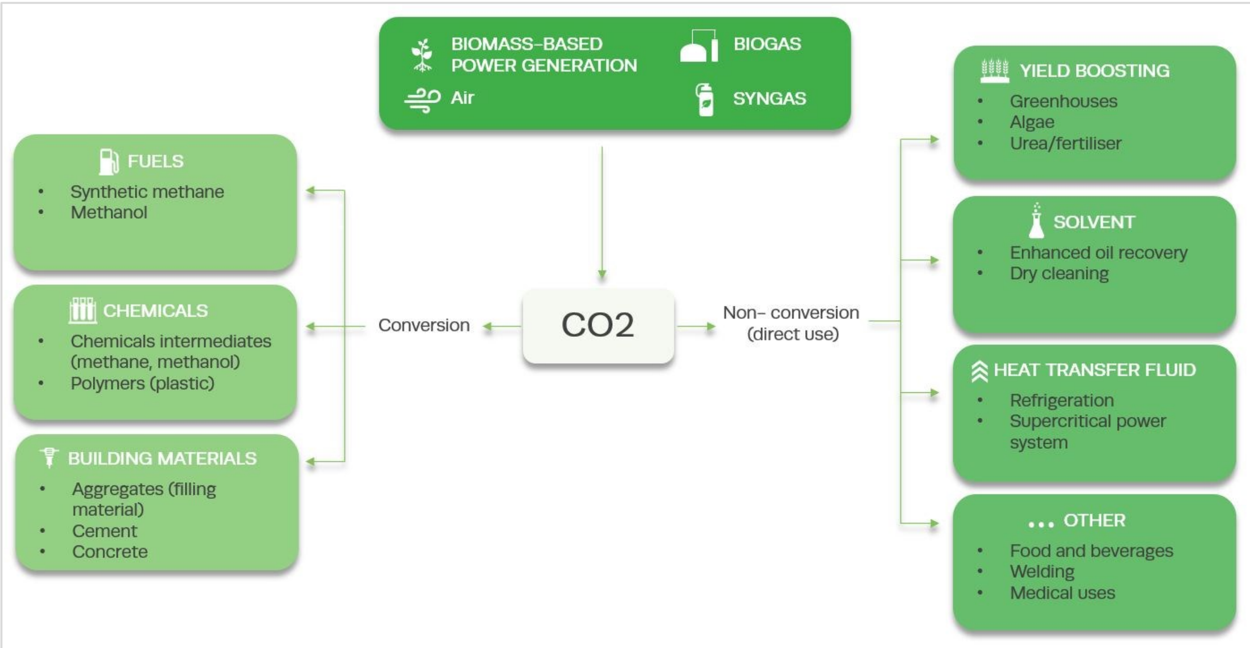
Since 2013, the number of new biogas and biomethane capacities fed by food and feed crops has shrunk drastically. The market has moved towards agricultural residues, organic fraction of municipal waste, industrial wastewaters and sewage sludge. Since 2017, newly installed biomethane plants have featured a larger use of municipal biowaste and sewage sludge than energy crops. Almost no new plants were established to run on food and feed crops, and thanks to current GHG emissions savings requirements this trend is set to continue in the future.

Chapter 3: Existing markets – CO_2 as a feedstock

Various CO_2 utilisation pathways co-exist today. These processes can be divided into the **pathways without conversion** (direct use of the CO_2 as feedstock), and those with **conversion** (which requires specific processing or chemical treatment of the CO_2 before utilisation) (Figure 6).

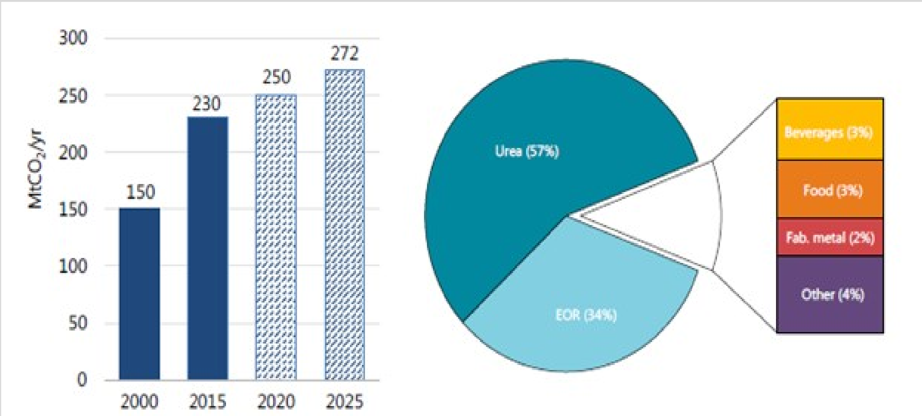
Some processes have been established for decades, such as the use of CO_2 in beverage carbonation and urea production. Conversion pathways are in constant development, examples of end-products include methanol and construction materials (see Chapter 4).

Figure 6: Simplified classification of pathways for C02 use



CO_2 has been in high demand in the past few years, driven by industrial sectors (Figure 7).

Figure 7: Growth in global demand of CO2 over the years (left); breakdown of demand in 2015 (right) Source: IEA Putting CO2 to use 9/2019



3.1. Food and beverages

The worldwide food and beverage industries consume **about 11 Mt CO_2 annually**[23], and it is one of the most established end uses of CO_2.

Applications include packaging (as a preservative agent increasing food shelf-life); carbonation of soft drinks, mineral water and beer; production of deoxygenated water; use of CO_2 as acidifier[24,]. These uses require **very high CO_2 purity.**

3.2. Greenhouses

When the air is artificially renewed inside a greenhouse, providing an additional flow of CO_2 can increase the growth rate of plants by 15 to 40%. CO_2 consumption depends on the crop type and on lighting control: lighting for 12 months means crops and CO_2 all year round. This outlet has a **significant seasonality**: consumption is highest in spring and lowest in winter.

Some greenhouse growers arbitrate their consumption according to the price of CO_2, which increases during the summer, because the advantage in productivity is not always sufficient to justify the additional costs.
CO_2 demand in greenhouses is estimated at around **5.000 Kt of CO_2 (2017 estimates)**[25]. The leader in the use of CO_2 in greenhouses is the Netherlands, with an estimated annual consumption of between 5 and 6.3 Mt CO_2[26].

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[23] Mikulčić, H., Skov, I. R., Dominković, D. F., Alwi, S. R. W., Manan, Z. A., Tan, R., ... & Wang, X. (2019), *Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO_2.* Renewable and Sustainable Energy Reviews, 114, 109338.
[24] Esposito, Elisa *et al*. *Simultaneous production of biomethane and food grade CO_2 from biogas: An industrial case study.* Energy & Environmental Science 12.1 (2019): 281-289.
[25] Tittarelli, F.; Båth, B.; Ceglie, F.G.; García, M.C.; Möller, K.; Reents, H.J.; Védie, H.; Voogt, W. *Soil fertility management in organic greenhouse: An analysis of the European context*. Acta Hortic. 2017, 1164, 113–126.
[26] Alberici, S. et al. (2017), *Assessing the Potential of CO_2 Utilisation in the UK*, Ecofys UK, Ltd, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf.

