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Hitchhiker's Guide to Carbon Capture and Utilisation

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Hitchhiker's Guide to Carbon Capture Utilisation (CCU)

1 Introduction: Giacomo Ciamician – The forefather of CCU

Carbon capture and utilisation is a topic that has been heavily discussed and developed in recent years and is seen as one of the key technologies and innovations for a sustainable future. Although the topic seems to be new, already more than 100 years ago some pioneers thought about a future based on photochemistry.

One of the most visionary scientists of that period was Giacomo Ciamician, professor of chemistry at the universities of Padova, Rome and Bologna. He was born 1857 in Trieste, at that time part of the Austro-Hungarian monarchy, from Armenian descent, and studied chemistry at the universities of Vienna and Gießen.

Ciamician can be seen as the scientific father of green chemistry and photochemistry. His first photochemistry experiment was published in 1886 and was titled "On the conversion of quinone into quinol". From 1900 to 1914 he published about 40 notes and nine memoirs on these topics.

In his visionary paper "The photochemistry of the future" in Science (Ciamician 1912) he wrote:

> *"On the arid lands there will spring up industrial colonies without smoke and without smokestacks; forests of glass tubes will extend over the plains and glass buildings will rise everywhere; inside of these will take place the photochemical processes that hitherto have been the guarded secret of the plants, but that will have been mastered by human industry which will know how to make them bear even more abundant fruit than nature, for nature is not in a hurry and mankind is. And if in a distant future the supply of coal becomes completely exhausted, civilization will not be checked by that, for life and civilization will continue as long as the sun shines!"*

This paper he also presented in a speech at the 8th International Congress on Applied Chemistry. He described the world's need for an energy transition to renewable energy and saw the possibility to use photochemical devices utilising solar energy to produce fuels and chemicals to power the human civilisation. Ciamician called for their development to make humanity independent from fossil feedstocks and also to rebalance the economic gap between rich and poor countries, long before such topics moved into focus in light of climate change and sustainability issues. He did most of his work at the University of Bologna, Italy, where he died in 1922.

G. Ciamician

2 Carbon Capture and Utilisation (CCU) – The principles

2.1 What does "Carbon Capture and Utilisation (CCU)" mean and what are the main benefits?

Carbon Capture and Utilisation (CCU) stands for the capture and utilisation of carbon dioxide (CO_2) as a carbon source to be used as a feedstock in the production of fuels, carbonates, chemicals and polymers. In some cases when syngas is the raw material of choice also carbon monoxide (CO), as a syngas ingredient, is used as a feedstock (see chapter 2.3 and chapter 3). The energy needed for the transformation of CO_2 must stem from renewable resources to provide an environmental benefit compared to other sources of carbon.

CCU is a business case: There is convincing evidence that numerous companies will invest in new technologies to implement and market products made from CO_2, replacing fossil feedstock and contributing to climate mitigation. As we show below, the potential volume of CCU is much bigger than commonly assumed and discussed. And the best part: We can immediately start with the implementation of CCU.

Carbon Capture and Sequestration (CCS) sounds similar, but is a completely different concept. CCS also starts with the process of capturing waste CO_2 from large point sources, but then transports it to a sequestration site and deposits it where it will not enter the atmosphere, normally an underground geological formation.

CCS is not a business case, but a long-term government programme for the storage of CO_2, which must be financed over many decades. The main problems are the identification of suitable sites and the acceptance of the population.

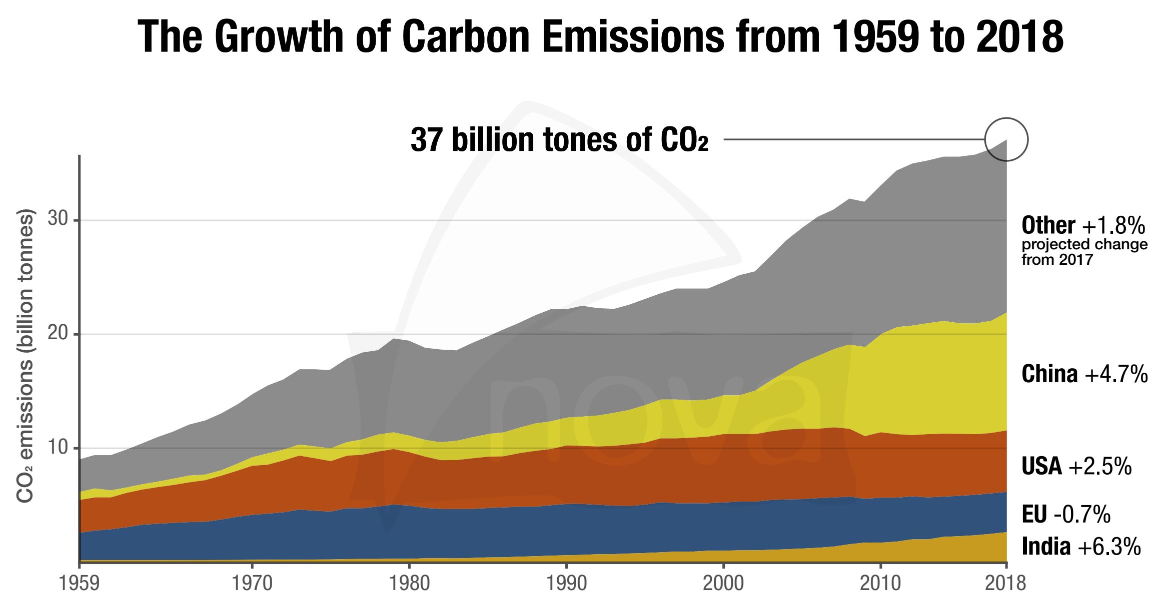
While CCS permanently stores CO_2 underground, CCU substitutes fossil raw materials and their CO_2 emissions. Both technologies contribute to climate mitigation and can complement each other – well coordinated in an overarching concept.

To learn more about the similarities and differences between CCU and CCS, see chapter 2.5 and 2.6.

2.2 Which sources of CO_2 are available?

CO_2 is available from several sources. For CO_2 utilisation, it can be captured from point sources in the industry, like power and production plants, as well as directly from the atmosphere (direct air capture). The captured CO_2 can be either “black” CO_2 from fossil origin (oil, coal, gas) or “green” CO_2 especially from fermentation facilities (food industry, biogas, bioethanol) or from other biomass converting industries (pulp and paper, biomass-based energy production). With direct air capture, CO_2 can be taken everywhere directly from the atmosphere.

In times of still increasing fossil CO_2 emissions (Figure 1) (Dennis et al. 2018), it makes great sense to start with a focus on large point sources such as power plants for CCU.



Figures show emissions from fossil fuels and industry
which includes cement manufacturing but not deforestation

Source: Global Carbon Project

All figures available at www.bio-based.eu/markets

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Figure 1: Growth of worldwide CO_2 emissions. Modified according to (Dennis et al. 2018).

Here, the technology to separate the CO_2 is commercially developed and allows to immediately scale up CCU in order to replace additional fossil raw materials. According to current developments and projections for direct air capture, a switch to direct air capture as a universal option will become feasible later on. Of course, it is important that this transition must not prolong the life of the fossil-based energy system.

2.3 What are the applications for CCU fuels, chemicals and minerals?

CCU leads to a broad range of applications where the CO_2 can be used as feedstock for chemicals, polymers, fuels, minerals and even proteins (see chapter 3). By combining CO_2 with hydrogen, several intermediates and end products can be produced, for example methane and methanol. These can, in combination with CO_2-based formic acid, be used as a base feedstock for all kinds of chemicals, polymers and fuels. Synthetic naphtha, which is able to directly replace crude oil naphtha in an existing refinery, can be produced from CO_2 and hydrogen via Fischer-Tropsch reaction and offers opportunities for the production of a wide range of fuels (kerosene, synthetic diesel and petrol). Synthetic naphtha also allows to derive basic chemicals for the production of higher-grade chemicals and polymers as well as long-chain waxes with high purity and value. Some other chemicals are by default directly synthesised from CO_2, for example urea and diverse polymers like polyurethanes and polycarbonates.

Outside of organic chemistry, CO_2 can be used for mineral processes, more precisely carbonisation of minerals into products for the construction industry and for a broad range of other applications.

2.4 How sustainable is the use of CO_2 in products compared to petrochemical or bio-based products?

In recent years, various research institutes have carried out life cycle assessments of fuels, chemicals and polymers from CO_2, and they come to a clear conclusion: CCU-based products have significantly lower greenhouse gas emissions than comparable fossil products – if the energy used to reduce CO_2 comes from renewable sources. Please find a more detailed example in the following paragraph as well as in chapters 5 and 6.

As expected, when you compare CCU-based products with bio-based products and their greenhouse gas (GHG) emissions, the results are not quite as distinct. However, CCU can in these cases score with much smaller area and water requirements. Timothy D. Searchinger from Princeton University (Searchinger et al. 2017) has calculated that the global average area required for the production of ethanol from wood is 85 times larger than what is required for photovoltaics (PV) and direct CO_2 utilisation. The reason for this is the considerably better yield of modern solar cells (20-25%, experts even consider efficiencies of 40% possible by 2050), compared to natural photosynthesis. Looking at the entire process chain of natural photosynthesis, including agriculture and downstream processes, usually only 0.1 to 0.3% of the solar radiation ends up in a final product.

2.5 Can the use of “black” CO_2 from fossil emissions be sustainable at all? Should CCU only be supported if “green” CO_2 or direct air capture is used?

There is considerable debate as to whether CCU based on fossil CO_2 sources can have positive climate effects or whether it is not just simply delaying the emission of CO_2 without any actual climate relevance. Take the example of a fuel made from fossil CO_2: the emissions from a natural-gas fired power plant are captured and converted into fuel with the help of renewable energy. When the fuel is burnt in the vehicle, the CO_2 is released back into the atmosphere. Where are the climate benefits?

In the above example, we have forgotten a crucial point: The CCU fuel from fossil CO_2 substitutes another fossil fuel, whose fossil carbon now remains in the ground. Instead of having emissions from both the natural gas-fired power plant and from fossil fuel combustion, the emissions of the natural gas-fired power plant are reused for the fuel combustion and then finally emitted once. This substitution is the key to greenhouse gas (GHG) reduction by CCU fuels, even when it stems from fossil CO_2.

The following set of illustrations are designed to help explain and visualise the possible benefits of reusing CO_2. The figures are theoretical examples and model ideal conditions with a 100% process efficiency, i.e. they contain no losses. This idealisation means that some other factors are not displayed in the illustrations, although they will have an impact in reality, e.g. the energy requirements for separation and purification of the CO_2.

