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Renewable Carbon – Key to a Sustainable and Future-Oriented Chemical and Plastic Industry

Definition, Strategy, Measures and Potential

Background paper of the Renewable Carbon Initiative (RCI), launched September 2020, www.renewable-carbon-initiative.com

www.renewable-carbon.eu

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This paper is the background paper of the “Renewable Carbon Initiative (RCI)”, which was launched in September 2020. All information about the RCI, including the target, member companies, partners and personal supporters can be found on the website **www.renewable-carbon-initiative.com**.

Executive Summary

Why do we need “Renewable Carbon”?

In order to fight climate change, we need to curb our consumption of fossil resources. This has been shown in many studies and several of them even quantify how much of the remaining fossil resources need to be left in the ground. In the energy sector this is possible through “decarbonisation”. However, this strategy is not feasible for organic chemistry, which is defined by the use of carbon. For the important chemical and plastic industries, we need to find alternative carbon sources in order to shift towards a more sustainable and climate-friendly production and consumption. We call these alternative carbon sources “renewable carbon”.

Staying with the widely-accepted concept of “decarbonisation” is not only inaccurate for the chemical and plastics industry, it is also potentially harmful, since it shifts attention from the necessity of carbon use and therefore from the question of the “right” carbon sources. Furthermore, in light of growing scarcity of other finite resources – metals, minerals, rare earths – carbon will be an important backbone of humankind’s product needs, since it is available in almost unlimited quantities in the atmosphere.

The equivalent to decarbonisation in the energy sector is a transition to renewable carbon in the chemical and plastics industries.

What is “Renewable Carbon”?

Renewable carbon entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere. Renewable carbon can come from the biosphere, atmosphere or technosphere – but not from the geosphere. Renewable carbon circulates between biosphere, atmosphere and technosphere, creating a carbon circular economy.

There are only three sources of renewable carbon:

Biosphere: Renewable carbon gained from all types of biomass

- Food crops
- Non-food crops
- Side streams, by-products and biogenic waste
- Includes measurable bio-based carbon content as well as “biomass balance and free allocation” approach

Technosphere and atmosphere: Renewable carbon from direct CO_2 utilisation (Carbon Capture and Utilisation (CCU), also Power-to-X)[1]

- Fossil point sources (while they still exist)
- Biogenic point sources (permanently available)
- Direct air capture

Technosphere: Renewable carbon from recycling of already existing plastics and other organic chemistry products

- Mechanical: limited quantities and qualities, limited in handling of mixed fractions
- Chemical: gasification, pyrolysis, solvolysis and more, early technology stage, first commercial plants in five years expected
- Enzymatical: early stage technology
- Incineration, but only with CO_2 capture and utilisation (CCU)

[1] In some instances, this can also include other carbon oxides than carbon dioxide, e.g. CO.

In order to provide the full benefits of these technologies, all of them should run on renewable energies in order to avoid additional fossil fuels consumption for the supply of carbon as a material. However, this is a long-term vision and the first steps should be taken as soon as possible to account for the urgency of the climate crisis. For CCU processes that require energy, the use of renewable energy is indispensable.

How realistic is a shift towards "Renewable Carbon"?

Of course, shifting relevant amounts of chemical and plastics production towards the use of renewable carbon will require significant efforts by the industry, by policy and by society as a whole. For the different sources of renewable carbon, different factors will determine their success. For biomass, land availability is extremely important and it depends on a large variety of political decisions and climate change impacts.

The provision of affordable renewable energy from solar, wind and hydro power is vital for all three sources of renewable carbon to decarbonise the required energy, but it is especially indispensable for CCU technologies (mostly in the form of green hydrogen). Our own calculations show that a range of 15 to 20 PWh would be required to cover the 2018 global carbon demand of the chemical industry by CO_2 utilisation with renewable energy, depending on the efficiency of electrolysis and further processes. Based on a typical photovoltaics (PV) yield of about 250 GWh/km^2/y in the Sahara we calculate: In order to produce 20 PWh from PV, an area of 80,000 km^2 is needed. This constitutes only 0.9% of the total area of the Sahara of 9,200,000 km^2.

Political support will also be extremely important to get this new concept and several related, but very young technologies off the ground. A range of measures are conceivable, among them the idea of a probably very effective fossil carbon tax (applied to fossil carbon as a feedstock, not to CO_2 as an emission). Similar concepts are also being discussed in the framework of the Green Deal proposed by the European Commission, where it is called "carbon border adjustment". Most importantly, political measures should push for a general switch to renewable carbon and not discriminate between the different sources. They should be technology neutral and let the market forces, regional availabilities and other factors decide which source of renewable carbon is chosen in a given context.

Last but not least, a large number of industries and researchers have indicated their agreement with the proposed strategy of switching to renewable carbon. This strategy is doable, will have significant positive impact on the climate if done right and will keep innovation, investment and employment in Europe.

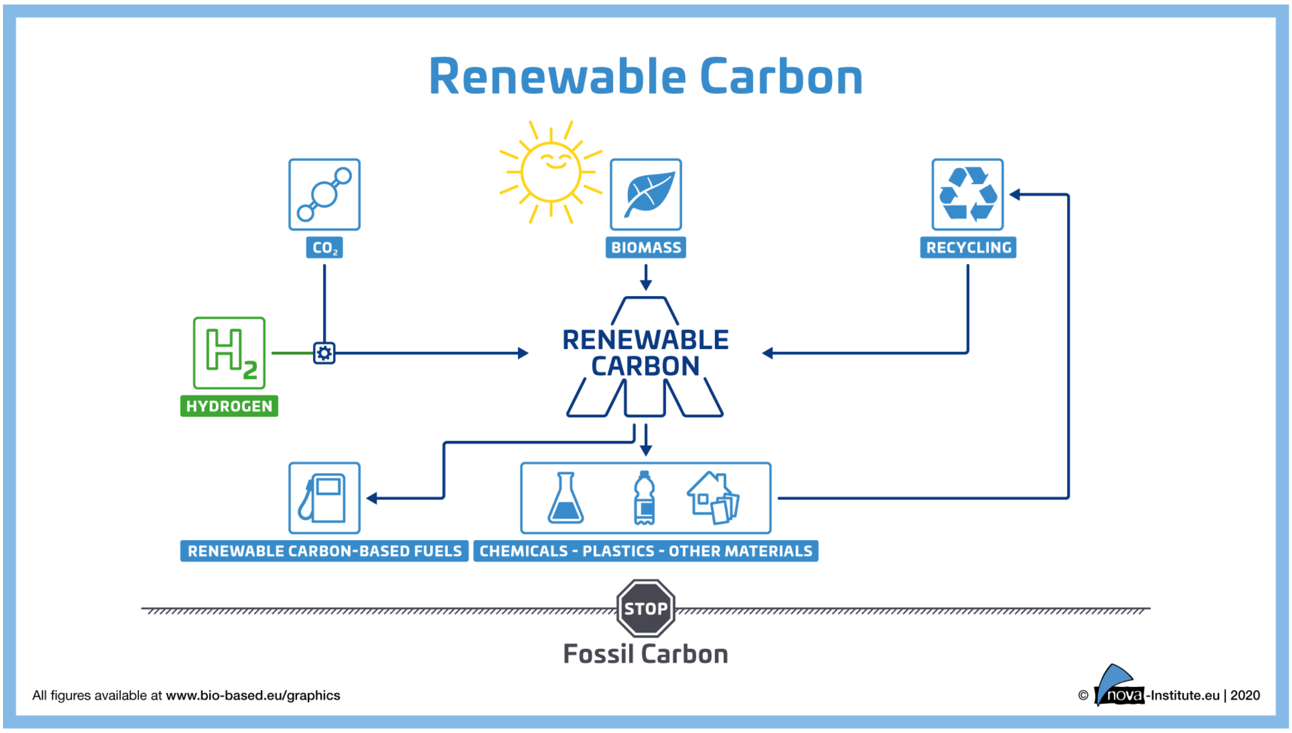

Figure 1: Renewable Carbon (nova-Institut 2020)

Why a Renewable Carbon Strategy?

The chemical and plastics industry is faced with enormous challenges in meeting the climate goals set by the European Union and the sustainability expectations held by societies around the globe[2]. The demand for energy must be further reduced through optimised processes and met by renewable energies. The products' sustainability during their use phase as well as at their end-of-life must be improved. A stringent circular economy needs to increase resource efficiency and minimise ecologically harmful loss pathways. "Political ambitions of such a nature require a shift in paradigms which must be supported by technological breakthroughs." (DECHEMA 2017)

Apart from the switch to renewables in energy supply, there is another very important, radical and unavoidable step towards achieving ambitious emission reduction targets, which is often overlooked: The change of the raw material base. In most countries, there is a clear and more or less consistent energy policy towards a 100 % renewable energy system based on solar, wind, hydro and other renewable energies. Apart from bioenergy, all of these deserve the term "decarbonisation". But there is no corresponding policy or strategy for the material sector, especially not for the chemical and plastics industry.