There is no European regulation concerning ventilated air in greenhouses, but greenhouse growers obtain their supplies from gas companies that only sell **food grade gas**. These on-site systems can be replaced with other CO_2 sources, for example, by coupling greenhouses located near an agricultural unit of anaerobic digestion, delivering economical and climate benefits at the same time.

Another important use in agriculture is **pest control**, where CO_2 is considered an alternative to products such as methyl bromide, phosphines and insecticides, compared to which it has the advantage of **leaving no residues after treatment**. The fumigating effect of carbon dioxide allows post-harvest treatment, especially in organic agriculture, increasing food safety and reducing production residues.

3.3. Fertilisers

With the ambition of minimising the total carbon footprint from global biomass production, the efficient use of land based on modern, more sustainable agricultural practices is of great importance.

Urea is one of the most known chemical products and can be used as a chemical fertiliser, in urea resins, urea–melamine resins and as an animal feed additive[27]. The most common method for the production of urea is **reforming natural gas**, producing carbon dioxide and ammonia[28]. Urea emits less CO_2 during production than nitrates, but upon spreading, the situation is reversed, since urea releases the CO_2 contained in its molecule. Urea also often releases more N_2O. The life cycle carbon footprint is therefore higher for urea than for nitrates. As CO_2 is consumed during urea production, **biogenic CO_2 represents an environmentally-friendly alternative**.

The industrial production of fertilisers in the EU-27 accounted for 18,100 kt in 2019. Approximately 72% of this production correspond to nitrogenous fertilisers, which include urea and ammonium nitrate[29]. Germany and France are the leading countries in fertiliser production within the EU. Regarding **nitrogen fertiliser consumption** in the EU-28 in 2019/2020, **urea represents 20%** of the total of 11,200 kt of nutrients.

3.4. Refrigeration

CO_2 is termed a "natural refrigerant", because it exists in the natural environment or comes from biological sources. Released into the atmosphere from refrigerating systems, it has a negligible effect. Compared to the fluorinated refrigerant alternatives, it is **natural, environmentally-friendly, non-flammable and cost effective over the long term**. It can be used in the transport sector as a more

[27] Mikkelsen, M., Jørgensen, M., & Krebs, F. C. (2010). *The teraton challenge. A review of fixation and transformation of carbon dioxide.* Energy & Environmental Science, 3(1), 43-81.

[28] Esmaeil Koohestanian, Jafar Sadeghi, Davod Mohebbi-Kalhori, Farhad Shahraki, Abdolreza Samimi, (2018). *A novel process for CO_2 capture from the flue gases to produce urea and ammonia*. Energy, Volume 144, pp. 279-285.

[29] Fertilizers Europe 2019. *INDUSTRY FACTS AND FIGURES*, Brussels, Belgium, 2019.

environmentally-friendly refrigerant compared to traditional ones. **Among the first refrigerants used almost 100 years ago**, its environmental benefits and properties qualify it as a good alternative.

Its use is incentivised by stringent European regulation on fluorinated gases (F-gas). The new F-gas regulation aims to reduce emissions of fluorinated greenhouse gases by around 90% by 2050 compared to 1990 levels.

3.5. Advantages of using biogenic CO2 from biogas

Capturing and upgrading CO_2 from biogas production generates positive externalities, such as environmental and social benefits. A summary of these benefits for common end uses of biogenic CO_2 are listed below (Figure 8).

Figure 8: Advantages of using CO2 from biogas

MARKETING

- Image impact (premium effect that can be marketed by the customer in its value chain)
- Biogenic status vs. fossil

TECHNICAL

- High CO2 concentration (typically >98%)
- No presence of carbon monoxide because biogas cannot have CO inside
- Typically very low concentration of NH3 the source gas before CO2 treatment plant <10ppm (typically removed in upgrading)
- Typically very low concentration of H2S and sulphur compound in the source gas before CO2 treatment plant <10ppm (typically removed in upgrading)
- The main contaminants in concentration (CH4 and air) are not toxic

ECONOMIC

- Locally produced (decentralised and de-risked model versus ultra-concentrated sourcing on few units … ref ammonia plant shut-down disorders)
- Price stability (no carbon tax nor carbon allowance within a mandatory carbon market)
- Programmable production
- Secured supply &/or exclusivity conditions

POLITICAL

- Synergies in a local bioeconomy ecosystem

EBA European Biogas Association

Chapter 4: Potential future markets

Other potential markets could open up in the medium to long term once economic models and/or technologies are mature and the right policy framework is in place:

- Production of renewable synthetic fuels
- Polymer manufacturing
- Semiconductor manufacturing
- Algae culture
- Building materials

Some of these markets will come from CO_2 conversion processes that have not yet reached technological readiness in an operational environment[30]. Others will use CO_2 directly and will be accessible once viable **economic models** are proven for biomethane producers. Accessing these potential markets will also **depend on the regulatory framework** as well as on the **geographical match** between the location of production and consumption, with a constant focus on short distances to keep transport costs in check. Fuel production, the manufacture of chemicals, including polymers, and building materials have been identified by the International Energy Agency (IEA) as **attractive products and services in the medium term**[31].

4.1. Production of renewable fuels

Utilising biogenic CO_2 as a CO_2 source to **produce synthetic fuels** provides an avenue to mitigate GHG emissions in transport and heating, and reduce dependence on fossil fuels.[32]

Synthetic fuels of renewable origin, also known as "electrofuels" (e-fuels), are produced by merging a carbon source and electrolytic hydrogen in so-called Power-to–X (PtX) processes[33]. A range of products can be obtained from these processes, including methane, methanol and dimethyl e-petrol or e-diesel[35]. Combustion of the resulting electrofuel generates zero CO_2 emissions if renewable electricity is used as the input. With the use of biomethane, even negative emissions can be achieved depending on the biomethane production pathways. CCU for production of synthetic renewable fuels represent the largest market for this solution, as there is a great need for fossil carbon source substitutes[26].

[30] Rodin, V., Lindorfer, J., Böhm, H., & Vieira, L. (2020). *Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO_2*. Journal of CO_2 Utilization, *41*, 101219.

[31] International Energy Agency (IEA), *Putting CO_2 to Use. Creating value from emissions*, September 2019.

[32] Due to inertness, CO_2 conversion is energy intensive when CO_2 is a single reactant. However, the conversion is more thermodynamically favourable when combined with a co-reactant that possesses higher Gibbs energy, such as hydrogen (H_2). Hence, biogenic CO_2 hydrogenation to synthetic fuels and chemicals is a promising approach to generating a sustainable process in which carbon dioxide is recycled efficiently.