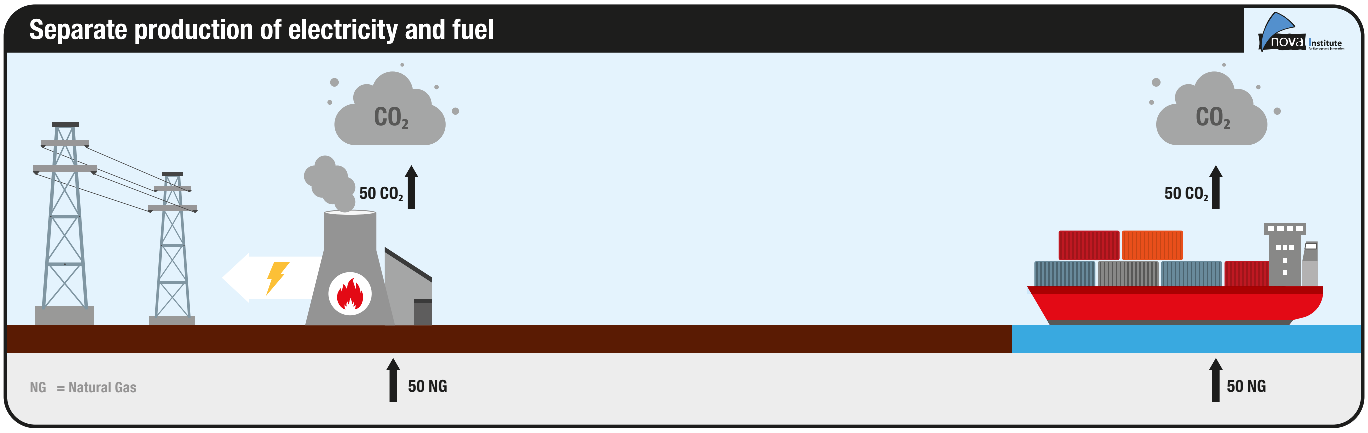

Figure 2: Independent production of electricity and fuel

In Figure 2 a typical production and emission process of electricity generation from a natural gas-fired power plant and a separate fuel generation for ship transport based on natural gas (NG) are depicted. In this “business-as-usual” system, emissions for both the electricity generation and the burning of the ship fuel enter the atmosphere and, in both cases, fossil carbon from natural gas has been utilised for energy generation.

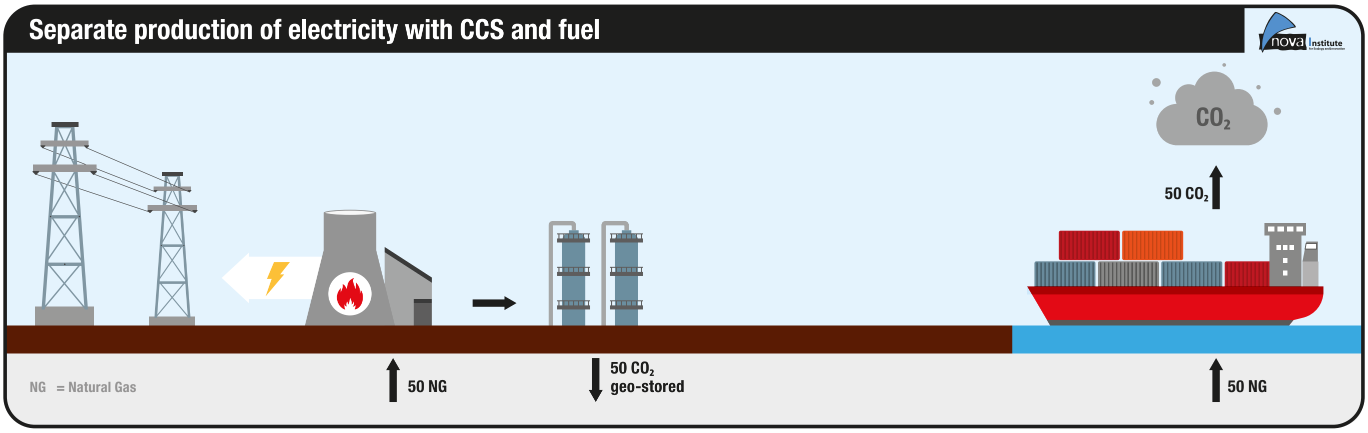

Figure 3: Separate production of electricity with CCS and fuel

Figure 3 shows the coupling of the electricity production process with a geo-storage system for the emissions of the natural gas-fired power plant (CCS). As a consequence of the CCS technology, the emissions of the plant are avoided and stored underground. At the same time, the ship fuel process remains unchanged. In total, and not considering emissions caused by separation and purification of the gas stream, the CCS process reduces the total greenhouse gas (GHG) emissions to the atmosphere by 50%.

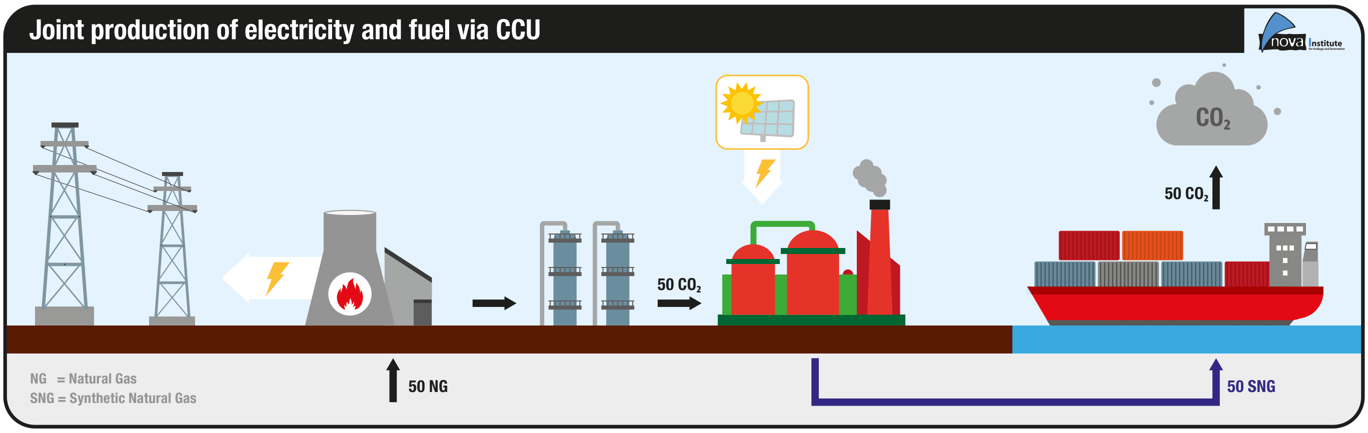

Figure 4: Joint production of electricity and fuel via CCU

In comparison Figure 4 now introduces a CCU process to the system. Here, the emissions from the natural gas-fired power plant are captured and transferred to a fuel production plant, which produces synthetic natural gas (SNG) under the use of renewable energy. The resulting SNG can be used as a substitute for the natural gas required as a ship fuel. In the end, the CCU process reduces the overall GHG emissions by 50%, just like the CCS process from Figure 3, but provides no dead-end short-term solution for the CO_2 due to limited storage and public acceptance issues. The CCU process leaves room for additional processes (e.g. direct air capture) that can be coupled and this way establishing a circular economy for CO_2 as described in Figure 7.

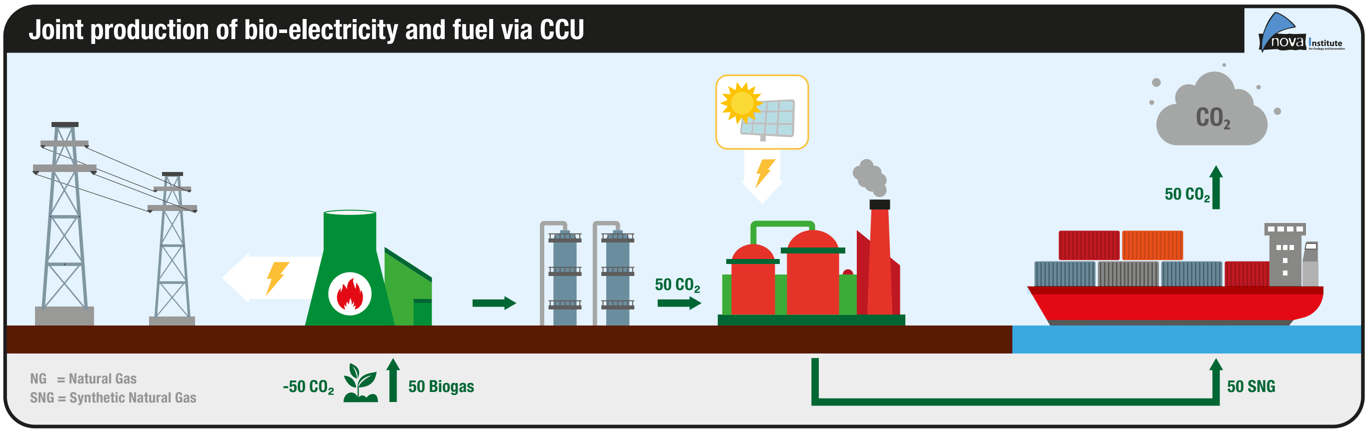

Figure 5: Joint production of bio-electricity and fuel via CCU

In the example of Figure 5 the electricity generation in the natural gas-fired power plant is based on renewable biomass (biogas), which is assumed to regrow and bind the same amount of CO_2 that gets released in the process of the electricity generation. Again, the resulting emissions are captured and transferred to the CCU process, which generates synthetic natural gas (SNG) as a substitute for standard ship fuel. Factoring in the CO_2 that was taken up by the biomass, overall emissions are reduced by 100%. The same amount that was released due to ship transport is covered by CO_2 uptake of the biomass.