Industry has to go beyond using renewable energy. All fossil carbon use has to stop, as the carbon contained in the molecules of chemicals and plastics is prone to end up in the atmosphere sooner or later. Only a full phase-out of fossil carbon will help to prevent a further increase in CO_2 concentrations."

However, it is not decarbonisation, like it is quite reasonably called for in the energy sector, that will help the chemical and material industry. After all, **organic chemistry cannot be decarbonised**, as it is entirely based on the use of carbon. This also includes the plastics industry – the modern world is inconceivable without its versatile polymers, unless you are prepared to accept considerable sacrifices or higher greenhouse gas emissions (International Council of Chemical Associations 2009).

The term decarbonisation[3] is simply inaccurate for organic chemistry, which is based on carbon – as is the entire life on earth. The term is used out of ignorance and as a direct analogue to the energy sector, but is absolutely not applicable to the chemical, plastics or biomass sectors. Even worse – the term is not only inaccurate, but also potentially harmful as it avoids the question of the "right" carbon sources. But such carbon sources are exactly what we have to provide.

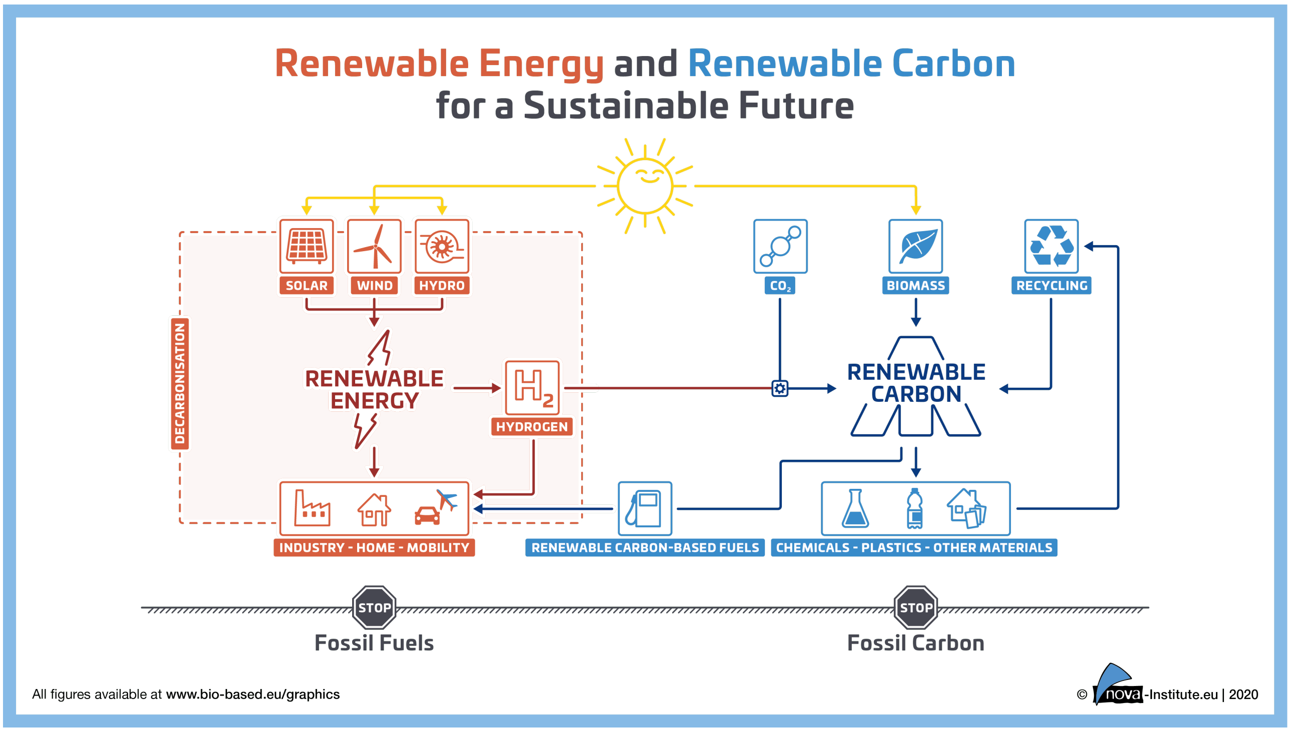

Figure 2: Renewable Energy and Renewable Carbon (nova-Institut 2020)

[2] "The German chemical industry supports ambitious global climate protection under the Paris Agreement. It also supports the EU target of 80 to 95 percent lower greenhouse gas emissions by 2050 – a contribution to achieving the internationally agreed long-term goals of Paris." (VCI 2018)

[3] The unfortunate use of the term decarbonisation goes back to the IPPC "Special Report on Global Warming of 1.5 °C" (2018), where decarbonisation is defined as: "The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport" (https://www.ipcc.ch/sr15/chapter/glossary/). The IPPC refers here exclusively to the energy sector, where extensive decarbonisation is indeed largely possible. Without further reflection, the term was and still is often applied to chemistry and materials, where the term is inaccurate as all organic chemicals and materials are based on carbon.

The future chemical and plastic industries need carbon – so what are the "right" carbon sources?

It is clear by now that only a full phase-out of fossil carbon extraction will help prevent a further increase in CO_2 concentrations. **All of the fossil carbon extracted from the ground will sooner or later be released into the atmosphere where the CO_2 concentration will go up as a consequence**. In other words: The world has a "carbon budget" which it cannot exceed if it wants to achieve the climate goals. Several campaigns have taken up this concept under the name "Keep it in the ground", as for example Greenpeace and the Guardian.

In a range of studies scientists have calculated more or less exactly how much more fossil carbon may be extracted from the ground until the climate goals must be abandoned. For instance, in a paper published by Nature magazine, McGlade and Ekins (2015) wrote (see also for example Muttitt et al. (2016) or Climate Council of Australia (2015)):

> *"Our results suggest that, globally, a third of oil reserves, half of gas reserves and over 80 % of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C."*

This means that for future economic activities, we need to make sure that carbon use does not entail additional carbon from the geosphere to be released into the atmosphere. The alternative carbon sources available as of now are: **Carbon from biomass, from direct CO_2 utilisation[4] and from recycling of materials already used.** These sources are summarised as "renewable carbon".

> The chemical industry may only develop into a sustainable sector once it bids farewell to fossil raw materials such as crude oil, natural gas and coal for good and uses nothing but renewable carbon as a raw material in organic chemistry.
> The equivalent to decarbonisation in the energy sector is a transition to renewable carbon in the chemical and plastics industries.

As long as the chemical industry continues to use additional[5] fossil carbon, it will add to the greenhouse effect in an increasingly significant fashion. "The global chemical industry accounts for approximately 10 % of the global energy consumption or 30 % of the total industrial energy demand worldwide. The demand is covered to 90 % by fossil resources, including the non-energetic or material demand for carbon and the energetic demand for process energy. The chemical industry is responsible for approximately 7 % of global anthropogenic GHG emissions or around 20 % of industrial GHG emissions" (Global Efficiency Intelligence 2018). The petrochemical feedstock accounts for 12 % of global oil demand, a share that is expected to increase driven by increasing demand for plastics, fertilisers, detergents and other products. Petrochemicals are rapidly becoming the largest driver of global oil demand. The growth in demand for petrochemical products means that petrochemicals are set to account for over a third of the growth in oil demand to 2030, and nearly half to 2050, ahead of trucks, aviation and shipping (IEA 2020).

There are two main reasons for this development: the sharp increase of solar and wind power as well as the progressing electrification of traffic will reduce the demand for fossil energy carriers. In the field of chemicals and plastics, however, most market observers expect the production to increase globally by three to four per cent each year as demand in furnishing, clothing, transport and packaging is set to grow strongly due to a rise in the global population and improved standards of living.

This means that the chemical and plastics industry's share of greenhouse gas emissions will dramatically grow in spite of comprehensive improvements in efficiency, and as a consequence public attention will undoubtedly increase. **Only a clear strategic focus on renewable carbon will prevent further damage to its reputation** – or may even help the industry to show itself in a more favourable light than before. With a future oriented renewable carbon strategy, the chemical and plastics industry can become a relevant part of the solution, rather than one of the main problems**.**

Apart from being a necessity for climate protection, the use of renewable carbon by the industry has another very strong argument in its favour: It can be an inexhaustible source of raw materials for the next millennia, especially if CO_2 from the atmosphere is used as a carbon source. It is the only raw material that is available to humans in practically unlimited quantities, also compared to metals and minerals which are already getting scarce in some cases.