[33] Mikulčić, H., Skov, I. R., Dominković, D. F., Alwi, S. R. W., Manan, Z. A., Tan, R., ... & Wang, X. (2019*). Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO_2.* Renewable and Sustainable Energy Reviews, 114, 109338.

A) Power-to-gas: H2 conversion to synthetic methane

Power-to-gas, with the use of biogenic CO_2 as a carbon source, can be a valuable option to produce renewable H_2, exploiting excess renewable electricity from renewable sources like wind or solar.

With the increasing penetration of variable renewables in the energy system, excesses can be recovered and stored via conversion into hydrogen (H_2) through water electrolysis. Renewable hydrogen needs to be transported to end users either by blending it into the existing gas network or by injecting it into a dedicated new network. Creating dedicated pipelines or local hydrogen networks requires considerable investment to ensure the infrastructure is ready. Therefore, converting hydrogen into synthetic methane could offer further flexibility to the energy system. This process, known as **methanation,** combines CO_2 with H_2 to produce synthetic CH_4 that can be injected into existing natural gas networks.
Synthetic methane has the same end-use applications as biomethane, can provide energy storage capacity and is a flexible renewable energy carrier and fuel.

Biogenic CO_2 from biogas and biomethane plants can be used as a feedstock for the production of **synthetic methane**. The potential of synthetic methane from biogenic CO_2 depends on several technological parameters, based on Wettstein *et al*[34] and the REGATRACE Project[35]. The technical potential of synthetic methane is **8.74 Mt of synthetic methane**, carrying **121.4 GWh of energy**.[36]

B) Methanol

Methanol is a cost competitive and safe fuel and can be used in vehicles, either directly[37], or as a blended component for gasoline.
Methanol can also be used as:

- a feed for fuel cells, where it is oxidised with air to CO_2 and water to produce electricity;
- a reactant for the MTO (methanol-to-olefins) process to produce ethylene or propylene;
- a reactant for the MTG (methanol-to-gasoline) process;
    - building block for the chemical industry; solvent; and
    - energy storage material[38].

The hydrogenation of CO_2 to produce methanol is one possible route towards the development of an economy where biogenic CO_2 is regarded as an abundant alternative carbon source.

[34] Wettstein, Sarah; Itten, René; Stucki, Matthias (2018), *Life Cycle Assessment of Renewable Methane for Transport and Mobility.*
[35] This project receives funding from the European Union's Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement no. 857796. See: https://www.regatrace.eu/
[36] Assuming the total amount of the estimated 24 Mt of biogenic CO_2 in 2020 that could be mobilised, together with 4.37 Mt of H2.
[37] Although it has half the volumetric energy density of gasoline or diesel.
[38] Ashok, Jangam, *et al. Catalytic CO_2 Conversion to Added-Value Energy Rich C1 Products.* An Economy Based on Carbon Dioxide and Water. Springer, Cham, 2019. 155-210.

4.2. Manufacture of polymers

Polymers and plastics generated utilising CO_2 include:

1. Polymers incorporating CO_2 directly into their structure, such as **polycarbonates**, a highly resistant material used to form aerosols, baby bottles, cardiac surgery equipment and instruments that require autoclaving.
2. Polymers formed from monomers created by the hydrogenation of CO_2, such as ethylene and propylene.

R&I is progressing in the field of polymers, and new approaches are emerging to produce polymers and high-value chemicals utilising CO_2 as a feedstock. The technology transforms CO_2 into polycarbonates such as polypropylene carbonate (PPC) and polyethylene carbonate (PEC) using catalysts in a reaction with an epoxide, a chemical compound used as a reagent[39].

The use of biogenic CO_2 in the synthesis of polymers can positively impact the footprint of these materials, making them more **sustainable**. According to Imperial College London[40], the polymers market using (biogenic) CO_2 presents four main advantages: (i) it locks up CO_2 in relatively stable materials; (ii) it substitutes fossil-based inputs; (iii) it produces materials that can directly substitute similar polymers; (iv) it is potentially economically attractive without subsidies.

4.3. Use as an inert gas in semiconductor manufacturing

The COVID-19 lockdowns disrupted supply chains and severely impacted the sourcing of semiconductor and electronic items. These challenges made the EU's dependence on these critical components more evident, and the development of a domestic industry of semiconductors and electronics is considered as a possible solution to supply chain disruption. Ultra-high purity CO_2 plays a key role in this sector[41]. Its properties make it more suitable in silicon wafer lithography[42], and it improves quality in immersion photolithography processes[43]. It can also be used **as a cleaning agent** of semiconductor films. Despite the small size of this market, the pricing of this CO_2 can exceed 10x normal food-grade CO_2.

4.4. Algae and microalgae culture

Algae use CO_2 as a primary source of food, from which to draw the energy necessary for their survival. Microalgae have the ability to fix CO_2 using solar energy with an efficiency 10 times greater than that of terrestrial plants. There have therefore been considerable efforts to apply the microalgae culture for both

[39] Epoxides include propylene oxide (PO) and ethylene oxide (EO) molecules. The production of polycyclohexene carbonate (PCHC) with cyclohexene oxide as the epoxide is also being explored.

[40] Alberici, S. et al. (2017), *Assessing the Potential of CO2 Utilisation in the UK*, Ecofys UK, Ltd, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf.

[41] *Carbon Dioxide in Semiconductor Manufacturing,* Specialty Gas Report May 2016_tcm17-419010.pdf (linde-gas.com)

[42] Lithography is a process used to pattern specific geometric shapes on a silicon wafer for circuit fabrication to produce electrical devices.

[43] Avoidance of bubbles.

CO_2 fixation and the production of valuable materials. Research has looked into finding and isolating suitable algal strains. Furthermore, photobioreactors with higher fixation rates and possible scale-up have been investigated[44].

Biogenic CO_2 can be used to **grow algae and microalgae** for the **production of biofuels** (bioethanol or biodiesel), as well as expensive **chemical compounds**, such as astaxanthin[45]. Microalgae culture can also be added to the treatment of wastewater, as they have the ability to remove heavy metals as well as some toxic organic compounds.

4.5. Building materials

Biogenic CO_2 can be used as an **input in the manufacturing processes of building materials**, such as cement, concrete and aggregates for building purposes.

They all use the same chemical process of **CO_2 mineralisation**, also known as carbonation. Mineralisation is a natural phenomenon, where calcium- or magnesium-containing minerals (e.g. olivine) react with carbon dioxide (CO_2) to produce calcium or magnesium carbonate ($CaCO_3$ or $MgCO_3$), also known as limestone or dolomite, one of the most abundant rock types formed throughout the history of the Earth. **This natural carbonation reaction**, which happens in nature over thousands of years, **can be purposefully accelerated** to take only a few minutes by using high CO_2 concentrations and optimised reaction conditions. The reaction leads to the creation of **stable products in which CO_2 is permanently captured (CCUS)**.