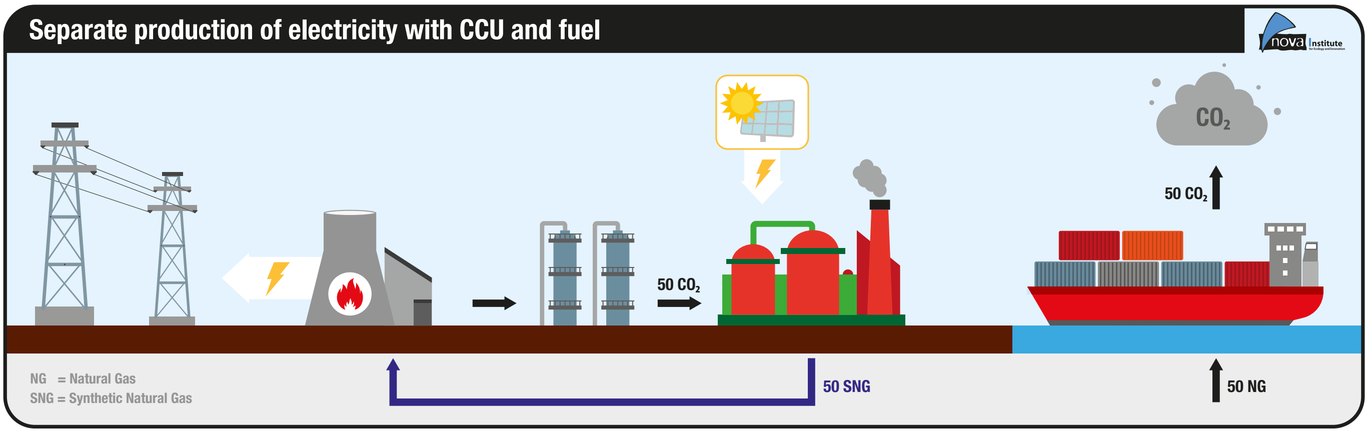

Figure 6: Separate production of electricity with CCU and fuel

Figure 6 shows the substitution of biogas for electricity generation in the natural gas-fired power plant with the use of SNG from captured fossil CO_2 via a CCU process. Here, the captured fossil CO_2 is incorporated into a circular system, as an alternative to the linear use of the captured biogenic CO_2 (Figure 5).

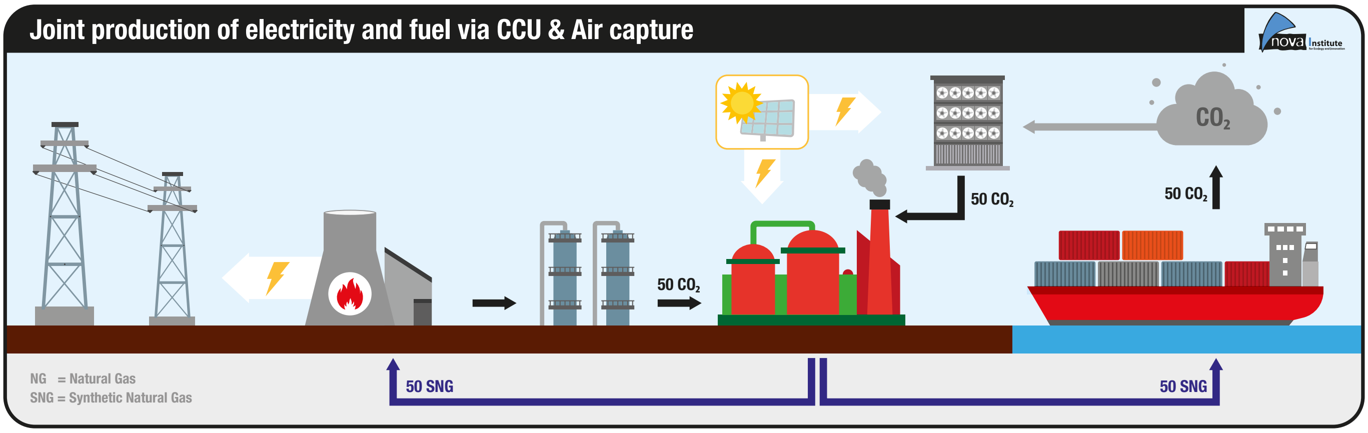

Figure 7: Joint production of electricity and fuel via CCU & Air Capture

In Figure 7 the CCU process for electricity generation of the natural gas-fired power plant via SNG (Figure 6) is coupled with direct air capture to provide the required CO_2 for SNG production to be used as a ship fuel. So, utilising renewable energy, the CCU process can produce SNG for both the electricity generation in the natural gas-fired power plant and as a ship fuel. Providing full circularity, the emissions from the natural gas-fired power plant are directly fed back into the CCU process, while the direct air capture covers the ship transport emissions. The resulting net balance of GHG emissions and CO_2 capture and utilisation is zero, indicating a 100% reduction in GHG emissions.

These examples impressively show that the use of fossil CO_2 can lead to a significant reduction in carbon footprint – and the reduction would have been even greater if "green" CO_2 had been used from biomass or direct air capture as described under idealised model conditions.

While the above figures model idealised conditions, it is necessary to verify that the emission reductions and carbon neutrality can be achieved in reality. The following two figures are based on numbers of a paper by von der Assen et al. (von der Assen et al. 2014) and show an example of a real case production of methanol from fossil feedstock (non-CCU reference system) in comparison to methanol production from CO_2 (CCU system). Once again, the key advantage for the CCU system is the use of emissions from another process, in this case electricity generation. Methodically, the two systems are compared with the help of the so-called system expansion, the recommended first choice in life cycle assessment. In a system expansion, co-products are considered alternatives to products with the same or similar function on the global market.

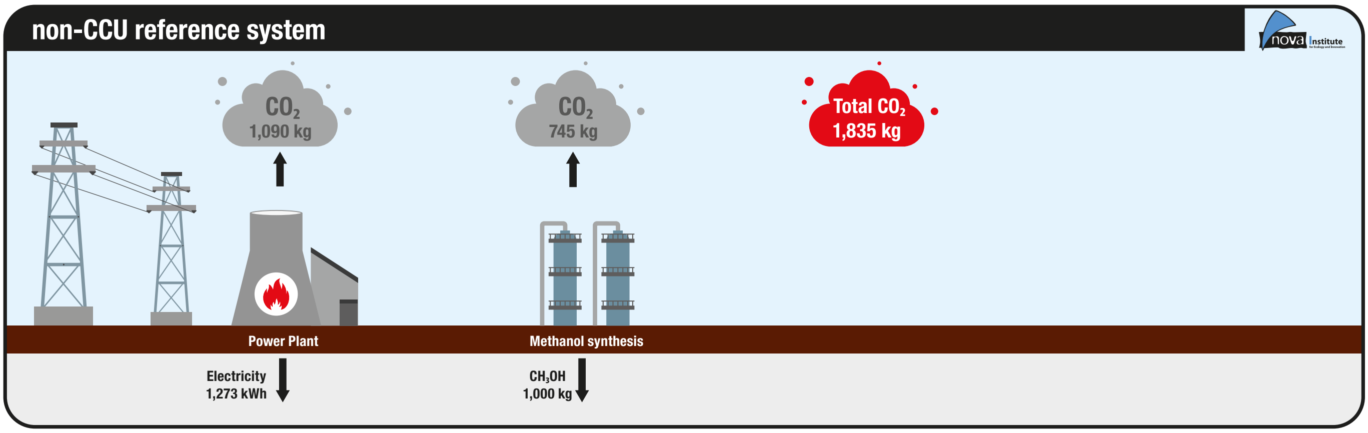

Figure 8: CO_2 emissions of a reference system producing electricity and methanol without using CCU technologies (based on von der Assen et al. 2014)

The numbers given in Figure 8 actually result from a life cycle assessment of a non-CCU reference system for methanol synthesis. Here, electricity (in a natural gas-fired power plant) and methanol (in an industrial facility) are produced independently of each other on the basis of fossil feedstocks. A natural gas-fired power plant produces 1,273 kWh electricity and emits 1,090 kg CO_2, while for the synthesis of 1,000 kg of methanol from natural gas, another 745 kg CO_2 are emitted. This can be referred to as a current "business-as-usual" scenario, with methanol synthesis and electricity generation as two independent activities.

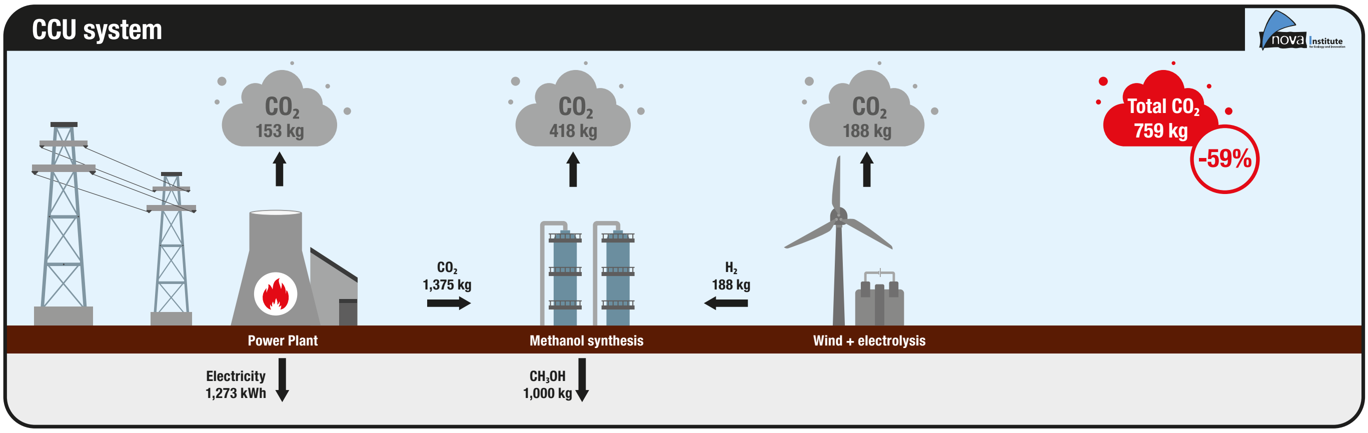

Figure 9: CO_2 emissions of the CCU system producing the same amount of electricity and methanol (based on von der Assen et al. 2014)

The results of the life cycle assessment of the CCU system used for methanol synthesis are shown in Figure 9. Here, the electricity generation of the natural gas-fired power plant is coupled with the methanol synthesis through a CCU process using renewable wind energy. The gas containing emission stream of the natural gas-fired power plant is captured and transferred to the methanol synthesis plant. The additionally required H_2 is provided by electrolysis using wind power. By transferring the majority of the CO_2 emissions from the natural gas-fired power plant to the methanol synthesis, GHG emissions can be reduced for both processes, even with the additional electrolysis process required. The production of one tonne of methanol and 1,273 kWh of electricity only produces 759 kg CO_2, this means that the CO_2-based methanol production is in this case favourable since it reduces the global warming impact by 59% compared to methanol production from natural gas.

Even though the CO_2 balances of the model cases with “green” carbon or direct air capture respectively are even better than the “simple” CCU (Figure 4 and Figure 9) there is no reason to support only CCU from biogenic sources or direct air capture – as long as there are fossil CO_2 emissions that can be substituted.

2.6 Is CCS better than CCU because it stores CO₂ longer? What is the market potential of CCU?

For CCU, the time span of CO_2 sequestration is not relevant – here the substitution of fossil-based products counts. What storage is to CCS, substitution is to CCU.

- With CCS, you can – in principle – capture all CO_2 emissions from fossil sources and sequester them.
- With CCU, you can – in principle – substitute all carbon from fossil sources (and therefore any additional fossil CO_2 emissions) through the use of renewable energies and CO_2 utilisation.

The amount is exactly the same!