> It is not CO_2 that is at the core of the climate problem, but the additional fossil carbon that we take out of the ground and which gets released in the atmosphere as CO_2 or other emissions. If the inflow is prevented, the CO_2 content of the atmosphere will no longer increase. The Renewable Carbon Initiative addresses exactly this core problem: Focus on phasing out fossil resources and use renewable carbon instead!

[4] The process of direct CO_2 utilisation is called "carbon capture and utilisation (CCU)" or "Power-to-X (PtX)". These processes can also cover other carbon oxides than carbon dioxide, e.g. CO.

[5] In other publications, what we describe here as "additional fossil carbon" is expressed as "fresh" or "virgin" fossil carbon. While we consider the terms fresh and virgin as ambiguous in combination with fossil carbon, in the end all terms mean the same fossil carbon.

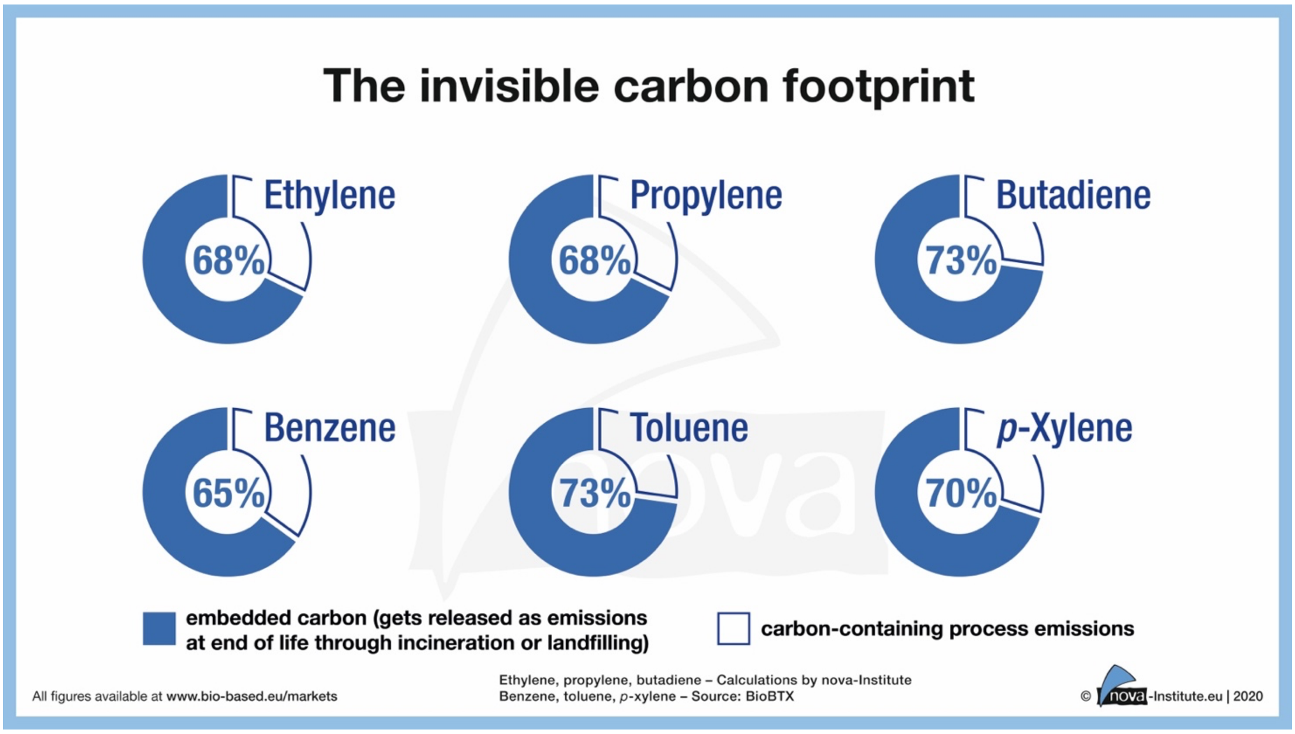

Figure 3: Carbon footprint of primary petrochemicals (nova-Institut 2020)

GHG Emissions and Carbon

At the global scale, the key greenhouse gases (GHG) emitted by human activities in CO_2 equivalents are (IPCC 2014)[6]:

- **Carbon Dioxide (CO_2), 76 %**: 65 % of all GHG emissions stem from fossil fuels and industrial processes, 11 % are emitted by direct human-induced impacts on forestry and other land use, such as through deforestation, land clearing for agriculture, and degradation of soils. Likewise, land can also remove CO_2 from the atmosphere through reforestation, improvement of soils, and other activities.
- **Methane (CH_4), 16 %:** agricultural activities, waste management, energy use, and biomass burning all contribute to CH_4 emissions.
- **Nitrous oxide (N_2O), 6 %:** agricultural activities, such as fertilizer use, are the primary source of N_2O emissions. Fossil fuel combustion also generates N_2O.
- **Fluorinated gases (F-gases), 2 %:** industrial processes, refrigeration, and the use of a variety of consumer products contribute to emissions of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6).

About 94 % of the GHG contain carbon. Only N_2O and SF_6 contribute to climate change without carbon in their molecule structure. **80 – 90 % of the carbon containing GHG contain fossil carbon from the ground**. The remaining carbon comes from forestry and agriculture and can be balanced by a sustainable circular bioeconomy, where the uptake and the release of carbon are the same, or by reforestation which could increase the uptake to even higher levels than the release.

As long as the existing carbon-containing GHG are kept in a circle, there is no damage done to the climate. The use of additional fossil carbon, however, is clearly the main cause of the greenhouse effect and climate change, no matter whether it is emitted as CO_2, CH_4 or several F-gases. The solution here can only be to **take the problem by the roots and stop bringing more fossil carbon into circulation.**

[6] Please note that the percentages are given in relation to CO_2 equivalents in terms of global warming potential (GWP). Since CH_4 for example has a much higher GWP than CO_2, this means that relative to mass, the emissions of CH_4 are much lower than 16 %.

Definition of Renewable Carbon – Biomass, Direct CO_2 Utilisation and Recycling

Definition

Renewable Carbon entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere. Renewable carbon can come from the biosphere, atmosphere or technosphere – but not from the geosphere.[7] Renewable carbon circulates between biosphere, atmosphere or technosphere, creating a carbon circular economy.

There are only three sources of renewable carbon. Renewable carbon comes from sources which can be (re)grown (biosphere), (re)captured (technosphere & atmosphere) or (re)cycled (technosphere):

Biosphere: Renewable carbon gained from all types of **biomass**

- Food crops
- Non-food crops
- Side streams, by-products and biogenic waste
- Includes measurable bio-based carbon content as well as "biomass balance and free allocation" approach

Technosphere and atmosphere: Renewable carbon from direct CO_2 utilisation

- Fossil point sources (while they still exist)
- Biogenic point sources (permanently available)
- Direct air capture

Technosphere: Renewable carbon from recycling of already existing plastics and other organic materials

- Mechanical: limited quantities and qualities, limited in handling of mixed fractions
- Chemical: gasification, pyrolysis, solvolysis and more, first demonstration plants are in operation, first commercial plants are expected soon
- Enzymatical: early stage technology
- Incineration, but only with CO_2 capture and utilisation (CCU)

Of course, for the utilisation and processing of these carbon sources, energy is needed. The CO_2 emissions associated with this energy must be considered in the overall balance. If the energy for the chemical reduction of CO_2 comes from fossil sources, this causes additional emissions. In this case the concept is corrupted and the authors of this paper are aware of this problem: for a long-term sustainability strategy, it is of utmost importance that the energy used as input stems from renewable resources only. This is especially true for direct CO_2 utilisation (here it is crucial), but also for the fuels used by farmers or energy needed to run recycling plants. However, it should also be clear that this applies to all economic endeavours and not only the sources of renewable carbon, so the demands made towards this innovative concept should not be more restrictive than they are made towards the industry in general. The good news is, though, that the world is on track towards using more and more renewable energies.