Producing building materials based on accelerated carbonation can **contribute to three major societal challenges:**

- **the mitigation of climate change**: CO_2 gets permanently sequestered (under the form of stable carbonate) in end products (see Chapter 2);
- **the management of waste** in the case of carbonation based on mineral waste: waste from various industry sectors is transformed into valuable construction materials, so no longer has to be disposed of in landfills;
- As a consequence, **the reduction of natural resource consumption**: these processes reduce the need to extract fresh mineral resources from quarries (the mineral waste pathway) and for water (in the case of concrete curing).

These alternative processes are therefore in line with the transition to a circular, resource-efficient economy, one of the objectives of the EU Green Deal[46].

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[44] Mikkelsen, M., Jørgensen, M., & Krebs, F. C. (2010). *The teraton challenge. A review of fixation and transformation of carbon dioxide.* Energy & Environmental Science, 3(1), 43-81.
[45] Astaxanthin can be used as a food additive, dietary supplement and in medicines.
[46] See European Communication, *The European Green Deal*, COM(2019) 640 final, 11.12.2019.

Two main routes of mineralisation are currently being deployed or developed, specifically concrete curing and mineral waste recycling.

A) Concrete curing

CO_2 can be **injected into the concrete mixing process,** producing ready-mixed concrete that is transported and set on site, or pre-cast concrete products. This does not require major changes in the process. CO_2 replaces water to produce calcium carbonate, and accelerates the hydration of the cement.

An alternative production process requires a novel cement and special curing chambers, but the amount of CO_2 taken up in the product is higher – up to 250 kg of CO_2 per ton of cement used.

The use of CO_2 in concrete mixing is already commercially available in Canada and the USA.[47]
Taking into account European consumption of CO_2 for **concrete production** estimated at 22.5 Mt/year[48], this environment-friendly practice could be extended to other European territories.

B) Mineral waste recycling

CO_2 can also be injected **as part of the recycling process of a large range of Ca/Mg-rich mineral waste** to manufacture diverse products such as aggregates (which can be used in road foundations or in the preparation of fresh concrete), construction bricks and blocks, concrete fillers, etc. The required mineral waste comes from various industrial sectors (power generation, steel, cement, mining, demolition, etc.): coal fly ash, steel slag, cement-kiln dust, bauxite residue and mine tailings.

CO_2 is reacted with these mineral waste streams to form carbonates (the form of carbon that makes up concrete). This conversion pathway is typically less energy-intensive than for fuels and chemicals, and involves permanent storage of CO_2 in the materials. Some CO_2-based building materials can offer superior performance compared with their conventional counterparts.

This technology is gaining traction. For instance, the British company Carbon8 specialises in using CO_2 to convert **waste materials** into aggregates as a component of building materials. In Italy, Sibelco and Rosetti Marino have started developing a new technology at Sibelco's Poviglio site for the permanent CO_2 sequestration by use of olivine[49]. The produced Ca/Mg-rich carbonates will be reused in the cement and ceramic industries.

[47] International Energy Agency (IEA), *Putting CO2 to Use. Creating value from emissions*, September 2019.
[48] Patricio, J. *et al., Region prioritization for the development of carbon capture and utilization technologies*, Journal of CO_2 Utilization, vol. 17, January 2017.
[49] Olivine is a high-purity magnesium–iron silicate mineral with the chemical formula $(Mg, Fe)_2 SiO_4$. It gets its name from its olive-green colour.

Chapter 5: CO_2 quality and purification technologies

Marketing CO_2 requires the elimination of impurities and the close monitoring of the product quality. Impurities in the CO_2 stream from biogas include sulphur components (typically hydrogen sulphide [H_2S] and carbon monoxide sulphide [COS]), methane, carbon monoxide, alcohols, aldehydes, ketones, aromatic hydrocarbons, ammonia, hydrogen, nitrogen and oxygen. The biogas industry has proven technologies to meet the most demanding quality requirements for biogas-derived CO_2.

5.1. CO_2 quality standards for different uses

In the food and beverage markets, the **E290 standard**[50] and the guidance from the European Industrial Gas Association (EIGA)[51] are used. The EIGA Guidelines describe **the minimum requirements for the food and beverage market,** and are considered as the reference guidance[52].

For other CCU applications, there are no specific standards or general accepted specifications. The quality required depends on each application, therefore on each customer or industrial gas supplier. However, the EIGA Guidelines tend to be the guiding specification for the complete CCU merchant market. As a consequence, all merchant CO_2-producing plants are generally designed to deliver one quality of liquefied CO_2, compliant with EIGA Guidelines.

For the CCS market, specifications formulated by the "Northern Lights" project are generally accepted for liquefied CO_2 transported by **barges or ships**. This project aims to transport fossil CO_2 captured in industrial processes by ships to a permanent storage in an underground saline aquifer[53]. The core concerns here are the corrosion protection of the transport assets as well as toxicity and solubility. For transport by pipeline in a gaseous form, a single specification does not exist. Several proposals have been provided, e.g. by the Porthos consortium[54], the US Department of Energy and the International Standard Organization. Yet none has been generally recognised as binding.

5.2. Specific requirements for biogas-derived CO_2 in the food and beverage market

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[50] Annex of Commission Regulation (EU) 231/2012 of 9 March 2012 laying down specifications for food additives listed in Annexes II and III to Regulation (EC) 1333/2008 of the European Parliament and of the Council (last amended by Commission Regulation (EU) 2020/771 of 11 June 2020).

[51] EIGA, Doc. 70/17 *Carbon Dioxide Food and Beverages Grade, Source Qualification, Quality Standards and Verification*

[52] They are in line with the internationally accepted guidelines for liquified CO_2 of the International Society of Beverage Technologists, which acts as a technical forum in this industry. See ISBT, Guidelines and Best Practices, https://www.isbt.com/resources-guidelines-best-practices.asp#BeverageGases

[53] Northern Lights project, https://northernlightsccs.com/

[54] To find out more about the Porthos project, see: https://www.porthosco2.nl/en.

Inputs to anaerobic digestion create risks of organic impurities and of nitrogen compounds depending on specific feedstock types.
Leading food and beverage companies only accept liquefied CO_2 from a source they have analysed themselves. Before accepting a delivery of liquid biogenic CO_2 from anaerobic digestion, they assess the risks involved with the source (i.e. variations in raw material supply and the risks of "unknown components").

Consequently, for biogas source, this qualification will be more challenging to obtain than for a chemical process-based source or a bio-ethanol plant with a quite constant feedstock. **An anaerobic digestion plant should aim for stability in the feedstock mix over a year and should ensure that the purification process can deal with many different impurities**.