Today, the remaining amount of fossil carbon is already sequestered underground in the form of oil and gas reserves:

- CCS means: we extract the fossil carbon, use the contained energy and then capture the CO_2 afterwards to sequester it again.
- CCU means: we leave the remaining fossil carbon sequestered and substitute it directly by renewable energy and CCU (for fuels, chemicals and plastics).

This becomes even more clear with the detailed examples in chapter 2.5 (Figure 3 and Figure 4) where a CCS process is directly compared to a CCU process.

The potential market volume of CCU is in principle the full petrochemical market. It is only limited by the availability of renewable energy. Chapter 2.3 described the variety of potential applications of chemistry for CCU. So in theory, the chemical industry can be fully built on CO_2 as its key carbon source. This way, society would not have to miss out on anything if the chemical industry was converted to renewable carbon.

2.7 Are renewable energies too valuable and not sufficiently available for CCU?

If we want to completely base our energy supply on renewable sources and our chemical supply on renewable carbon from CCU, renewable energy will for a long time remain a scarce commodity. Therefore, questioning the optimal use of the available renewable energy is important.

What is the answer in the case of CCU? It depends on the application. If there are environmentally better alternatives with a direct use of renewable energy, CCU should only be used in exceptional cases. However, if CCU is the best alternative for a specific process or product, the use of renewable energies becomes extremely sensible for CCU.

For a more detailed answer, we will take a closer look at fuels derived from CCU in the next paragraph. Which CCU fuels are a good alternative and which are not? Apart from some fuels described there, another highly interesting sector is organic chemistry, which is entirely based on carbon and where sustainable carbon will become increasingly important. Here, too, there is nothing better than CCU as a feedstock base.

2.8 Which CCU fuels make sense from a sustainability perspective?

Simply put, if an electric drive is available, its efficiency is unbeatable when powered by renewable electricity – today, about 70% of the renewable energy can be utilised for driving. In contrast, CCU fuels will hardly be able to convert more than 20% of their renewable energy input into actual driving, even in the future (Table 1). CCU fuels will therefore have no chance to compete as a sustainable energy source for cars and trucks (which can alternatively be powered by battery and induction) in the long run and they can therefore only be a transitional solution. And even then, they must never delay the introduction of electromobility.

Table 1: Energy efficiency from renewable electricity to the wheel (passenger car)

	Today	Future
Electric car (battery or induction)	69%	> 75%
Fuel cell	26%	> 30%
CCU fuel	13%	> 20%

Nonetheless, as a transitional solution CCU fuels for passenger cars can be important, because they offer a cleaner solution for the existing automotive infrastructure that can quickly reach larger volumes. This applies in particular to synthetic diesel (dimethyl ether (DME) / polyoxymethylene dimethyl ethers (OME)), which, in addition to lower CO_2 emissions, has lower overall emissions, especially of fine dust. Passenger cars can also be used to test, improve and mainstream the first commercial CCU fuels. For long distances, the electric car could then run as a hybrid, with an electric drive plus range extender, preferably a fuel cell that runs on green hydrogen or CCU derived methanol.

The situation is completely different for aviation kerosene and long-distance shipping – here, liquid fuels are and will be indispensable in the long run. In both cases, CCU fuels are by far the best choice. CCU kerosene is the only solution for sustainable aviation fuel, even when compared to bio-based kerosene. The production process for CCU kerosene compared to bio-based kerosene shows significant advantages: lower carbon footprint, based on the use of emitted CO_2 as a feedstock, much lower space requirements compared to cultivated biomass needed for bio-based kerosene and optimal production conditions in the desert, based on the high and cost-efficient supply of solar energy as the necessary renewable energy source. Therefore, the technology would significantly reduce the pressure on biodiversity that maybe caused by agricultural and forestry systems.

Air traffic is showing above-average growth rates and so far, there are little to no viable ideas on how it could be transformed into a more sustainable, climate-friendly field. CCU kerosene is the solution. One of the most important objectives proposed by many CCU experts would be a mandatory quota for CCU kerosene, which should be introduced internationally as soon as possible.

2.9 For sustainable, organic chemistry, the use of CO_2 is crucial

The chemical industry can only become sustainable if it completely abandons fossil feedstocks such as crude oil, natural gas and coal and strictly uses only renewable carbon as a raw material for organic chemistry. The only available sources for renewable carbon are recycling, biomass and direct CO_2 usage. The reasons for this as well as the explanations in the following paragraphs can be found in more detail in nova paper #10 (Carus and Raschka 2018).

A sustainable chemical industry cannot be achieved with decarbonisation, as is rightly and sensibly called for as a solution in the energy sector. Organic chemistry cannot be decarbonised because it is defined by the use of carbon. The same applies to the plastics industry, without whose versatile polymers the modern world would be inconceivable – or only with a considerable renunciation and higher greenhouse gas emissions.

What decarbonisation represents in the energy sector is the switch to renewable carbon for the chemical and plastics industries. Only by completely eliminating fossil carbon, a further increase in CO_2 concentrations in the atmosphere can be avoided. Sooner or later, all the fossil carbon that is extracted from the soil is released into the atmosphere and increases CO_2 concentrations.

As long as the chemical industry uses fossil carbon, it continues to contribute to the greenhouse effect; and this in an increasingly relevant way. While today the material use (incl. asphalt) of crude oil accounts for only about 8% of the total use, experts expect this proportion to increase to about 30% by 2050. There are two reasons for this: Firstly, there is a continuously decreasing demand for fossil fuels promoted by the strong expansion of solar and wind energy and the increase in the use of electric cars. Secondly, most market researchers worldwide see an annual increase in production of chemicals and plastics by 3–4%, as the demand for living space, clothing, mobility and packaging continues to grow strongly due to our increasing world population and rising living standards.

However, this also means that the share of chemicals in greenhouse gas emissions will continue to grow despite all the industry's efficiency gains and will then increasingly move into the focus of public attention. Only a clear strategy towards renewable carbon can prevent further damage to the image of the chemical industry and acting early might even turn it positive.

If sufficient renewable energy is available, direct CO_2 use is an inexhaustible and sustainable carbon source for chemistry. Calculations show that only about 2% of the world's deserts would be sufficient to cover the entire carbon demand of the chemical industry in 2050 using photovoltaics and CO_2.

2.10 Additional benefits of CCU for the expansion of renewable energies

CCU fuels and chemicals allow for a considerably stronger expansion of renewable energies than possible with today's technological means, since surplus solar and wind energy can be used for the production of CO_2-based products if they are otherwise not used due to lack of demand in the power grid. This sector coupling leads to a much more efficient use of renewable energies and price stabilisations since the demand for expensive control energy will be reduced.

In addition, it is even possible to use CCU technologies for energy storage, which helps mitigating the fluctuations of energy systems depending on wind or solar energy. With CCU, solar energy could be harvested in summer for heating in winter, for example by producing and storing CO_2-based methanol.

In conclusion, CCU can become a key driver of innovation and investment for the transition from a fossil to a renewable energy system and renewable carbon for the chemical industry.

For further details, please see chapter 5 "CCU and Sustainability".

2.11 Summary and outlook: How to find support from policy?

CCU as a technology is still more or less in its infancy. Success or failure will depend to a large part on the framework conditions in which entrepreneurs are going to develop this business. While the negotiations around the REDII and the ETS revision (see chapter 4) in the last few years have shown that CCU is more and more present on the political agenda, the level of support is still quite low – even though hesitant progress has been made in the REDII. The following list presents a collection of measures that could be helpful to promote this technology in a sustainable way and thus foster climate friendly innovation in the European Union:

- **Taxation of fossil carbon in chemicals and plastics.** To date, the chemical industry does not pay any taxes for their fossil carbon anywhere around the globe. It would be quite possible to introduce a carbon tax, if not globally, then only regionally, e.g. in the European Union. Imported products would then be taxed, while the tax could be refunded for exports.
- Discontinuation of any funding programmes in the fossil domain. Every year, the G7 countries spend at least USD 100bn for the production and consumption of oil, gas, and coal (Simon 2018).
- Higher fossil CO_2 prices in emissions trading.
- **Political reward / preference for chemicals and plastics with low greenhouse gas emissions;** this would directly benefit chemicals and plastics made from renewable carbon.
- Development of certificates and labels that indicate the share of renewable carbon in products.
- Setting renewable carbon quotas in “drop-in” products in the chemicals and plastics industries (e.g. 30% of polypropylene must be made from renewable carbon by 2030), for aviation kerosene and for fuels for long distance shipping.
- Obliging chemical and plastic companies to issue an annual report on the percentage of renewable carbon used in their production.
- Tax credits for the capture, storage and use of CO_2 as implemented by the Bipartisan Budget Act of 2018 in the US (Martin 2018).
- **Further and improved financial support for research, development and implementation** of sustainable technologies of the future in the field of CO_2 technologies for the provision and use of renewable carbon (CCU).
- Strong expansion of renewable energies and inclusion of CCU as a storage option and supplier of renewable carbon.

3 Implementations of (semi)commercial CO_2 utilisation plants

Carbon Capture and Utilisation (CCU) is of huge interest for university research and development and additionally highly appreciated and accepted by politicians as a potential future business case for renewable carbon. But this business case is not only a future perspective, it can and is already successfully realised today. As it can be seen from Figure 10, the technologies are ready. Differently as assumed by the majority of decision-makers the CCU field is steadily growing and by now there are several successfully implemented commercial plants for CO_2 conversion and utilisation. About 70 research projects, start-ups and established companies are currently using or planning to use CO_2 or off-gases for the production of fuels, chemicals, polymers, proteins and gases for energy storage and chemicals. These projects are ranging from lab, pilot, demonstration and pre-commercial to commercial scale. Here (see chapter 3.1), a selection of the 12 most advanced projects and companies at commercial scale is shown to underline the fact that CCU technologies are already successfully performed and not only a possible perspective for the future.

3.1 CO_2 utilisation via synthesis of fuels, gases, polymers and other chemicals

In general, CCU can be realised via biotechnological or chemical CO_2 conversion processes. While biotechnological conversion processes are based on microbial or algae-mediated fermentation, chemical conversion is based on conventional catalytical chemical processes. The projects / plants are listed according to the respective conversion process used (Table 2 und Table 3). Table 2 shows selected implemented or planned plants for the synthesis of CCU fuels as ethanol, n-butanol, methanol or diesel and synthetic naphtha. Table 3 on the other hand shows plants for other products made from CCU such as proteins, gases, polyols and polymers.