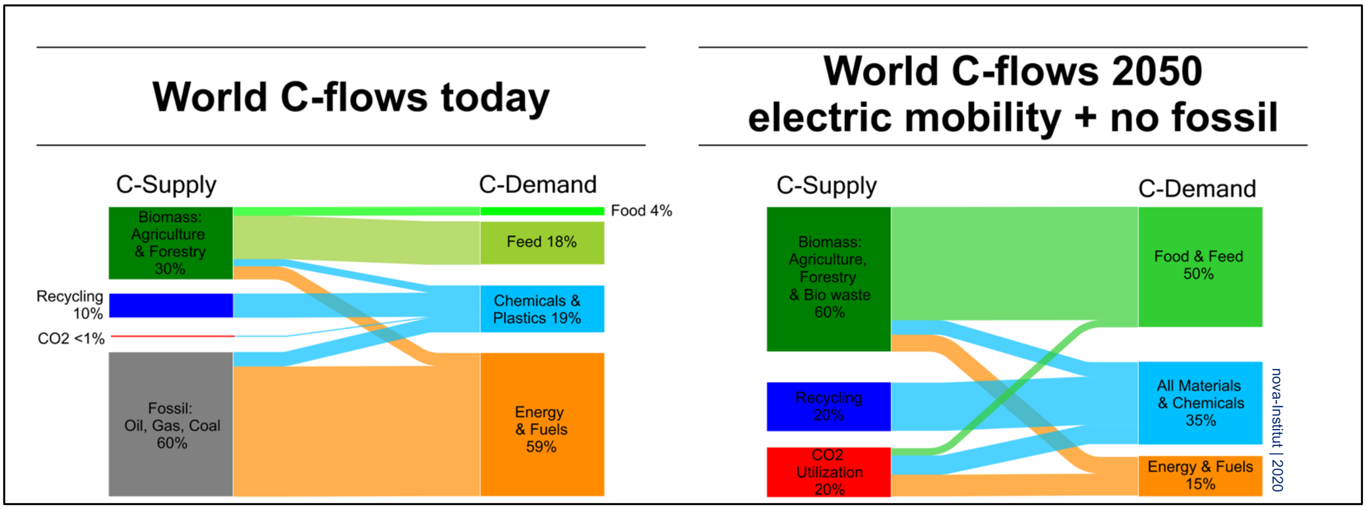

Figure 4: Flow of carbon through world economy for today and for 2050 in a scenario with no fossil C and a focus on electric mobility (nova-Institut 2020)

[7] The authors are aware that carbon both from captured fossil CO_2 emissions or from recycled fossil plastics originally stems from the geosphere. Also, biomass uses geospheric carbon to some extent, whereas petroleum originally comes from the biosphere. The interconnections are complex, but for the sake of a usable definition, this wording has been chosen. It should be clear that the focus is always on substituting additional fossil carbon from the geosphere.

All three sources are essential for a complete transition to renewable carbon, and all of them should ideally be used by the industry, supported by politics and accepted by the population. It is crucial to avoid conflicts and internal struggle between the three options of renewable carbon in the future, as they still exist today. These "brother wars" have only one winner: fossil carbon. To avoid using any additional fossil carbon, we need the smartest mix of all three.

We need a future materials policy – a policy on renewable carbon. Which of the renewable carbon options comes into play in a specific case should be decided by technology and market forces and not by politics. It depends on regional factors and concrete applications. Policy should provide a general market pull for renewable carbon, without regulating the individual renewable carbon streams which could also lead to undesirable side effects with a high risk.

Similar Concepts and Strategies

It is obvious that the chemical and plastics industry has to change its carbon source. Other scientists besides nova have also taken up and described this idea. Some important examples should be mentioned:

The VTT Technical Research Centre of Finland recently published the discussion paper "The Carbon Reuse Economy" (Lehtonen et al. 2019). Key definitions, impacts and drivers are in a nutshell:

> *"In the carbon reuse economy fossil carbon is left in the ground while aboveground carbon circulates without accumulating to the atmosphere. ... we believe that the carbon reuse economy can have a significant role in mitigating climate change and creating new business based on sustainable carbon."*

This definition and view are very similar to that of nova.

VTT identifies as the main drivers:

- Potential of carbon reuse to displace the use of fossil resources for energy, fuels, chemicals and materials.
- Potential to expand the regional raw material resource bases.
- Potential for new business cases based on the sustainable supply of carbon.

Already in 2016, the Finnish consulting company Pöyry (2016) used the term "recarbonisation" in a similar way, but with limitation to biogenic carbon:

> *"We need a 'recarbonisation revolution' of global material flows. We have to increase biomass and decrease non-renewable materials such as metals and minerals in the movement of global trade. Recarbonisation also means going from fossil carbon to biocarbon. The recarbonisation revolution gives us a simple way to define the bioeconomy: recarbonise materials, decarbonise energy."*

TNO, the Netherlands Organisation for applied scientific research, also uses the term "recarbonisation" in the framework of its VoltaChem project, including explicitly direct CO_2 utilisation (TNO 2019):

> *"**Recarbonisation** is the answer to the question of how to make materials such as plastics in a fossil-free future. And how to produce the chemicals that lead to products such as medicines, paints, cosmetics, and more. Almost all relevant molecules contain carbon, so we must not decarbonize here – it would mean the end of the chemical industry.*
>
> ***Closing the carbon cycle.** So, if we no longer use fossil fuels, where do we get the carbon? The responsible way is to tackle this in a renewable and circular way. That is recarbonisation: returning carbon to the start of the industrial value chain. Used materials can be the source of such renewable carbon – then we are talking about recycling of products. But we can also close the carbon circle by using atmospheric CO_2. Or biomass – which in fact is a form of naturally captured CO_2."*

In the roadmap for the Dutch Chemical Industry towards 2050, the authors use the term "Circular & Biobased", not including the direct CO_2 utilisation, which is mentioned as an additional area (VNCI 2018):

> *"The pathway Circular & Biobased strongly aims at closing the materials chain through recycling (both mechanical and chemical) and the use of biobased feedstock. In this pathway, the use of biobased materials as raw materials is central, and products come back to the sector via a strong focus on closure of the materials chain. New business models occur, with a focus on high value production creation and circularity."*

The German Association of the Chemical Industry VCI talks about "carbon cycle management" in its 2018 position paper (VCI 2018):

> *„The potential in the reuse or mechanical recycling of waste is limited for carbon-containing products. But there are other options for carbon cycles, such as feed-stock recycling or energy recovery of waste. The latter can also help close the carbon cycle through the material use of CO_2 and the bioeconomy."*

Also, the European Commission includes the three non-fossil carbon sources in its Plastics Strategy (EC 2019): „It was estimated that plastics production and the incineration of plastic waste give rise globally to approximately 400 million tonnes of CO_2 a year. Using more **recycled** plastics can reduce dependence on the extraction of

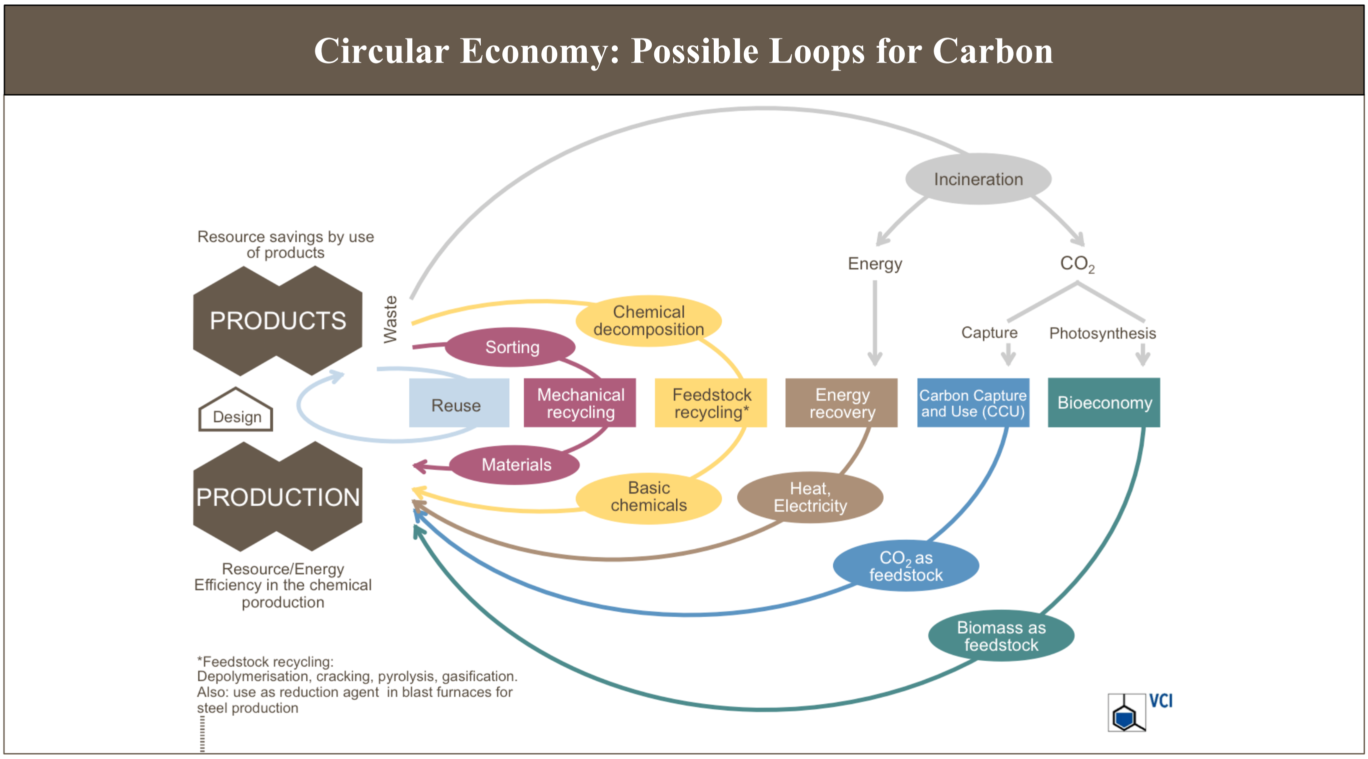

Figure 5: Circular Economy: Possible Loops for Carbon (VCI 2018)

fossil fuels for plastics production and curb CO_2 emissions. According to estimates, the potential annual energy savings that could be achieved from recycling all global plastic waste is equivalent to 3.5 billion barrels of oil per year. … Alternative feedstocks, including **bio-based feedstocks** and **gaseous effluents** (e.g. carbon dioxide or methane) can also be developed to avoid using fossil resources. Currently, these feedstocks represent a small but growing share of the market."