As mentioned above, EIGA prescribes **specific guidelines on "source qualification" for liquefied CO_2 from biogas sources[55]:**

1. A **risk analysis** is conducted to account **for any chemical and biological health risks**, covering the feedstock as well as the digestion process itself. AD plants running purely on crops and their residues are subject to the **same criteria as "yeast-based fermentation sources"** (as for bio-ethanol plants), which are a commonly accepted source for merchant food-and-beverage grade CO_2 worldwide. AD plants that use waste or a mixture of crops and waste will be required to perform more detailed risk analysis.
2. Each batch of liquefied CO_2 must be analysed in respect of the minimum requirements already mentioned.
3. Any change in feedstock will require approval and revision of the risk assessment.
4. The AD plant and its feedstock will have to comply with European Implementing Regulation 142/2011[56] on CO_2 quality for the food and beverage sector.

It is also strongly recommended that a "Food Safety Management System" (e.g. ISO 22000) is in place at the anaerobic digestion plant.

5.3. Technologies to co-produce biomethane and bio-CO2

The best known and most mature technologies are **sorption methods**, including adsorption and absorption techniques, and **separation**, which refers to membrane use and cryogenic methodology[57]. More than ¾ of the biomethane plants currently active use either **membrane separation** (39%), water scrubbing (22%) or chemical scrubbing (18%) as upgrading technologies (Figure 9).

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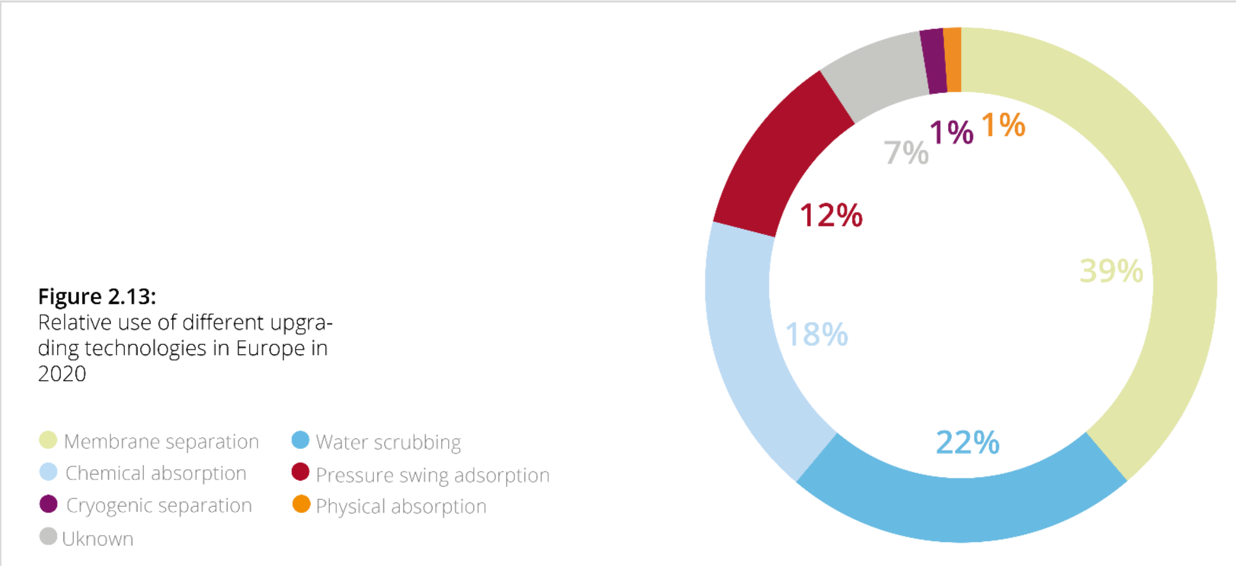
[55] Referred to as "AD-plants" for "Anaerobic Digestion" in the EIGA Guidelines.
[56] *Implementing Regulation (EU) 142/2011 of 25 February 2011 implementing Regulation (EC) 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation 1774/2002 (Animal by-products Regulation).*
[57] Adnan, A.I.; Ong, M.Y.; Nomanbhay, S.; Chew, K.W.; Show, P.L. *Technologies for Biogas Upgrading to Biomethane: A Review.* Bioengineering, 2019, *6*, 92. https://doi.org/10.3390/bioengineering6040092

Since 2013, there has been a shift from chemical scrubbing towards membrane separation. 76 of the plants that started operations in 2020 – 47% of the total number of newly installed plants that year – are known to use membrane separation as their upgrading technology.

Figure 9: Relative use of different upgrading technologies in Europe in 2020 (source: European Biogas Association, Statistical Report 2021)



In general, **high concentrated CO_2 (up to 99% purity) can be obtained with any of the alternatives**.

- Physical or chemical absorption are mature technologies that provide a spectrum of separation options. For instance, amine (chemical absorption) has high affinity for CO_2, which allows its capture from biogas, and, after the process, the rich amine is further heated in the regeneration still column, where the CO_2 is liberated, regenerating the amine.
- Membrane systems are extremely adaptable to various gas volumes, CO_2 concentrations, and/or product-gas specifications. Using a membrane for biogas upgrading, the feed stream is separated into a methane-rich (residual) stream on the exterior of the membrane fibre and a carbon dioxide-rich (permeate) stream on the interior of the membrane fibre, easy to recover for further applications.
- Cryogenic separation has the advantage of enabling direct production of liquid CO_2, which is needed for certain transport options, such as long-distance haulage. However, a disadvantage of cryogenic separation of CO_2 is the amount of energy required to provide the refrigeration necessary for the process[58].

[58] *CO_2 Capture Project, Three basics methods to separate gases*, 3_basic_methods_gas_separation.pdf (co2captureproject.org)

5.4. Technologies available to ensure compliance with market requirements

From the technological point of view, there are no obstacles to making CO_2 from biogas fully compliant with all merchant market or CCS quality requirements.

Purification and liquefaction processes available on the market today are capable of treating CO_2 from biogas sources and of generating a liquefied CO_2 that is fully compliant with the most stringent requirements (i.e. the EIGA's).

Even for the additional risk assessments required by the food and beverage market, there are proven technologies available that can not only eliminate typical impurities, but also mitigate any other risk raised by the qualification analysis. These technologies include:

- Water scrubbing (removal of alcohols, ammonia, etc.)
- Sulphur removal processes (removal of hydrogen sulphide, carbon oxide sulphide, etc.)
- Catalytic incineration processes (converting all remaining organic impurities into CO_2 and water)
- Activated carbon purifiers (removal of small traces of organic, taste/odour and sulphur components)
- Liquefied CO_2 scrubbing (removal of oxygenates)
- Liquefied CO_2 distillation (removal of CH_4, CO, H_2, O_2, N_2, organic volatiles, etc.)
- NO_x filters

Several European companies can provide all these purification technologies as well as CO_2 liquefaction units. They are exporters and world leaders in innovation in this field.