As a good example in Table 2, the 2007 established company LanzaTech Inc. uses a biotechnological approach to convert steel flue gases (carbon monoxide (CO), CO_2 and the hydrogen (H_2)) into ethanol. In 2018, they could already prove that their produced ethanol can be subsequently upgraded to alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) which was successfully used within a fuel mix for a commercial flight of Virgin Atlantic. In 2019, in the course of the EU-funded Steelanol project, LanzaTech Inc. will open a plant in Belgium together with ArcelorMittal and Sulzer Chemtech AG. This plant will be able to convert the flue gases from the ArcelorMittal steel plant into about 80 million litres of ethanol annually.

Since 2011, Carbon Recycling International from Iceland has been working with a power-to-liquid plant on a commercial scale. With energy from hydro power and geothermal power, CO_2 from a geothermal power plant off-gas and hydrogen generated by electrolysis are converted to 4,000 t/a of methanol. This so-called Vulcanol™ can directly be used as a fuel or it can be blended in standard gasoline as well as being used for biodiesel production.

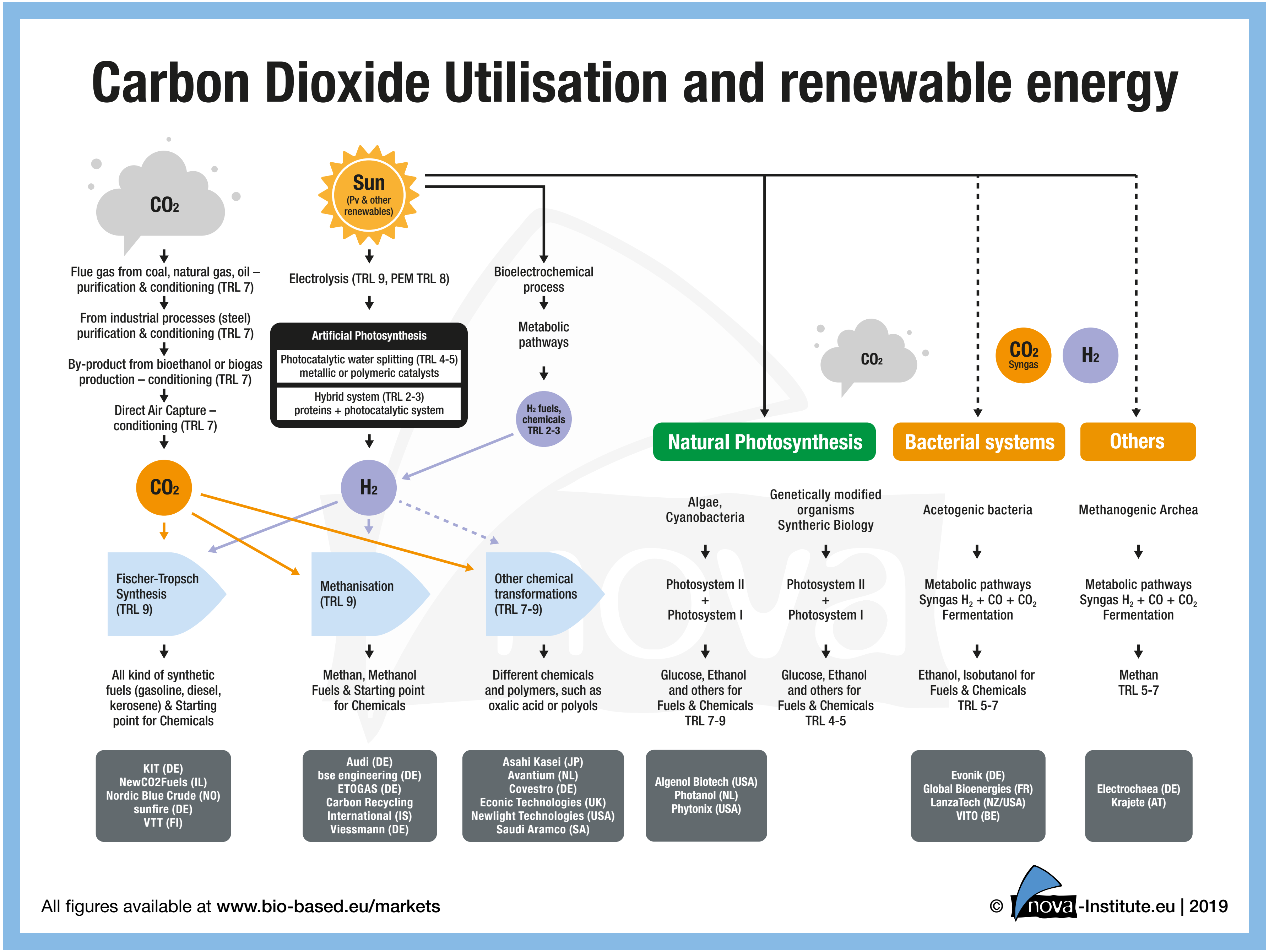

Figure 10: Overview of current CO_2 utilisation technologies with renewable energy

Table 2: Selected implemented plants for the synthesis of CCU fuels. The CO_2 utilisation / conversion processes are split into biotechnological ones based on microbial or algae-mediated fermentation and chemical ones based on conventional chemical conversion processes.

CCU fuels								
Company	Headquarter	Scale	Production site				Start date	End product
			City	Country	Status	Capacity		
Biotechnological CO / CO_2 conversion processes								
LanzaTech Inc.,	USA	commercial	Ghent	Belgium	under construction	62,000 t/a	2019	ethanol and e.g. n-butanol and kerosene
		commercial	Shougang	China	in operation	48,000 t/a	2018	
		commercial	Gurgaon	India	under construction	34,000 t/a	2019	
		commercial	Nelspruit	South Africa	under construction	52,000 t/a	2019	
		commercial	Modesto	USA	under construction	35,000 t/a	2019	
Phytonix Corp.	USA	commercial		USA	planning	> 500,000 t/a	2019 / 2020	n-butanol
		commercial		Europe	planning			
Chemical CO_2 conversion processes								
Carbon Recycling International	Iceland	commercial	Grindavik	Iceland	in operation	4,000 t/a	2011	methanol
Nordic Blue Crude AS	Norway	commercial	Herøya	Norway	under construction	8,000 t/a	2020	diesel, kerosene naphtha, wax
Sunfire GmbH	Germany	demonstration	Dresden	Germany	in operation	> 3 t/a	2014	

Table 3: Selected implemented plants for the synthesis of CCU proteins, gases, polyols, polymers and others. The CO_2 utilisation / conversion processes are split into biotechnological ones based on microbial or algae-mediated fermentation and chemical ones based on conventional chemical conversion processes.

CCU proteins, gases, polyols, polymers and others								
Company	**Headquarter**	**Scale**	**Production site**				**Start date**	**End product**
			City	**Country**	**Status**	**Capacity / output power**		
Biotechnological CO_2 conversion processes								
Algenol Biotech	USA	commercial	Fort Myers	USA	in operation		2014	spirulina, colorants, proteins
Electrochaea GmbH	Germany	commercial (demonstration)	Avedøre	Denmark	in operation	50 Nm^3/h / 0.5 MW	2016	methane
		commercial (demonstration)	Solothurn	Switzerland	in operation	35 Nm^3/h / 0.35 MW	2018	
		commercial (demonstration)		Hungary	planning	500 Nm^3/h / 5 MW		
Photanol B.V.	The Netherlands	demonstration	Delfzijl	The Netherlands	planning	20 t/a	2020	organic acids, chemicals
Chemical CO_2 conversion processes								
Asahi Kasei Corp.	Japan	commercial		Taiwan	in operation	150,000 t/a	2007	polycarbonates
Audi AG	Germany	commercial (demonstration)	Werlte	Germany	in operation	300 Nm^3/h / 3 MW	2013	methane
Covestro AG	Germany	commercial	Dormagen	Germany	in operation	5,000 t/a	2016	polyols, polyurethanes
Econic Technologies Ltd.	United Kingdom	commercial (demonstration)	Runcorn	United Kingdom	in operation		2018	polyols
Newlight Technologies, Inc.	USA	commercial		USA	in operation	23,000 t/a	2014	polyhydroxy-alkanoates

But not only CCU fuels are already produced and available at commercial scale. Also, other chemical intermediates and end products can be produced from CO_2 (Table 3). For example, methane is of huge interest as a means for energy storage. The German company Electrochaea GmbH established a biotechnologically coupled power-to-gas process at commercial demonstration scale with an energy output of 0.5 MW in Denmark. In 2018, they further scaled their technology to a 1.7 MW plant in Switzerland within the EU-funded Store & Go project.

The most advanced technology within the CO_2-based materials sector was established by the German Covestro AG already back in 2006. This cardyon® technology uses epoxides with CO_2 captured from an ammonia production plant and a polyol to form a polyether-polycarbonate polyol (5,000 t/a) which can be used for polyurethane synthesis in flexible foams. This way the produced material, for example mattresses, contains up to 20% of CO_2. The versatile application of this technology was demonstrated further in 2018 with the launch of a sports flooring, based on CO_2, from the Polytan GmbH.

3.2 CO_2 mineralisation via production of carbonate materials

Besides these CO / CO_2 conversions into a wide range of fuels, chemicals and polymers the incorporation of CO_2 in carbonate materials is one of the most advanced and one of the longest established approaches for converting CO_2. Through the used mineral carbonation technology (MCT) CO_2 reacts with calcium and / or magnesium ions present in for example brine source or clinker waste from limestone combustion processes. The carbonates resulting from this process, calcium carbonate and magnesium carbonate, can be used as ingredients in medicine for gastric acid regulation or in the case of calcium carbonate as food additive, as filler in the paper industry or as construction material, e.g. concrete / cement.

Several start-ups and companies worldwide have been active in this field of CO_2 sequestration with subsequent indirect utilisation since 2007, the following listed companies for example are producing carbonates as end products or finally embed the produced calcium carbonate (synthetic limestone) in concrete.
Carbonate production:

- Mineral Carbonation International (Australia),
- Tandem Technical (Canada),
- Carbon Capture Machine (Scotland),

Concrete production based on calcium carbonate:

- CarbonCure Technologies, Inc. (Canada),
- Carbicrete (Canada),
- Solidia Technologies (USA),
- Blue Planet (USA),

3.3 Carbon utilisation via chemical recycling

Next to the established mechanical recycling for a circular use of plastic waste, chemical recycling is emerging slowly as an alternative way of re-using materials. The process results in re-obtaining the smallest molecular components of the plastics, the building blocks, by combustion, pyrolysis or gasification. This way chemical recycling allows to start an entirely new production and fresh value chains from recycled materials. These are not restricted to the reuse of the plastics, since chemical recycling can lead to the synthesis of diverse chemicals, methanol, ethanol and hydrocarbons, as well as purified, food grade CO_2. Aside from Showa Denko K.K. from Japan, that has been capturing and purifying CO_2 from the gasification of plastic waste for use in beverages already since 2003, BASF SE started its commercial demonstration project on chemical recycling in 2018 in which new plastics are generated from pyrolysis oil. Also, the Finnish biofuel producer Neste is interested in participating in the chemical recycling sector by supporting ReNewELP from the United Kingdom in establishing a commercial plant for the synthesis of a wide range of liquid hydrocarbons, chemicals and new plastics via its developed Catalytic Hydrothermal Reactor (Cat-HTR) technology. Additionally, in 2018 the chemical company LyondellBasel Industries announced a collaboration with the German Karlsruhe Institute of Technology (KIT) to further expand their activities in mechanical recycling (via its joint venture with Suez, Quality Circular Polymers B.V.) to chemical recycling.