More and more companies are declaring targets to stop using fossil carbon in their products in the future, whereby the option of direct CO_2 use is so far often overlooked. Two examples should suffice. The large Dutch chemicals and polymer producer DSM announced in 2019 (DSM 2019):

> *"Royal DSM, a global science-based company active in nutrition, health and sustainable living, today announces at the K-Show that its engineering plastics business will offer a full alternative range of its existing portfolio based on bio-and/or recycled-based materials by 2030. In this way, DSM Engineering Plastics is taking the next step in its sustainability journey in alignment with DSM's purpose-led performance-driven strategy, enabling a circular and bio-based economy."*

And US toy giant Mattel also announced in 2019 (Mattel 2019):

> *"Mattel, Inc. (NASDAQ: MAT) today announced its goal to achieve 100 % recycled, recyclable or bio-based plastics materials in both its products and packaging by 2030."*

Why "Renewable Carbon"? Is this the best term?

As shown in the overview, existing papers use different terms. Some authors state that only biomass is actually renewable carbon. Carbon from recycling and CO_2 utilisation should not be called renewable, but rather recycled carbon.

Strictly speaking, one could try to establish that distinction. But we prefer to continue talking about renewable carbon in all three sources. Above all, because a real distinction is hardly possible. CO_2 from direct air capture is certainly not recycled carbon: the technical plant uses the same CO_2 as plants or trees. On the other hand, it is usually said that in bioeconomy, CO_2 is used in a circular fashion. Which means that after all, biogenic carbon is also recycled carbon. Do algae, fed with fossil CO_2 from power plants, supply recycled or renewable carbon? And what about mechanically recycled bio-based plastics? Are they recycled or renewable? These discussions are complicated and distract from the main arguments.

In the end, it is important that no additional fossil carbon is released into the atmosphere, and this is the case for all three alternatives if done right.

Renewable Carbon from Biomass

Plants convert CO_2 from the air **and solar energy into biomass through photosynthesis.** The biomass is then used as food and animal feed, chemical feedstock, material or as an energy carrier. In 2016, the European Union covered 14 % of the carbon required within organic chemistry applications through biomass (Piotrowski et al. 2016). Over the past few years that figure has grown consistently, increasing from eleven per cent in 2008.

The biomass used in this context breaks down into either primary biomass straight from fields and forests or biomass derived from biogenic waste and side streams, e.g. generated by the agriculture and forestry sector, the food, feed and chemicals industries, the production of wood and paper as well as by private households. Utilising this kind of "organic waste" in a sophisticated manner is key to a bio-based circular economy.

For a truly comprehensive and sustainable raw materials strategy, dogmas such as "no food crops for industrial use" are not helping much. The more recent political focus on so-called second-generation biomass, such as wood or straw, makes biomass utilisation by the chemicals industry complicated and expensive. These raw materials frequently require upstream processing and converting, which often does not result in a better sustainability footprint compared to first-generation solutions (Dammer et al. 2017). While general shortages in the food sector exist, these pertain to protein, whereas sugars for example are copiously available. There is currently a global excess production of sugar while awareness campaigns are launched and taxes are introduced to further reduce the human intake of sugar. At the same time, in a comparison of all cultivated plants, sugar beet and sugar cane excel with an unsurpassed yield and per-acreage-efficiency. However, the chemical industry currently shies away from processing more sugar because of a fear of negative repercussions on their reputation ("No food for industrial use"). Alas, what a wasted opportunity.

Biomass: Pros in a nutshell

- Food crops:
  – Commodities, established in high volume, good logistics
  – Food crops: Protein-rich by-products
- Wide range of non-food feedstock – no direct food competition, positive image
  – wood and lignocellulosic by-products and side streams
  – biogenic waste from industry and households
- Low GHG footprint compared with fossil resources
- New green chemical pathways
- Biotechnology as sustainable process technology

When it comes to using biomass, **comprehensive sustainability assessments** are indispensable for any given region to identify the most suitable local type of biomass for certain applications in order to keep unwanted side effects at bay. In discussions on land use, direct and indirect land use changes (LUC and iLUC) and food security there should be much higher consideration of the enormous risks climate change poses to agricultural land and food production, and at the same time how widely biomass products may help reduce greenhouse gas emissions.

How much of the chemical industry's raw material demand can be covered by biomass until 2050? Experts suggest that the 14 % share seen in the year 2016 may double or even triple by 2050. At the end of the day, among other things, the societal and political acceptance for main agricultural products (such as wheat, corn or sugar beet) to be used as feedstock in the chemicals sector will determine how much of this potential can be realised. On the surface, their use seems to undermine food security, in-depth analyses show, however, that they rather contribute to a reliable supply of food[8]. Also, efforts made for biodiversity conservation and climate change may have an impact on the availability of land. On the other hand, once the demand in biofuels starts to decrease gradually as the decarbonisation of transport advances, land becoming available may be harnessed for the chemical industry to increase its biomass rates without the need for additional arable land.

The utilisation of biomass makes particular sense wherever functional and complex molecular units remain intact after chemical conversion, so they can be used further. For instance, oleochemical, natural rubber and lignin applications qualify in this respect as do numerous novel bio-based components such as e.g. organic acids and furan-based products. Washing, cleaning and care agents as well as polymers based on these new components frequently outperform existing products with regard to their health and environmental benefits. Additionally, industrial biotechnology may help manufacture complex molecules using short and gentle processes and made-to-measure production organisms. Lignin, for instance, little used to date and a by-product of wood processing, may be a future candidate in the production of aromatic compounds.

Biomass: Cons in a nutshell

- Limited total volume
- Low land-efficiency
- Potential pressure on land and biodiversity[9]
- Potential competition with food crops and a possible threat to food security

[8] So-called food crops often have the best efficiency-per-acreage values, deliver high-quality proteins as by-products and provide an additional buffer for the food market in times of crisis, cf. Carus and Dammer (2013)

[9] "… so-called sustainable alternatives that would put unacceptable pressures on natural resources such as forests and agricultural land, which have already been overexploited" (Greenpeace USA 2019)

Renewable Carbon from direct CO_2 utilisation ("Carbon Capture and Utilisation")

One almost endlessly available source of renewable carbon is the carbon dioxide (CO_2) and other carbon oxides (e.g. CO) contained in exhaust gases, waste air and the atmosphere, which may be utilised as a raw material for the chemical industry by means of a number of technologies.

Nowadays, **fossil CO_2** and CO is mainly obtained from fossil point sources such as power plants, steel and cement/lime plants as well as chemical industry factories. For some of these industries, owing to the specific technologies used there, the generation of CO_2 will remain unavoidable in the decades to come. **Biogenic CO_2** is typically generated during the fermentation process of the food and animal feed industries but also in biogas plants, when combusting biomass or in the paper industry. The largest reserve of CO_2 exists in the atmosphere, from which CO_2 may be retrieved using specialised facilities in a process called **direct air capture** (Carus et al. 2019).

In order to make the carbon contained in CO_2 usable once more, it must be chemically reduced, which requires large amounts of energy. From an ecological viewpoint, this means that only **renewable energies or existing process** energy qualify as options. And this in turn means that, in order to be able to use the CO_2 itself as a source for raw materials, there must be massive, worldwide growth in renewable energies such as solar and wind energy, hydropower and geothermal energy.

Provided there is sufficient renewable energy available, direct CO_2 utilisation is an inexhaustible and sustainable source of carbon for the chemical industry. Our own calculations demonstrate that a size of just one to two per cent of the Sahara area would be sufficient to cover the chemical industry's entire carbon demand in 2050, which will continue to grow from today with a CAGR of 3-4 %, by means of photovoltaics and CO_2 utilisation!