Chapter 6: BIO-CCU in practice

DENMARK

Korskro biogas plant (update)

Location: Korskro, Denmark (Nature Energy)
Status: in operation
AD feedstock: manure
CO_2 use: food industry
Production: 16,250 tons/year of biogenic CO_2

The biomethane plant in Korskro, Denmark has been in operation since 2019. It processes about 500,000 tons of biomass annually, of which around 75% is manure and litter from cattle, pigs and minks. This plant recently upgraded its production size and added a carbon capture unit. The total capacity of biomethane production increased from 22 million m³ (in 2019) to 49 million m³ of biomethane. The CO_2 separated in the biogas upgrading process is now captured and processed. After purification, the biogenic CO_2 is used in the food industry and beyond. Annually, 16,250 tons of biogenic CO_2 is captured and utilised, which is equal to 25% of Denmark's CO_2 demand.

Avedøre

Location: Avedøre, Denmark
Status: in operation
AD feedstock: wastewater
CO_2 use: -
Production: 800 tons/year of biogenic CO_2

Electrochaea's first commercial-scale P2G pilot plant was integrated into the Avedøre WWTP operated by BIOFOS. Operation of the 1MWe demonstration plant started in April 2016 and continued until 2019. In total, the plant was operated for >3,500 hours, both with raw biogas from the wastewater treatment plant's anaerobic digester, as well as with purified CO_2 from an amine wash upgrading facility run by Ammongas A/S. Heat generated in the P2G process was captured and utilised in the WWTP operations. The system has flexible operational modes and responds rapidly to available energy, so it could also provide frequency regulation services to the Danish power grid. The gas produced contains more than 98% methane and less than 1% hydrogen and CO_2, exceeding the requirements for gas grid injection in Denmark and certified by ETV. The first grid injection took place in September 2019. With a power consumption of 1MWe, the plant has the capacity to inject up to 1,200 m3 per day of biomethane into the natural gas grid, at the same time preventing the release of 800 tons of CO_2 per year. The plant was built and operated with the support of the joint BioCat project, including seven European consortium partners, and was funded by the Energy Technology Development and Demonstration Program (EUDP) of the Danish Energy Agency.

ENGLAND

Carbon Harvest Project (Future Biogas)

Location: East Anglia, United Kingdom
Status: under development, operational in 2025
CO_2 use: underground storage in the seabed of the North Sea
Production: 15,000 tons/year of biogenic CO_2 per AD plant

This ongoing Project Carbon Harvest will aggregate biogenic CO_2 from across the UK and transport it to the Northern Lights project. New AD plants will be built without subsidies with the aim of becoming carbon capture plants. Existing plants will have retrofit liquification to biogas upgraders. The main feedstock for the new plants will be crops that are suited to the local rotations and soil types, contributing to a soil-positive farming system that ensures sustainability of production. The project aims to build 3 to 4 AD plants per year, with an annual liquid CO_2 production of 15,000 tonnes per plant. The first AD unit is planned to be commissioned at the end of 2024, in time for Northern Lights opening in 2025. The total production in 2025, with the addition of retrofit of existing AD plants in the UK, is intended to reach 200,000 tonnes per year.

FRANCE

Metha Treil

Location: Loire-Atlantique, France
Status: in operation
AD feedstock: livestock effluents, cover crops or corn silages, vegetable by-products
CO_2 use: greenhouses
Production: 1,500 tons/year of biogenic CO_2


©Agrikomp

Metha Treil is located in Loire-Atlantique, western France, and specialises in the production of gaseous fuels. SAS Metha Treil brings together farmers and market gardeners on an anaerobic digestion unit, where three farms provide inputs for AD, and at least one of the two market gardeners uses CO_2 for the growth of its greenhouse crops. The anaerobic digestion plant includes, among other technology, two 1,800 m³ digesters, which are fed by livestock effluents, silage from cover crops or corn and vegetable by-products. Biomethane upgrading is carried out using membrane filtration technology. The biogenic CO_2 recovery process recovers the lean gas at the outlet of the upgrading module, and through a succession of thermodynamic and physical operations, isolates the CO_2 in the liquid phase. 1,500 ton/year of CO_2 are produced. The CO_2 is stored in a vertical tank, before being transported, once or twice a week, to the greenhouse site in Saint-Philbert-de-Grand-Lieu.

Germany

Revis Bioenergy

Location: Cloppenburg, Germany
Status: Currently under development, operational by 02/2023
AD feedstock: Manure
CO_2 use: -
Production: 103 tons/year of biogenic CO_2

Revis Bioenergy is putting in place a fully circular industrial scale biomethane, biogenic CO_2 and organic fertiliser production unit in the Cloppenburg region. The unit will produce approximately 125 tons per year of liquid biomethane, 178 tons per year of dried fertilizer, 43 tons per year of liquid fertiliser and 596,000 tons per year of clean water. Moreover, it will produce 103 tons per year of biogenic liquid CO_2. The benefits are twofold – both for the farmers economically and for society with the abatement of methane emissions, providing a large societal greenhouse gas savings. It is the first operation of this large scale in Europe, providing carbon-negative fuel for transport or carbon-negative fuel to heat homes as replacement for fossil natural gas.

Italy

Agricultural Cooperativa Speranza


©Agricultural Cooperativa Speranza/ EFA News

Location: Candiolo, Italy
Status: under operation since 2008
AD feedstock: agricultural by-products and animal wastes
CO_2 use: industrial gases and mineral water industries
Production: 4,000 tons/year of biogenic CO_2

Agricultural Cooperativa Speranza is based in Candiolo, Italy. Currently seven farms are associated with over 2,000 hectares of land owned or managed. The Cooperative owns two biogas agricultural plants (built in 2008 and in 2010) fed by all agricultural by-products and animal wastes (manure and slurry) of the members and of some neighbouring non-member farms. These feedstocks are used to produce renewable electricity (sold to the grid), liquified biomethane (bio-LNG), biogenic CO_2, digestate and heat. In 2020, the cooperative built a new biomethane plant, which produces 300 m3 biomethane/hour. The gaseous biomethane is liquified and all the carbon dioxide from the upgrading is captured. Actual CO_2 production is 4,000 tons a year. The carbon dioxide, which in Italy is currently extracted from underground wells and imported from other countries, is sold to a local company that deals with industrial gases and to a local company that bottles mineral water.