It should be noted that chemical recycling – strictly speaking – is not a CCU technology, since it does not only capture and subsequently use CO_2 as a feedstock. Instead it makes use of a wider range of carbon containing gases or other carbon containing materials. Despite of this, it should be considered as a potential expansion of the CCU technology area that might be a promising tool to additionally provide and support the supply of the chemical industry with renewable carbon.

All the above-mentioned implementations for CCU, that of course illustrate only a part of an already established, steadily growing innovation area, underline the not yet exhausted potential of technologies in this field to supply the (petro)chemical industry and the transitional fuel industry with renewable carbon.

Although not all mentioned technologies, such as chemical recycling, are strictly using CO_2 as a feedstock, but also off-gases mainly containing carbon monoxide (CO), syngas or pyrolysis oil, they prevent the emission of carbon-containing waste gases or materials into the environment and allow the circular use of carbon that will alleviate the use of fossil resources.

4 The policy framework of CCU

4.1 CCU in the Renewable Energy Directive after 2020 (REDII)

The new renewable energy framework of the European Union, coming into force in 2020, includes support measures for transport fuels won from carbon capture and utilisation. It is the first time that such measures are part of a regulatory document on EU level. During the negotiations preceding the agreement on the revised Renewable Energy Directive (REDII), it became clear that many policy makers were previously not aware of the potential of the technology. Within a relatively short time, the topic grew roots in Brussels' discourses. Both sceptics and supporters made loud claims and for the most part, it was unclear whether CCU would be included favourably in the Directive or not. The final agreement outlines the following conditions and measures for CCU fuels:

Overall, there will be a 32% share of renewable energy in the European Union's energy consumption in the sectors transport, electricity and heating and cooling. For the transport sector alone, a share of 14% renewable energy carriers is envisaged. This 14% share for the first time can also be fulfilled by CCU fuels.

Definitions

The REDII recognised two types of CCU fuels, which are defined as follows:

"**'Renewable liquid and gaseous transport fuels of non-biological origin'** means liquid or gaseous fuels which are used in transport other than biofuels whose energy content comes from renewable energy sources other than biomass" (Art. 2 (s)). These fuels are often called "**ReFuNoBio**". All CO_2 sources are accepted for producing them, as long as the CO_2 source is not elastic (meaning that the emission source does not respond to demand from the CCU process) and the energy sources for transforming it into fuels is renewable and not biomass.

"**'Recycled carbon fuels'** means liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin […] and waste processing gases and exhaust gases of non-renewable origin which are produced as an unavoidable and not intentional consequence of the production process in industrial installations" (Art. 2 (ff)). These are CCU fuels stemming from flue gases from steel or concrete production.

As mentioned above, both types of fuels can be used to fulfil the 14% renewables share in the transport quota. **ReFuNoBio** can be counted for the quota all over the EU, their inclusion is defined mandatory in the REDII. Whether or not **recycled carbon fuels** can also be counted for the quota is at the Member States' individual discretion.

In addition to the overall minimum share of 14% renewables, there is a sub-quota for advanced biofuels in the Directive: 0.2% in 2022, 1% in 2025 and 3.5% by 2030 (based on materials listed in Annex IX A). However, producers that supply fuels in the form of renewable electricity or ReFuNoBiO are exempt from this minimum share requirement. **This means that CCU fuels do not count as advanced biofuels**.

Greenhouse gas emissions

Regarding greenhouse gas (GHG) emission savings, the Directive sets the following conditions:

The greenhouse gas emission savings from the use of ReFuNoBiO excluding recycled carbon fuels shall be at least 70% as of 1 January 2021. Appropriate minimum thresholds for GHG emission savings of recycled carbon fuels shall be established through LCA that takes into account the specificities of each fuel. The threshold shall be set by the Commission at the latest by 1 January 2021. By 31 December 2021, the Commission shall adopt a methodology for assessing greenhouse gas emission savings from both kinds of CCU fuels, which shall ensure that no credit for avoided emissions be given for carbon dioxide whose capture already received an emission credit under other legal provisions. (Art. 25)

Use of electricity

When electricity is used for the production of ReFuNoBiO, either directly or for the production of intermediate products, the **average share of electricity from renewable energy sources in the country of production**, as measured two years before the year in question, may be used to determine the share of renewable energy.

However, **electricity obtained from direct connection to an installation** generating renewable electricity

(i) that comes into operation after or at the same time as the installation producing the renewable liquid and gaseous transport fuel of non-biological origin and

(ii) is not connected to the grid or is connected to the grid but can provide evidence that the respective electricity has been provided without importing electricity from the grid,

can be fully counted as renewable electricity for the production of that renewable liquid and gaseous transport fuel of non-biological origin.

In addition, electricity that has been imported from the grid may be counted as fully renewable if the electricity is produced exclusively from renewable energy sources and the renewable properties and any other appropriate criteria have been demonstrated, ensuring that the renewable properties of this electricity are claimed only once and only in one end-use sector. This can be proven through certificates.

No level playing field with biofuels yet

While these measures mean significant progress by setting up the first legally binding framework for CCU fuels in the EU ever, there are still some unfair distortions in the legislation compared to other forms of energy provision. 'Unfair' in this context means that it is not justified by scientific evidence:

- Advanced biofuels receive double counting for fulfilling the quota, CCU fuels do not. CCU fuels may only receive 1.2x counting if they are used for shipping and aviation (same as other fuels that are used for these purposes).
- CCU fuels need to achieve 70% min. GHG emission savings, biofuels only 65% (so far only determined for ReFuNoBiO, not for recycled carbon fuels).
- ReFuNoBiO are always included in the quota – for recycled carbon fuels the decision is up to the Member States.

It is unclear from the legislation why these provisions where included that prevent a completely equal treatment of CCU fuels. While CCU fuels are still quite new and not well known, the evidence so far suggests that they are even superior to biofuels from a climate perspective. Therefore, it can only be speculated why they receive this unfair treatment.

4.2 CCU in the EU Emissions Trading System (ETS)

The EU Emissions Trading System (ETS) is the largest greenhouse gas emission trading scheme in the world and a cornerstone of the European Union's efforts against climate change. By putting a limit on overall emissions from covered installations, the instrument monitors over 11,000 factories, power stations or other installations. This limit gets reduced annually and within the limit, companies can buy and sell emission allowances as necessary to cover their own emissions. The ETS will enter its 4th phase from 2021-2030, where the annual decline of emission allowances increases to 2.2% in order to reach a total reduction of 43% in 2030 compared to the level of 2005.

CCS applications have a special position within the ETS – there is no obligation to surrender allowances if emissions are verified as captured and transported for permanent storage. Despite lengthy debates in the course of earlier revisions, the same is not the case for CCU applications, meaning that companies have to purchase emission allowances for emissions they capture and utilise again for another process or product. But in early 2017, the European Court of Justice (ECJ) set precedent by ruling that the European Commission exceeded its competence with the currently valid regulation on monitoring and reporting (MRR), and that the CCU process of Schaefer Kalk for the production of precipitated calcium carbonate is indeed deductible.

Although the ruling is specific to the process of Schaefer Kalk and Schaefer Kalk only, it has opened the door for CCU applications within the ETS. In the current situation, companies would have to file individual lawsuits for their own processes (with companies considering this option and their chances), but in light of the upcoming phase 4, the MRR and the regulation on verification and accreditation (Zimmermann et al. 2018) are under review anyway. In order to avoid a flood of lawsuits, a general position towards CCU applications in the ETS should be established.

While the EU Member States are still negotiating, two aspects seem to be key in order to include CCU in the ETS while still pursuing the goal of climate protection:

- Additional energy for the CCU process will have to be renewable or offset in order to avoid the peril of causing more emissions (via capture, purification and transport) than were originally captured.
- Among the variety of available CCU technologies, some are undesirable in terms of a future based on renewable carbon, for example if they cause lock-in effects of current, fossil-heavy technologies e.g. in the steel industry. For these cases, a solution needs to be found.

In terms of implementation feasibility, experts estimate that the verification of additional data and methodologies for accounting for the transferred and deductible carbon, requires an additional effort of 30% compared to the existing standard verification process of emissions reporting. The larger scope appears to be reasonable and realisable in practice and, accompanied by clear guidance, can provide the framework needed for the implementation of emission reductions at ETS installations via transferred CO_2 to CCU processes.

5 CCU and Sustainability

Aside from the significant advantages in greenhouse gas emission reductions presented in chapter 2.5 and 2.6, there are several broader sustainability aspects for which CCU provides advantages. Table 4 evaluates fuels and chemicals derived from fossil energy sources, biomass and CO_2 regarding their impact on important environmental categories, paving the way for an initial assessment of the environmental footprint of CO_2 utilisation. It is always assumed that the energy to reduce CO_2 is either provided by the emission gas itself (synthesis gas, e.g. from the steel industry) or is generated using renewable resources such as the sun, wind, water or geothermal heat. The use of fossil energy sources to reduce CO_2 would lead to very unfavourable energy and CO_2 balances and as a consequence is neglected here.

Table 4: Evaluation of fuels and chemicals from various carbon sources against the background of environmental sustainability criteria

	Fuels and chemicals		
C source	**fossil-based (crude oil, natural gas and coal)**	**bio-based (all types of biomass)**	**CO/CO₂-based in combination with renewable energies (sun, wind, water, geothermal heat)**
Greenhouse gas emissions	High: in particular due to the release of fossil carbon into the atmosphere	Low to medium: biogenic carbon is recycled. Emissions are caused by fertilisers, pesticides and herbicides	Low: carbon is recycled
Land use	Low	High	Low: per surface area, PV uses solar radiation 50 times more efficiently than the best-performing plants
Water use	Normally low, exception: accidents	Low to high: depends on the region and the crop	Low
Availability	Finite, only local occurrence	Limiting factor: the land required; generally globally available, but of different local qualities	No limiting factors: both time- and volume-wise to cover the entire fuels and chemicals demand, covering ca. ten per cent of the deserts with PV systems would be sufficient; globally available anywhere
Contribution to circular value creation	no	yes	yes
Repercussions on the food supply, land, water and biodiversity	Normally low, exception: accidents	Medium to high: depends on local procedures	Low
Solar efficiency (conversion of solar radiation into the final product)	-	< 0.5%	> 10%
Storage of solar energy	long-term storage of solar energy from millions of years	agriculture: seasonal, forest: over decades	unlimited long-term storage in fuels and chemicals
Stability in supply	Depends on geopolitical situation	Crop dependent; can vary due to natural conditions	Stable supply is theoretically possible
Specific risks	Risk of accidents such as oil spills, shipping accidents and other disasters severely impacting the marine environment as well as the local economy	Long-term damage by inappropriate management e.g. biodiversity loss, groundwater depletion, nitrate leaching; risk from climate change	Usually high energy demand to utilise CO2. Required energy needs to be "clean" (renewable) to not cause more emissions than are avoided.