It only takes a simple chemical reaction to turn CO_2 and hydrogen (H_2), the latter of which may be obtained from renewable energies, into **methane, methanol, formic acid, ethylene and alcohols**, which in turn may be used to produce the bulk of today's chemicals. The Fischer-Tropsch process adds **naphtha, diesel, kerosene and long-chained waxes**, permitting even **today's refinery structures for the production of platform chemicals to be maintained and, at the same time, decoupled from fossil raw materials**. New chemical catalysts allow for the development of novel CO_2-based chemicals and polymers, and even complex organic molecules may be directly obtained from CO_2 thanks to **biotechnological, electrochemical and hybrid solutions**.

If the chemical industry switches to renewable carbon, society would not have to relinquish anything it has become used to over time.

> *"Almost all chemical products currently manufactured from fossil raw materials can be produced from carbon dioxide."*
> *(Lehtonen et al. 2019)*

In the medium to long term, considerable progress is also expected in the development of artificial photosynthesis and photocatalysis, with the aid of which sunlight is to be used directly for the production of chemicals. The foundation are developments based on novel nanomaterials and polymer systems, through which efficient use of solar radiation, water splitting and CO_2 reduction can be directly coupled with the synthesis of the desired products. Commercial systems with artificial photosynthesis are expected to be on the market by 2050.

Green, Grey and Blue Hydrogen

Most of the processes for CCU or Power-to-X (PtX) require hydrogen (H_2) for chemical reduction of CO_2 in order to obtain the carbon (C) for further utilisation as fuel or chemical. The most environmentally friendly and, from this perspective the only fully acceptable choice for use in CO_2 utilisation, is the so called "green hydrogen", which is produced from water by electrolysis powered by renewable electricity. The results are very pure and the process has an extremely low or even non-existent carbon footprint.

So far, the most common way to produce hydrogen is from fossil methane (CH_4) via steam reforming. This process is associated with considerable CO_2 emissions. Such "grey hydrogen" is completely unsuitable for the production of renewable carbon, as additional fossil carbon is released into circulation and finally the atmosphere.

"Blue hydrogen" has been proposed by the natural gas industry as the cheaper alternative to green hydrogen. This is a process in which the hydrogen is still produced from fossil methane via steam reforming, but in which the CO_2 is captured and stored elsewhere in a stable form. (Carbon Capture and Storage (CCS)). CCS may well be workable, however there are doubts around our ability to manage and finance the storage of captured carbon through future decades and probably centuries or even millennia. Humankind cannot be too careful with these issues. If it is not 100 % certain that through the production of "blue hydrogen" no fossil C will enter the atmosphere in the long term, the whole concept is a deceptive package that undermines and sabotages the whole idea of renewable carbon – only to keep the natural gas industry in business.

Compared to the utilisation of biomass, direct CO_2 utilisation has some considerable advantages: The requirement for space and water is significantly below the one incurred by the utilisation of biomass. In 2017, Searchinger et al. calculated that on world average, the area requirement for the production of ethanol from wood is 85 times higher than the one for ethanol production from photovoltaics and direct CO_2 utilisation (Searchinger et al. 2017). The reason for this discrepancy is the **significantly better yield of modern solar cells** (20-25 %; experts even believe efficiency rates of 40 % to be possible by 2050) compared to natural photosynthesis, where – considering the entire process chain including agriculture and down-stream processes – only 0.1 to 0.3 % of solar exposure ends up in the final product.

Economic and Employment Effects of CCU

Under current conditions, renewable carbon from CCU is generally more expensive than fossil carbon from crude oil or natural gas. **It will never again be as easy and cheap to access carbon as it has been in the fossil age.** How much more expensive CCU fuels or chemicals are exactly, depends on a number of factors but mostly on the price at which renewable energy can be obtained. As a rule of thumb, price parity with fossil fuels could be achieved at electricity prices of 1.5 to 2 eurocents per kWh (Carus et al. 2019).

In terms of employment, it is expected that a switch to renewable carbon will lead to positive effects. According to Eurostat, more than 65,000 employees (EU-28) (4,000 in Germany) 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.

In addition, there are already hundreds of start-ups developing new technologies for the production and use of renewable carbon. “A third important driver for CCU is the potential for new business cases based on the sustainable supply of carbon for value-added products. Economic feasibility is a long-term prerequisite for the viability and large-scale realisation of CCU concepts. In addition, there are CCU business cases, such as high-value specialty chemicals and materials that can be justified solely on an economic basis” (Lehtonen et al. 2019). For more details on the economic aspects of CCU, please see nova-Paper #11 on Carbon Capture and Utilisation (Carus et al. 2019).

Direct CO_2 utilisation: Pros in a nutshell

- Very high potential in volume (almost unlimited)
- Low demand for land and water, low carbon footprint
- High TRL technologies available
- Almost all chemicals and plastics can be produced from CO_2
- High employment potential
- Inexhaustible source of carbon for the next millennia

Direct CO_2 utilisation: Cons in a nutshell

- Potential lock in effects using fossil point sources
- Competition on limited renewable electricity
- High investment necessary

Renewable Carbon from Recycling

Currently politicians mainly count on recycling schemes to preserve fossil resources. In a circular economy, **the recycling of existing plastic materials and other organic chemistry products** is, without any doubt, an important source of renewable carbon which could and should be exploited more comprehensively.

However, one should **not succumb to the illusion that recycling will be able to provide the lion's share of renewable carbon in a sustainable manner.** Recycling must not be turned into an incontrovertibly true principle that is applied without any sustainability assessments. For instance, the recycling industry's huge energy requirements should be fully covered by renewable energies to prevent the indirect release of additional fossil CO_2.

Still, there are more open questions regarding recycling as a panacea for our raw materials problem. Which amounts and which grades of recyclable plastics and other products may reasonably be collected and recycled in reality? Which product characteristics are achievable with recycled plastic materials and how much new material must be added in the process? Discussions about the large-scale utilisation of post-consumer plastics as railway sleepers and paving stones reflect the awkward search for suitable applications for materials of an inferior quality. Does the effort involved possibly even outweigh the benefits? How does the environmental footprint of recycling compare to the exploitation of other renewable carbon sources? How can waste and recycling streams be managed and standardised?

If mechanical recycling is complemented by different types of **chemical recycling** in a next step, which means the breaking down of plastics into their chemical components – including monomers, syngas and pyrolysis oil – the application range of the intermediate products will become far larger and expected quality losses will be clearly lower or even non-existing. Completely new are biotechnological processes for the treatment of waste from the chemical and plastics industry. However, sustainability analyses will have to show how these new technologies perform when compared to other solutions as well.

The role of the process called **thermal recycling**, which de facto dominates today, is set to change, if its CO_2 emissions will be captured and utilised. This innovation will mean the waste incineration will no longer release any CO_2 into the atmosphere. Waste streams that require substantial recycling efforts, either mechanically or chemically, may continue to qualify for thermal recycling even in a sustainable economy, as the exploitation of the released carbon-rich exhaust gases contributes to material recycling at the same time.

Recycling: Pros in a nutshell

- Most important end-of-life option for plastics in the future circular economy
- Strong recycling targets in the European Union will guarantee access to renewable carbon from recycling
- Chemical recycling: Basically no loss of quality compared to virgin feedstock

Recycling: Cons in a nutshell

- Complex infrastructure required for collection and sorting
- Chemical recycling only at demonstration level, final evaluation not yet possible
- High investment necessary

Sustainability in the renewable carbon concept – a three-level approach to sustainable materials

Sustainability is one of the most critical topics of our times and has rightly moved into the centre of many discussions today. Products are designed with sustainability in mind, industries try to transform into more sustainable patterns, policies regarding or including sustainability are increasing on the agenda, and the public is requesting more concentrated efforts toward it. In particular climate change and biodiversity (which also suffers under climate change) are crucial topics for a sustainable future and should be considered when sourcing raw materials. We want to highlight that the Renewable Carbon Initiative fits superbly into sustainability thinking with the following three-level approach. This approach consists of three key questions when considering a sustainable chemical or material application.

The **question on the first level** is: **Is carbon needed in the application or can the application be decarbonised?** Most material applications, such as chemicals, plastics and a variety of materials (e.g. textile fibres), are based on organic chemistry and require carbon on a permanent basis – in contrast to the energy sector, which can be largely decarbonised sooner or later with electricity and hydrogen. A peculiar case is the transport sector, as it is in a phase of transition but has some notable exceptions. For example, the aviation sector will likely stay dependent on carbon-containing fuels (such as kerosene) in the long term.

The **question on the second level** is: If the application requires carbon in the long run, **what carbon should be used in the future?** We have argued in detail that the answer should be renewable carbon. Today, about 90 % of the worldwide demand is covered by fossil carbon – crude oil, natural gas and coal. In the future, the decision should be made to use increasingly more renewable carbon, until finally only renewable carbon is used. This would stop the influx of additional fossil carbon from the ground completely, avoiding its large contribution of 80 % to the entire global greenhouse effect.