NORTHERN IRELAND

Greenville Energy Ltd


©Greenville Energy Ltd

Location: Northern Ireland
Status: under operation since 2012
AD feedstock: crop residues, food waste and livestock effluent
CO_2 use: dry ice
Production: 5 tons/day biogenic CO_2

Greenville Energy Ltd is a farm-based biogas production company located in Northern Ireland, which started anaerobic digestion operations in 2012, converting a wide range of organic and animal waste into renewable biogas. In 2018, Greenville Energy installed the first bio-LNG facility of its kind in the world, where raw biogas is upgraded into methane and CO2, to produce Renewable Liquid Natural Gas and Liquid Carbon Dioxide. The bio-LNG is utilised to provide electrical and thermal energy to local companies with high energy demands. The liquid carbon dioxide (with a production of 5 tons/day) is processed into solid dry ice for use in industry. As the company continues to grow, under its sustainable and zero emissions compromise, it expects to produce bio-LNG for use as road vehicle fuel in the future, to fuel its own fleet of waste vehicles from the waste they process.

NORWAY

RENEVO

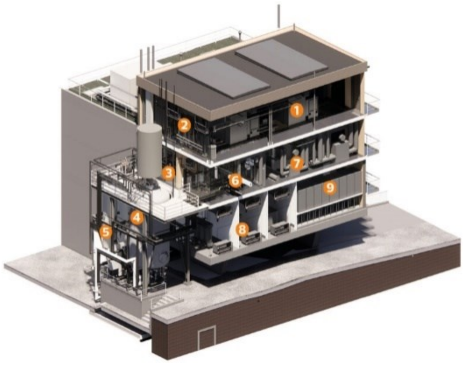
Location: Stord, Eldøyane, Norway
Status: under development.
AD feedstock: salmon fish residues and livestock manure
CO_2 use: commercial uses, such as dry ice
Production: 11 tons/day of biogenic CO_2 (estimate)

RENEVO is a project that will operate in Stord, Eldøyane, West-Norway, and will liquify biogas in a production plant based on cryogenisation. The production plant will utilise salmon fish residues and livestock manure as feedstock. The outlet of the AD plant will produce biogas, which will be upgraded to biomethane and biogenic CO_2. The gases will be liquified and stored in individual tanks. Estimated biogenic CO_2 production will be 11 tons/day. Liquified biogenic CO_2 will be sold for commercial uses, such as dry ice production.

SWITZERLAND

Dietikon

The world's largest power-to-gas (PtG) plant will soon be built in Dietikon, Switzerland. The Swiss energy supplier Limeco is partnering with Viessmann subsidiaries microbEnergy and Schmack Biogas (biogas from wastewater treatment plants) to build the plant, which will convert biogenic CO_2 and hydrogen into methane. The technology was developed and brought to production maturity by Viessmann subsidiary microbEnergy. The technology supplier for the electrolysis is Siemens. The companies involved jointly signed the contract for services in this major forward-looking project. According to Limeco Managing Director Patrik Feusi, the electricity from the waste treatment plant and the sewage gas from the utility's wastewater treatment plant are the two most important ingredients in the power-to-gas process - and are the same location.



Location: Dietikon, Switzerland
Status: under development
AD feedstock: wastewater
CO_2 use: methane production (power-to-gas)
Production: -

STORE&GO Project

Location: Solothurn
Status: demonstration plant commissioned in May 2019
AD feedstock: wastewater
CO_2 use: -
Production: -

Electrochaea's demonstration plant based on second generation power-to-gas in Solothurn featured major improvements in design, automation and energy efficiency, and was commissioned in May 2019. The 0.7 MWe system was part of the funded STORE&GO project, and was integrated into the Hybridwerk Aarmatt site, with interconnections to the existing hydrogen production and heating infrastructure, and to a purified CO_2 stream from a close-by wastewater treatment AD plant. The first gas grid injection was achieved within 96 hours of start-up, and maintained during >80% of operation. Up to February 2020, >1,200 hours of operation were achieved, with 11.2 tons of renewable gas being injected (173 MWh). The process has proved to have great flexibility: on/off cycles with immediate recovery after various shut-down periods were demonstrated successfully as well as 0%-100% capacity load factor tests maintaining high gas quality (> 97% CH_4 in product gas).

Chapter 7: Removing regulatory barriers to roll out biogenic CO_2 capacity

Far from producing only renewable energy, biomethane production facilities are circular economy hubs, turning organic materials from different streams into several products: a renewable energy carrier, organic fertilisers (digestate) and industrial gas (biogenic CO_2). Consequently, the regulatory framework should ensure that the capture, use and storage of biogenic CO_2 from the biogas sector are rewarded for their environmental benefits. Policymakers should also set drivers to facilitate the uptake of biogenic CO_2 and derived products. The biogenic CO_2 value chain should be recognised in the EU sustainable finance framework.

7.1. Creating a market for biogenic CO2 by rewarding its environmental benefits

A) The use of biogenic CO_2 must be recognised in the accounting of CO_2 emissions avoidance to create a demand for it

This should be done for both the activities included in the European Trading Scheme (ETS), like chemical industries, and those that are not in the ETS, such as agriculture and small industries.
The rules on the monitoring and reporting of emissions should recognise:

- the use of *biogenic CO_2 as alternative carbon feedstock* (preferential treatment over fossil CO_2);
- the use of *biogenic CO_2-based fuels* (like synthetic methane) as CO_2 neutral (like sustainable biogas);
- the *purchase of carbon removal credits* on voluntary carbon markets.

This recognition should also be reflected in GHG emissions accounting by member states for the agriculture (use of biogenic CO_2 in greenhouses) and building industries (use in the making of construction materials). The use of biogenic CO_2 as a replacement for fossil CO_2 would then be incentivised.
Outside the ETS scope, international GHG emissions accounting tools for companies (including the GHG Protocol Corporate Standard) should factor in the use of biogenic CO_2 as displacing its fossil counterpart.

B) A European certification framework should enable the reliable issuance and trade of carbon removal credits

Establishing a credible certification system for carbon removal is the first essential step towards achieving a net contribution from carbon removals in line with the EU climate-neutrality objective.
Biogenic CO_2 can be stored underground or in construction materials, and in combination with renewable energy production, can achieve negative emissions. Lack of comparability and common rules for the certification of carbon removal also undermine the emergence of this market.

These issues should be addressed at European level, with the provision of a standard framework for existing certification that can enhance transparency of certification schemes and reporting, and the reliability of a product's green claims. Such solid foundations would contribute to a better business environment and ensure take-up for carbon removal and biogenic CO_2 utilisation.

C) European legislation should ensure that biomethane plant operators are incentivised for the co-production of biogenic CO_2 as a product

Rules on the GHG emissions accounting of biomethane production and use should consider the savings from the permanent storage and the utilisation of the captured biogenic CO_2 as an alternative to fossil CO_2. The regulatory framework should secure a financial incentive for plant operators to capture, purify and sell biogenic CO_2.

7.2. Accelerating the uptake of biogenic CO2 by setting up demand-side drivers

The use of biogenic CO_2 can be incentivised through **three types of measures**:

1. A target – setting a credible indicative target for the share of biogenic CO_2 in industrial sectors;
2. Compulsory disclosure of the origin (fossil/biological) of the CO_2 used in products, including beverages;
3. Pricing – biogenic CO_2-derived (motor or heating) fuels should have preferential tax treatment.