Table 4 clearly shows the environmental benefits and the specific advantages of CO_2 utilisation. Compared to other carbon sources, fuels and chemicals derived from CO_2 generally produce the lowest greenhouse gas emissions because they do not release any additional fossil carbon and renewable energies harvest solar radiation much more efficiently than natural photosynthesis, the standard process for the production of any biomass. The latter is due to the high level of solar efficiency and the low land use compared to the production of biomass. Searchinger et al. discussed this aspect (Searchinger et al. 2017). The authors show that the bioenergy conversion efficiency is a mere 0.1 to 0.2 per cent, i.e. only 0.1 or 0.2 per cent of the solar energy makes its way to the final product (e.g. ethanol). The net solar conversion efficiency (PV) however ranges between 11 and 44 percent and thus outperforms biomass utilisation by a factor of 122 to 295. When solar energy is converted into liquid fuels harnessing CCU technologies, efficiency levels of above 50 percent are feasible even today, i.e. the conversion efficiency of solar CCU to liquid fuels beats biomass by a factor of 50 to 150.

> *"The increasing practicality of solar energy tilts the land use equation further against bioenergy whenever it can be used. Even if 100 ha of good land were to become theoretically available for climate mitigation, they could generally provide at least as much energy and at least 100 times more carbon mitigation if 1 ha were used for solar and 99 to restore forests."*

One specific advantage of CO_2 utilisation is the fact that this carbon source is infinitely available without any time- and/or volume-related limitations. On the one hand, there will be enough CO_2 in the atmosphere in the long run, while on the other hand carbon is recycled, i.e. it is pulled from the atmosphere or industrial sources and while or after its utilisation it is released again, replenishing the CO_2 storage which is the atmosphere. The potential of renewable energies to cover human demand is almost unlimited. According to calculations by nova-Institute, the entire 2050 demand in fuels and chemicals may be met by harnessing photovoltaic systems covering less than ten per cent of the world's deserts combined with CCU technologies.

Another two aspects merit our attention. The access to raw materials is "democratised". In the future, everybody, no matter where they are on the planet, will generally have the opportunity to harvest carbon using renewable energies and CCU technologies and to produce fuels, chemicals or plastics out of it. These products allow solar energy to be stored over a long period of time without any losses.

Even present analysis shows that the utilisation of CO_2 in combination with renewable energies is the most sustainable path to fuels, chemicals and plastics and, from an ecological point of view, can explicitly and substantially contribute to a sustainable economy. Nine out of the 17 Sustainable Development Goals of the United Nations are directly addressed through CO_2 utilisation in combination with renewable energies.

- #2 **Zero hunger** – CO_2 for proteins as an alternative protein supply, either for feed or even for food.
- #7 **Affordable and clean energy** – CO_2-based economy can help to facilitate an energy transition, CCU fuels and chemicals provide clean energy storage (if based on renewable energy) that helps to balance renewable energy supply fluctuations and supports an expansion of renewable energy.
- #8 **Decent work and economic growth** – CO_2 utilisation can become one of the major growth areas in a low-carbon circular economy
- #9 **Industry, innovation and infrastructure** – CO_2 utilisation is a growing industry field with enormous potential → New and innovative biotechnological and chemical ways of using CO_2 and the use of non-purified CO_2 will open the door for more applications.
- #10 **Reduced inequalities** – CO_2 is a ubiquitous resource, as this resource can be found everywhere, thus inequalities in the accessibility of resources can be reduced.
- #11 **Sustainable cities and communities** – Local production possibilities of CO_2-based fuels and chemicals allow cities and communities to become more sustainable and independent.
- #12 **Responsible consumption and production** – CCU is based on reusing carbon in a circular economy, which aims to increase responsible consumption and production.
- #13 **Climate action** – CCU can contribute to decreased CO_2 emissions, by substituting fossil carbon in fuels and chemicals by recycling carbon from fossil and biogenic point sources or the atmosphere.
- #15 **Life on land** – CCU requires much less space than the use of biomass as a renewable feedstock.

CO_2 utilisation is in line with efficiency and consistency strategies, without however requiring a more stringent sufficiency strategy. Imminent raw material bottlenecks, known from fossil and bio-based systems, will largely be a matter of the past thanks to the utilisation of CO_2 in combination with renewable energies.

6 Life Cycle Assessment and CCU

For years now there have been intensive discussions on how CCU processes should be treated methodically in life cycle assessments (LCA). Of particular interest is the choice of method for dealing with multi-functionality: If a process yields more than one product/output, it is necessary to clearly define how the environmental impacts are assigned to the whole system or to specific products/outputs. For CCU processes, multi-functionality is nearly always the case, as the CO_2-containing gas stream is usually a waste or side-product stemming from the production of another product. But for the choice of method, the distinction between waste and side-product is highly important. LCA standards such as ISO (ISO 2006) and ILCD (European Commission JRC 2010) deliberately leave considerable room for manoeuvre, depending primarily on the goal and scope. This means that the appropriate method has to be selected according to the question the LCA intends to answer. When utilising CO_2, there are some particularities that lead to a reignition of the old discussion about choosing the correct method (Fehrenbach 2017):

- CO_2 is both a raw material and an impact category.
- CO_2 can come from different sources: fossil or biogenic point sources, the atmosphere or even from natural gas.
- The various methods have considerable implications for the CO_2 supplier and also for the CO_2 user. Depending on the method chosen, CO_2 use can become attractive or unattractive for the supplier or the user.

Table 5 shows which methods are available in order to balance the ecological load that the CO_2 brings into the further utilisation process for different CO_2 sources.

In order to compare entire **production systems**, e.g. comparing traditional fossil-based production with CO_2-based production, system expansion is the ideal solution. With this method, you can identify whether a production system is better or worse for different impact categories without distortion through allocations or credits. Moreover, a cross-sectoral shift of burden is not possible here. In addition, it avoids the risk that each sector, supplier and user, will claim arbitrarily calculated CCU bonus for itself. System expansion is particularly important on a political level, and the results are solid and hardly assailable. Various international organisations and projects have published specific recommendations for CCU in autumn 2018 that suggest to always apply “system expansion” additionally to the selected method (Michailos 2018; Zimmerman et al. 2018) in order to investigate whether the entire approach is beneficial. This is of special relevance as CCU is combining both the emitter as well as the processor in one value chain. While the emitter experiences significant emission reductions, a production based on CO_2 as a resource might be less efficient than using a different carbon source. Only the integration of both effects may show the full potential of CCU.

However, when it comes to the balance of specific CO_2-based products and their comparison to other products, system expansion is of little help. In these cases, allocation methods for the CO_2 and subsequent processes have to be selected. There are several sensible methods and all of them have specific advantages and disadvantages. As mentioned above, the choice of the method is a result of the goal and scope of the LCA and also of considerations like data availability, etc.:

- Substitution and crediting: This method tries to break down the system expansion to the product level. In practice, this is difficult to achieve in complex systems. Especially assigning the credit for an equivalent product can involve considerable distortions and uncertainty. Uncertainty, on the other hand, also occurs in the alternative choice of allocation methods. Both are based on more or less objective decisions that strongly influence the results in each case.
- Allocation: This method divides the environmental impacts of a multifunctional process between the various products. The allocation can be based on different metrics, for example economic value or weight. In principle, an economic allocation is always possible. For CO_2, both the ETS price and the market price (if the CO_2 has been purified accordingly) can be used. Allocation by mass or energy / exergy can be a good choice, but in some process chains these physical allocation methods make no sense (see Table 5).
- If CO_2 is regarded as a waste, a cut-off approach can be used in the same way as in recycling, i.e. the impacts of the upstream processes will not be attributed to the waste. Two options can be considered: The first is a distinct cut-off between the CO_2-generating and the CO_2-using system. The delimitation of the investigation system should take place at the point where the CCU begins, at point of separation. We refer to this as cut-off A. Alternatively, fossil CO_2 emissions stay with the CO_2 emitter, and the CO_2 using system instead takes up CO_2 virtually from the atmosphere. We refer to this as cut-off B. This approach is fundamentally possible, but methodologically vulnerable, due to decoupling the calculated impacts from the actual CO_2 flows. As a consequence, subsequent products can be thought of as “greenwashed”. For this reason, we recommend cut-off B only in combination with a preliminary test that compares the entire system via system expansion.
- CO_2 from the atmosphere (direct air capture) is a rather simple situation: here, the entire energy and material consumption can usually be entirely assigned to CO_2 capture. Allocations, credits or cut-offs are therefore not applicable, as the process is mono-functional and fully intended to “produce” CO_2. Should a future direct air capture process generate a co-product, e.g. potable water, then the multi-functionality methods can be applied too.

The worldwide efforts towards a uniform methodology for CCU have the goal of evaluating the use of CO_2 in fuels, chemicals and materials in principle and to steer strategically in the right direction. However, the methodical approaches should be used consciously, depending on political and societal contexts. This way, the necessary flexibility to tailor the LCA to a specific goal is maintained.

Table 5: LCA methodologies for different CO_2 feedstocks (nova-Institut 2018). √ indicates that it is feasible to use the method for the given source, – indicates that it is not feasible to use the method.

	CO_2 as a product					**CO_2 as waste**		
	System evaluation	**Product evaluation**						
CO_2 source	**System expansion**	**Substitution / Credit**	**Allocation by Mass**	**Allocation by Energy / Exergy**	**Allocation by Economy**	**Cut-Off A (at point of separation)**	**Cut-Off B (virtual uptake)**	**50/50**
Biogenic point sources (biogas)	√	√	√	√	√	√	√	√
Fossil point sources (coal power plant)	√	√	—	√	√	√	(√)	√
Fossil point sources (chemistry)	√	√	√	√	√	—	—	—
Natural gas (water gas shift reaction)	√	√	√	√	√	√	(√)	√
Mineral processes (cement)	√	√	√	—	√	√	—	√
Waste (waste incineration)	√	√	—	√	√	√	(√)	√
Syngas (steel industries)	√	√	√	—	√	√	(√)	√

7 Economy of CCU

Under current conditions, renewable carbon from CCU is generally more expensive than fossil carbon from crude oil or natural gas. How much more expensive CCU fuels or chemicals are exactly, depends on a number of factors. The most decisive factor is the price at which renewable energy can be obtained for hydrogen production in the CCU process. The following rules of thumb can be derived from several economic analyses for methane or methanol from CO_2 or Fischer-Tropsch based on synthesis gas:

- Price parity with fossil fuels can be achieved at electricity prices of 1.5 to 2 eurocents per kWh.
- Price parity with biofuels can be achieved at electricity prices of 3 to 4 eurocents per kWh.