If an application needs carbon and this carbon is renewable, we arrive at the third level, which allows no turning back. The **question on the third level** is**: What is the most sustainable carbon from the renewable carbon family?** Which renewable carbon source is the most sustainable, most efficient and socially acceptable solution for a certain application in a given region? Biomass, CO_2 or recycling? Biomass from wood, sugar beet or metropolitan biogenic waste? Captured CO_2 from fossil power plants, from fermentation or from the atmosphere (direct air capture)? Or recycled carbon from old plastics via mechanical, chemical or enzymatic recycling?

While the third level is the most difficult to answer, it is also the most important question to consider in order to identify the best solution in a given circumstance. Answers will differ from situation to situation with no universally superior option. In Sweden and Finland, the most sustainable carbon will probably come from wood, in South America certainly not. At good sugar beet locations, these plants and their carbon might be the favourites. In biomass-poor locations and countries with good green hydrogen supply, captured CO_2 use will be ideal, and in regions with a strong chemical industry, chemical recycling will be a prominent option.

Some key arguments for and against the three renewable carbon sources can be found on the previous pages, where we have summarised the pro and cons of each in a nutshell. Various sustainability certification systems for sustainable biomass or ideological reservations (“no animal products”, “don’t use fossil emissions”, “no food crops”, “no GMO”) can provide further guidance in order to identify the most sustainable option for a specific case. The renewable carbon family is already powerful and diverse in its application, offering a wide range of options – technically speaking, there is already a renewable carbon alternative for practically every application today. With continuous research and development, it will become even more sustainable, with increased affordability and applicability at the same time.

Future Scenarios for the Chemical Industry based on Renewable Carbon

When considering potential volumes of the different renewable carbon sources, it can be assumed that in a sustainable future chemical industry, bulk chemicals will primarily rely on chemical CO_2 utilisation through methane, methanol and naphtha, while specialty chemicals and complex molecules will more likely be produced from biomass (and CO_2 fermentation). At the same time, mechanical, chemical and enzymatical recycling will reduce the need for additional renewable carbon overall.

During the last years, several studies have been published in which future scenarios for the chemical industry are developed. These also include scenarios in which CO_2 is the primary raw material source in order to understand what this means, for example, for the provision of renewable energy.

In the publication "Climate change mitigation potential of carbon capture and utilization in the chemical industry" by RWTH Aachen University and partners, several scenarios are described and discussed. As a summary, the authors conclude: "Chemical production is set to become the single largest driver of global oil consumption by 2030. To reduce oil consumption and resulting greenhouse gas (GHG) emissions, carbon dioxide can be captured from stacks or air and utilized as alternative carbon source for chemicals. Here, we show that carbon capture and utilization (CCU) has the technical potential to decouple chemical production from fossil resources, reducing annual GHG emissions by up to 3.5 Gt CO_2-eq in 2030. Exploiting this potential, however, requires more than 18.1 PWh of low-carbon electricity, corresponding to 55 % of the projected global electricity production in 2030. Most large-scale CCU technologies are found to be less efficient in reducing GHG emissions per unit low-carbon electricity when benchmarked to Power-to-X efficiencies reported for other large-scale applications including electro-mobility (e-mobility) and heat pumps. Once and where these other demands are satisfied, CCU in the chemical industry could efficiently contribute to climate change mitigation" (Kätelhön et al. 2019).

Our own calculation shows that a range of 15 to 20 PWh would be required to cover the entire carbon demand of the chemical industry today by CO_2 utilisation with renewable energy, depending on the efficiency of electrolysis and further processes. Our own calculation also shows that for the production of 20 PWh solar power, only 0.9 % of the Sahara region is needed (see below). This area could cover the global non-energetic carbon demand of the chemical and plastics industry from 2018.

Based on a typical photovoltaics (PV) yield of about 250 GWh/km^2/y in the Sahara we calculate: In order **to produce 20 PWh from PV, an area of 80,000 km^2 is needed. This constitutes only 0.9 % of the total area of the Sahara of 9,200,000 km^2**. The total area of deserts worldwide is 30,000,000 km^2.

It depends on various factors how much electricity will be available in total worldwide in the future. Depending on different scenarios (IEA 2018; IRENA 2019; Ram et al. 2019), the estimated 20 PWh represent a share of 14 % to 44 % of global expanded electricity production in 2050, mainly based on renewable energies.

The calculated reduction of annual GHG emissions by up to 3.5 Gt CO_2-eq in 2030 (Kätelhön et al. 2019) would mean 11 % of the reduction efforts needed to reach the allowed 24 Gt CO_2e (in the 1.5 °C IPCC scenario) compared to the emission level of 55 Gt CO_2-eq in 2019.

Another study entitled "ROADMAP CHEMIE 2050 – Towards a Greenhouse Gas Neutral Chemical Industry in Germany" was published by DECHEMA and FutureCamp in 2019. The study develops three possible scenarios for the German chemical industry, of which the scenario "greenhouse gas neutral path 2050" is of particular interest in our context (DECHEMA 2019).

"The new, electricity-based processes will increase the electricity demand of the German chemical industry to 685 TWh per year from the mid-2030s, which is more than the total electricity production in Germany of 2018. [...] Companies would have to invest around 68 billion euros more between 2020 and 2050, most of it from 2040 onwards. The conversion of the basic chemical processes examined in the roadmap alone entails additional investments of up to around 45 billion euros. The roadmap of the German chemical industry shows that a largely greenhouse gas-neutral chemical production in Germany by 2050 is technologically conceivable. New methods of cycle management, CO_2-free hydrogen production and the use of CO_2 as a raw material make this possible. The extent to which chemistry can realise this technical potential depends on several factors." (DECHEMA 2019)

Based on the data of this study, nova-Institute has calculated the oil price that would be necessary to make a complete switch to CO_2 cost neutral. The result is $200 per barrel, more than three times compared with today's crude oil price.

High-ranking scientists from Oxford and Princeton have developed comprehensive scenarios for the use and sequestration of CO_2. The scenarios also include economic analyses of which CCU pathways will become competitive by 2050. On chemistry, they write: "The estimated utilization potential for CO_2 in chemicals is around 0.3 to 0.6 Gt CO_2 yr−1 in 2050, and the interquartile range of breakeven costs obtained from the scoping review is $80 to $320 per tonne of CO_2." (Hepburn et al. 2019)

Future scenarios for plastic industry

A future scenario for the plastics industry might look as follows: Due to its annual growth of three to four per cent, the global production of plastics will soon reach the mark of 400 million tonnes per year. Pronounced recycling efforts might hold the continuously growing demand for new plastics between 400 million and 500 million tonnes by 2050. This need could then be covered by, for example, 30 % biomass and 70 % direct CO_2 utilisation. The total of biomass required to do so would amount to roughly 1 % of biomass currently used around the globe in all fields of application (13 – 14 billion tonnes, of which 60 % alone are attributable to animal feed for the production of milk and meat). A size of less than 1 % of the Sahara Desert would suffice to cover this 70 % by means of photovoltaics and CO_2 utilisation.

Richard Northcote, the late Chief Sustainability Officer at Covestro chemical group, said in April 2018:
"Can you imagine in 2050, for example, that we're not touching oil as an industry, but we are basically taking CO_2 out of the air and we are creating all these products? Then you have an industry that is totally circular. That is the dream. We are not anywhere near that, but if you start looking at what you can achieve when we start really harnessing AI and other things, who knows where we could get to in terms of chemistry?"