Such measures would overall incentivise the transition to a circular model in CO_2-consuming industries and in the renewable fuel sector.

7.3. Recognising the environmental value of bio-CCU and bio-CCS value chains in the sustainable finance framework

The European Union is developing a classification system that identifies environmentally sustainable economic activities: **the "Taxonomy of sustainable activities"**[59]. This classification is part of a wider European framework on sustainable finance that includes the disclosure regimes of companies and financial products and labelling systems, such as the proposed EU Green Bond Standard. It has also become a benchmark for EU public funding instruments, such as the Just Transition Fund and the European Investment Bank's climate lending policy.

The impact of the Taxonomy on the finance sector as well as on EU funding programmes is likely to be far-reaching. If bio-CCS and bio-CCU value chains based on anaerobic digestion and biomass gasification are

[59] According to the Regulation 2020/852, an environmentally sustainable activity is one that makes a "substantial contribution" to at least one of six environmental objectives, whilst ensuring that this activity will "do no significant harm" (DNSH) to any of the other five objectives and also meet minimum social safeguards. The six environmental objectives are: climate change mitigation; climate change adaptation; the sustainable use and protection of water & marine resources, the transition to a circular economy, pollution prevention and control, the protection and restoration of biodiversity & ecosystems.

not recognised as sustainable by the Taxonomy, they will suffer as a result of a lack of access to private finance for its development. **These value chains should rather be considered as sustainable based on their contribution to the objectives of “climate change mitigation” and “transition to a circular economy” as soon as possible**.

Annexes

Annex 1: Concentration and capture costs

CO_2 source	CO_2 concentration [%]	Capture cost [USD/tCO_2]
Natural gas processing	96 – 100	15 – 25
Coal to chemicals (gasification)	98 – 100	15 – 25
Ammonia	98 – 100	25 – 35
Bioethanol	98 – 100	25 – 35
Ethylene oxide 98 – 100	98 – 100	25 – 35
Hydrogen (SMR)	30 – 100	15 – 60
Iron and steel	21 – 27	60 – 100
Cement	15 – 30	60 – 12

Source: IEA, *Putting CO_2 to use*, 2019.

Annex 2: Existing European biomethane facilities combined with bio-CCU(S)

Country	Name or Location	Feedstock type	Use of biogas	CO_2 end use	CO2 production
UK	Guy&Wright Farm	Waste crops	CHP	Greenhouses	
UK	UK Wight Farm	Crops	Upgrading	Food grade CO2	
Ireland	Greenville	Agri waste	Bio-LNG	Dry ice	5 T /d
Italy	Coop Speranza	Agri residues	Bio-LNG	Food grade CO2	8,5 T/d
Italy	Montello SpA	OFMSW[60]	Upgrading	Food grade CO2	200 T/d
Italy	SESA SpA	OFMSW	Upgrading	Food grade CO2	45 T/d
Italy	Caviro SpA	Agri residues	Upgrading	Food grade CO2	45 t/d
Italy	Biogas Wipptal (project)	Manure	Bio-LNG	Food grade CO2	15 /T d
France	Metha Treil SAS	Agri waste	Upgrading	Greenhouses	3.5 T/d
France	Agrogas pays de Trie	Agri waste	Upgrading	Food grade CO2 (ongoing)	8 T/d
Norway	Stord Island (project)	Salmon	Bio-LNG	Dry ice	11 T/d
Switzerland	Dietikon (project)	WWTP[61]	Methanation	SNG	100 Nm3/h
France	Pau	WWTP	Upgrading	SNG	50 Nm3/h
Germany	Augsburg	Biowaste	Upgrading + liquefaction	Dry ice, wastewater neutralization, snow jets, fire extinguishers	5 T/year
The Netherlands	Luttelgeest	Agri-residues and biowaste	Upgrading	Greenhouses	
The Netherlands	Westdorpe	Manure and organic by-products	Upgrading	Greenhouses	20,000 tonnes/year

[60] Organic Fraction of Municipal Solid Waste (OFMSW)
[61] Wastewater Treatment Plant (WWTP)

Glossary

Biochar	Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention of improving soil function and reducing greenhouse gas (GHG) emissions from biomass that would otherwise decompose rapidly (International Biochar Initiative, 2018).
Biogas upgrading	Process of separation of methane from CO_2 and other gases in small concentrations from the biogas.
Biomass	Biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin ("Renewable Energy" 2018/2001 Directive).
Carbon offsetting	Actions or activities that compensate for the actual emission of carbon dioxide or other greenhouse gases into the atmosphere by other activities.
Carbon removal	Absolute reduction of CO_2 emissions in the atmosphere by a human production system that removes and durably stores the carbon dioxide. Also called "carbon dioxide removal".
Carbon-negative fuel or energy	Fuel or type of energy production process that has a carbon footprint lower than neutral, having a net effect of removing carbon from the atmosphere.
CCU or "Carbon Capture and Utilization"	Systems that include the capture of CO_2 for its use (pure CO_2 or CO_2-containing gas mixtures) as a feedstock to produce fuels, chemicals and materials. When these products are made by using both biogenic CO_2 and low-carbon or renewable energy sources, they can displace their fossil-based versions and thus reduce net carbon emissions into the atmosphere. When using biogenic CO_2, we will refer to these systems as "bio-CCU".
CCS or "Carbon Capture and Storage"	Systems that include CO2 capture for its transport and storage, allowing the permanent removal of CO_2 from the atmosphere. When the stored carbon originates from biomass, we refer to "bio-CCS".
CO_2 hydrogenation	Chemical reduction reaction that occurs between CO_2 and hydrogen in the presence of a metal catalyst. By adding hydrogen atoms to CO_2, hydrogenation changes the structure of the molecule, obtaining different C_2+ compounds such as methane or methanol.
CO_2 mineralisation	Process created by reacting CO_2 with calcium and or magnesium contained in natural minerals or in mineral wastes to produce carbonate-based aggregates. These aggregates can be used as construction materials or to make roads.
Gasification	Physico-chemical oxygen-depleted process in which the carbon-containing components of the biomass break down into syngas instead of being completely combusted. The syngas can be upgraded into biomethane.
Inert gases	Gases that do not form chemical reactions with other chemical substances under a set of given conditions, and therefore do not form chemical compounds.
Methanation	Combination of hydrogen with carbon dioxide to produce methane. When the hydrogen and the carbon dioxide are of renewable origin, the synthetic methane is deemed renewable.

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About the EBA

The EBA is the voice of renewable gas in Europe. Founded in February 2009, the association is committed to the active promotion of sustainable biogas and biomethane production and their use across the continent. The EBA today counts on a well-established network of over 200 national organisations, scientific institutes and companies from Europe and beyond.

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