Currently, only very small quantities of renewable electricity are available at these prices and they are usually available for limited periods of time or regionally restricted at that. It is therefore not surprising that most CCU plants are built where either CO_2 and hydrogen are present together in the exhaust gas stream (e.g. syngas from the steel industry) or where renewable electricity is very cheap, as in Norway or Canada, where hydroelectric power is available around the clock for around 3 eurocents per kWh.

However, renewable energies are continuously becoming cheaper globally and in windy or sunny regions they are already often the cheapest way to generate electricity. This is even true in Germany: According to the Federal Network Agency, the average hammer price in the year 2018 was 4.3 eurocents per kilowatt hour for newly planned wind farms. At the Leipzig electricity exchange, the price for wind and solar power in excess times falls to only 3 eurocents per kWh.

The price differences between fuels and chemicals from petroleum or CO_2 will become smaller and smaller in the future, mainly for the following reasons:

- Improved CCU technologies and biotechnology
- Increasing crude oil / natural gas prices and higher biomass prices
- Stricter CO_2 limits and higher prices in emissions trading (e.g. ETS in Europe)
- Decreasing costs for renewable energy
- Growing surpluses of solar and wind power
- Increasing political support of CCU for low-GHG fuels and chemicals

It is therefore only a matter of time, before CCU technologies become cheaper than today's petrochemicals. The strong expansion of renewable energies is providing a particular boost. These are not only generally becoming cheaper, but the surplus times at which more renewable electricity is generated than is currently needed are constantly increasing and lead periodically to particularly low electricity prices.

The example of Germany, which now has a share of about 40 % renewable electricity, clearly shows this. "Due to a lack of cables, however, not all the capacity of the wind turbines can be used. The operators of the wind farms then receive compensation, which must be paid by the electricity customers via the grid fees. According to the Federal Network Agency, this was 610 million euros last year, 237 million euros more than in 2017. Compensation claims also rose in the first quarter of 2018 – by 86 million euros to 224 million euros." (Handelsblatt 2018)

In the next years, these compensation payments are expected to rise to one billion Euros per year, only in Germany. It would make much more sense to use renewable electricity for the production of hydrogen, methane, methanol or kerosene than to pay compensation for unproduced wind electricity. Sooner or later this will happen as the excess amount of wind and solar power grows each year.

Imagine what capacity of CCU systems one could build with this capital of one billion Euros. It would allow to build the entire infrastructure for the future chemical and plastics industry based on renewable carbon.

Macroeconomic effects

According to Eurostat, more than 65,000 employees (EU-28) worked in oil and gas production in Europe in 2016. If the raw material base were to be converted to renewable carbon, this figure would increase considerably – decentrally produced renewable carbon would certainly require 5 to 10 times the number of employees. It will never again be as easy to produce carbon as it is in the fossil age. Whether from recycling, biomass or CO_2, renewable carbon will need and create more economic activities and jobs per ton of carbon than in the petrochemistry.

In Europe, 120,000 people are employed in oil refining, mainly in refineries. Instead of being relocated to the boreholes in the crude oil countries, with renewable carbon these refineries can continue to operate in Europe and the jobs are maintained.

In addition, there are hundreds of start-ups developing new technologies for the production and use of renewable carbon. Overall, the chemical industry's switch to renewable carbon will create or maintain several hundred thousand new jobs in Europe, and this in new, innovative and promising sectors. By switching to renewable carbon based on regionally available renewable energies and CO_2, an increasing independence from imported fossil (and biogenic) raw materials is achieved. At the same time, the carbon supply security for the chemical industry is increased in a sustainable manner.

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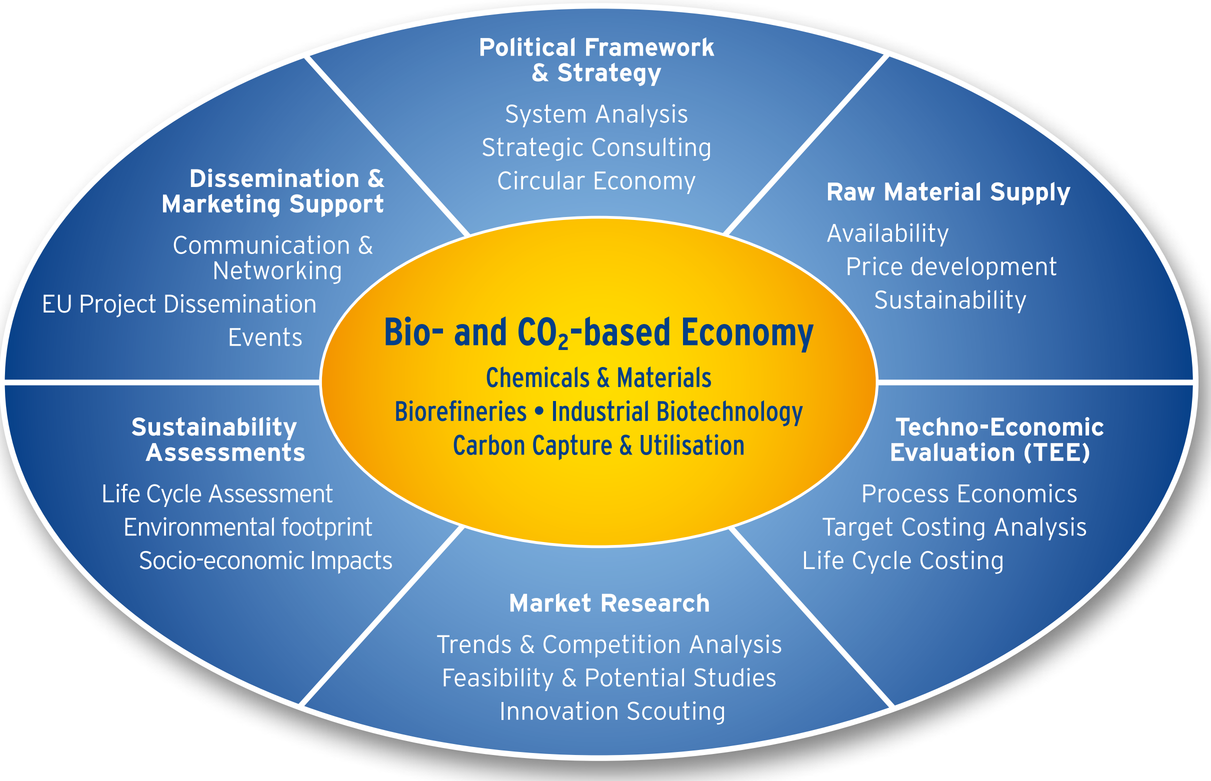

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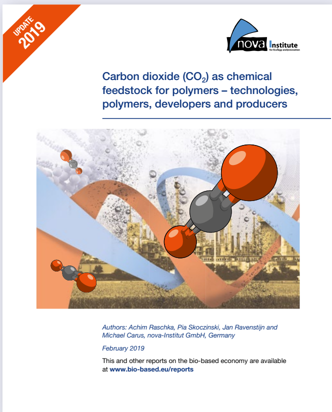

UPDATE 2019

Carbon dioxide (CO_2) as chemical feedstock for polymers – technologies, polymers, developers and producers

Authors: Achim Raschka, Pia Skoczinski, Jan Ravenstijn and Michael Carus, nova-Institut GmbH, Germany

February 2019

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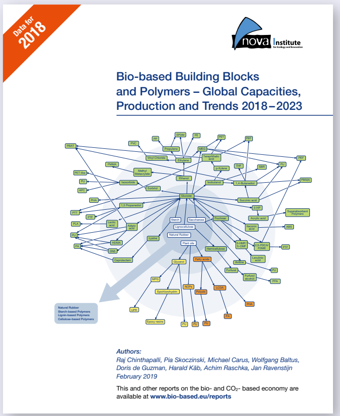

Data for 2018

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Authors:
Raj Chinthapalli, Pia Skoczinski, Michael Carus, Wolfgang Baltus, Doris de Guzman, Harald Käb, Achim Raschka, Jan Ravenstijn
February 2019

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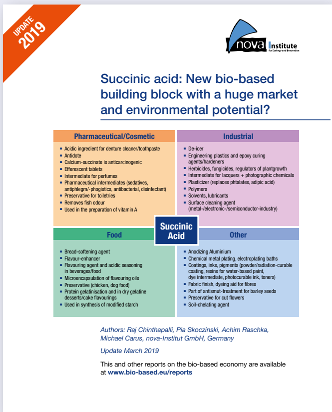

UPDATE 2019

Succinic acid: New bio-based building block with a huge market and environmental potential?

Pharmaceutical/Cosmetic
- Acidic ingredient for denture cleaner/toothpaste
- Antidote
- Calcium-succinate is anticarcinogenic
- Effervescent tablets
- Intermediate for perfumes
- Pharmaceutical intermediates (sedatives, antiphlegm/-phogistics, antibacterial, disinfectant)
- Preservative for toiletries
- Removes fish odour
- Used in the preparation of vitamin A

Industrial
- De-icer
- Engineering plastics and epoxy curing agents/hardeners
- Herbicides, fungicides, regulators of plantgrowth
- Intermediate for lacquers + photographic chemicals
- Plasticizer (replaces phtalates, adipic acid)
- Polymers
- Solvents, lubricants
- Surface cleaning agent (metal-/electronic-/semiconductor-industry)

Succinic Acid

Food
- Bread-softening agent
- Flavour-enhancer
- Flavouring agent and acidic seasoning in beverages/food
- Microencapsulation of flavouring oils
- Preservative (chicken, dog food)
- Protein gelatinisation and in dry gelatine desserts/cake flavourings
- Used in synthesis of modified starch

Other
- Anodizing Aluminium
- Chemical metal plating, electroplating baths
- Coatings, inks, pigments (powder/radiation-curable coating, resins for water-based paint, dye intermediate, photocurable ink, toners)
- Fabric finish, dyeing aid for fibres
- Part of antismut-treatment for barley seeds
- Preservative for cut flowers
- Soil-chelating agent

Authors: Raj Chinthapalli, Pia Skoczinski, Achim Raschka, Michael Carus, nova-Institut GmbH, Germany

Update March 2019

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Succinic acid: New bio-based building block with a huge market and environmental potential?
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