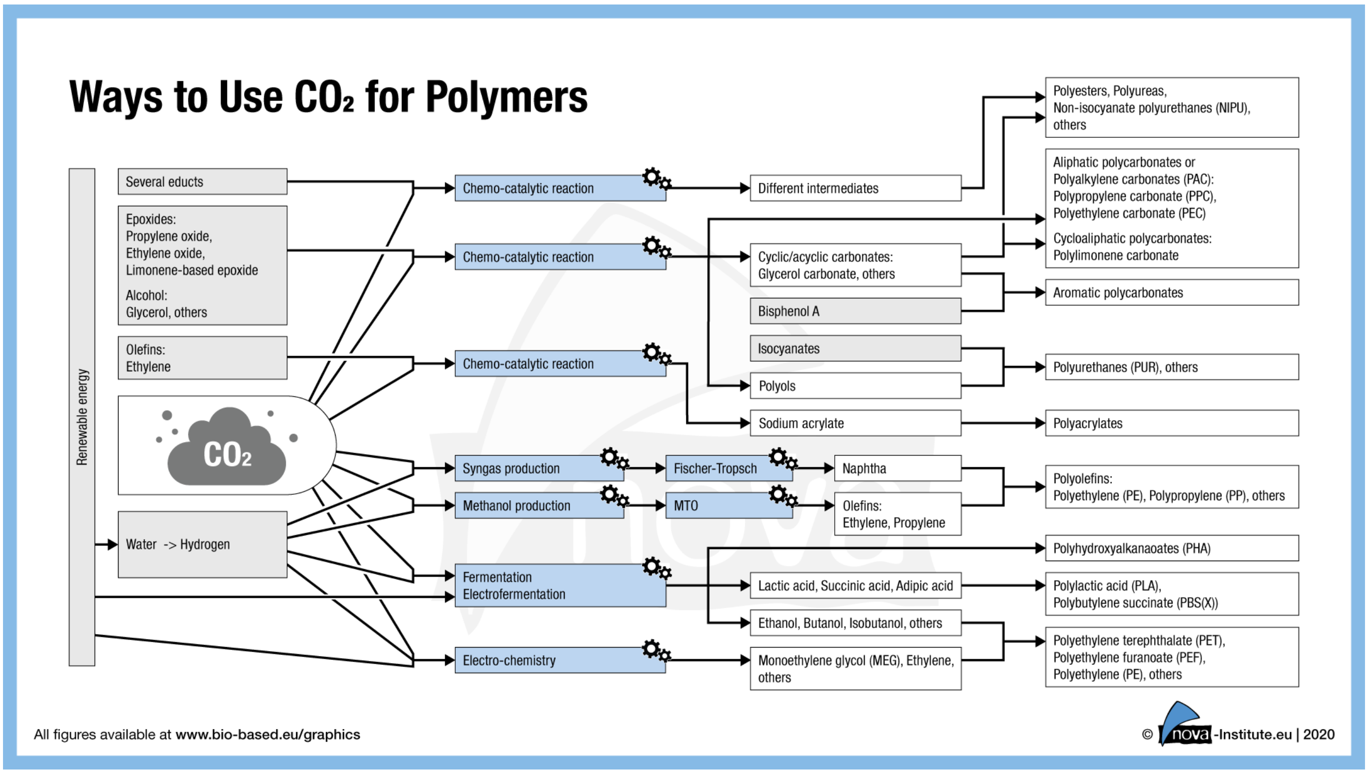

Figure 6: Different routes for the production of CO_2-based polymers (nova-Institut 2020)

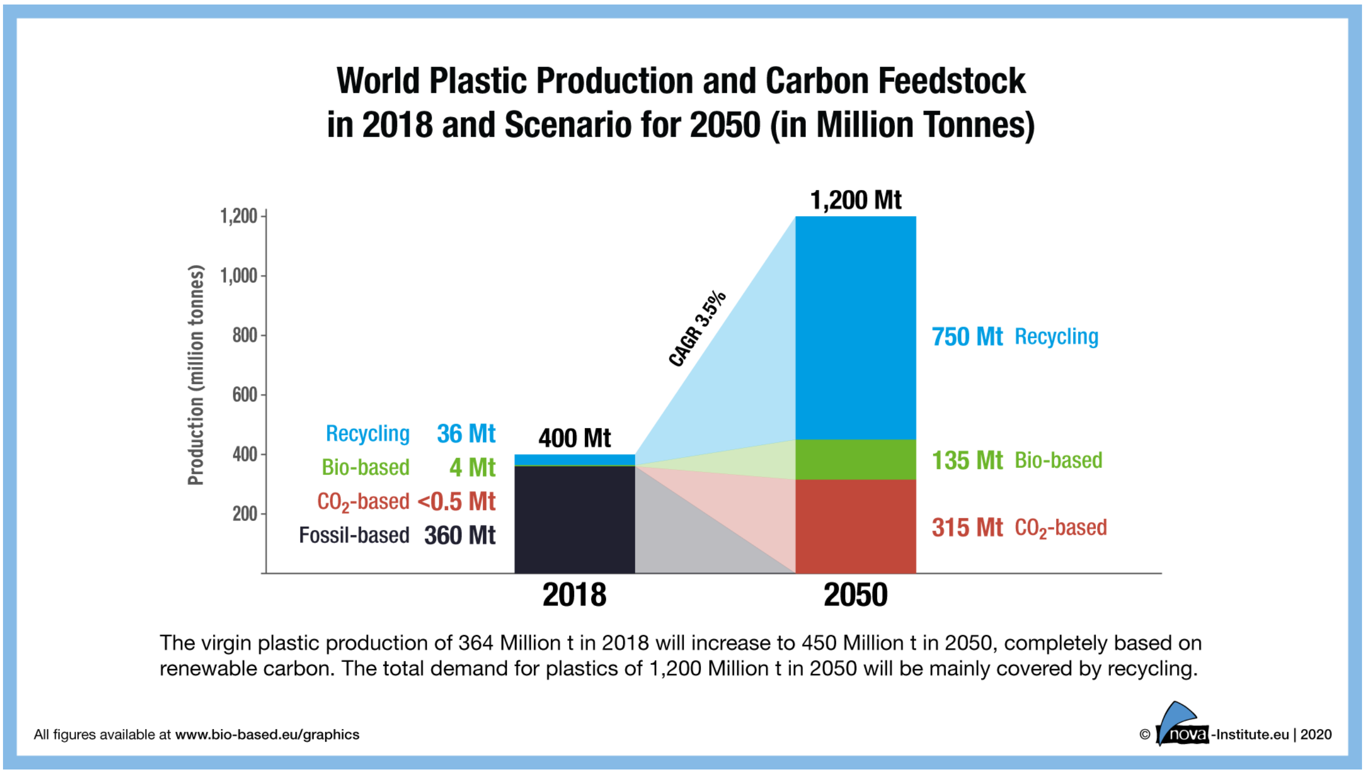

Figure 7: A possible scenario for the world plastic production based on renewable carbon (nova-Institut 2020)

Political Measures to Support a Quick Transition to Renewable Carbon

Policy makers could make use of the following **instruments and measures** to promote the chemical industry's shifting to renewable carbon from recycling, biomass and CO_2 utilisation:

- **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 fossil carbon tax if not globally, then only regionally, e.g. in Europe. 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 costs for fossil CO_2 emissions in the emissions trading system (ETS).** As a first step towards a carbon tax, at least prices for traded fossil CO_2 emissions should be increased to make this instrument more effective. Several voices have called for this step in the last few years (see for example VDI nachrichten, 2018-06-15 or VDI nachrichten, 2018-07-20).

- Development of **certificates and labels** which indicate the **share of renewable carbon** (total share of recycled material, biomass and CO_2) in products.

- Establishing **quotas of renewable carbon in "drop in" products** in the chemical and plastics industries (e.g. 30 % of all polypropylene must be made from renewable carbon by 2030). Binding targets could also be set for higher amounts for a later point in time (e.g. 2050).

- Obliging companies from the chemical and plastics industries to issue an annual report about the **percentage of renewable carbon used in their production processes** ("Reporting"), creating a company ranking based on the used share of renewable carbon in their production.

- **Tax credits** for the sequestration, storage and utilisation of CO_2. This is currently under debate in the United States Congress. (Martin 2018)

- **Tightening of environmental requirements for chemicals** (no hormone-active plasticisers, improved degradation behaviour of detergents and solvents etc.) This will mean a systemic preference of biomass-based solutions, in particular the fermentation of biomass/CO_2.

- **Systematic expansion of mechanical and chemical recycling.** Considerable funding for R&D work will be required in order to further develop chemical recycling, improve its efficiency and examine its sustainability.

- Additional and improved financial support for **research, development and implementation** of sustainable future-oriented technologies in the field of material biomass and CO_2 technologies used to provide and utilise renewable carbon (Carbon Capture and Utilisation (CCU)).

- **Massive expansion of renewable energies and green hydrogen grids, in combination with CCU** as vehicle for storing energy and for providing renewable carbon to the chemical and plastic industry.

Politics should target all of its measures at renewable carbon and not confine itself to biomass, direct CO_2 utilisation or recycling – all three paths must be followed simultaneously in order to be able to abandon fossil raw materials entirely as soon as possible. The current strong focus on recycling and the circular economy must comprehensively be expanded to include the utilisation of biomass and CO_2 as raw materials for the chemical industry. Which technology is most appropriate for different applications and in different regions with their specific circumstances and networks from an economic, ecological and social standpoint must be evaluated by sustainability analyses, not by political dogma. Even small changes in market conditions may cause cascades in innovation.

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Michael Carus studied physics at the University of Cologne. He worked as a scientific staff member for nuclear energy and environment at the University of Tübingen, as a scientific journalist for different professional magazines, at the KATALYSE-Umweltinstitut in Cologne (environment and resources), for the US company Tektronix GmbH in Cologne (IT) as well as for the company Flachglas Solartechnik GmbH in Cologne (solar power) until founding the nova-Institute for Political and Ecological Innovation together with other scientists in 1994. Since then, Michael Carus is acting as board member and managing director. He is a member in many societies, associations and international organisations. Michael Carus is science-based consultant on company strategies and policy in different countries around the world.

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