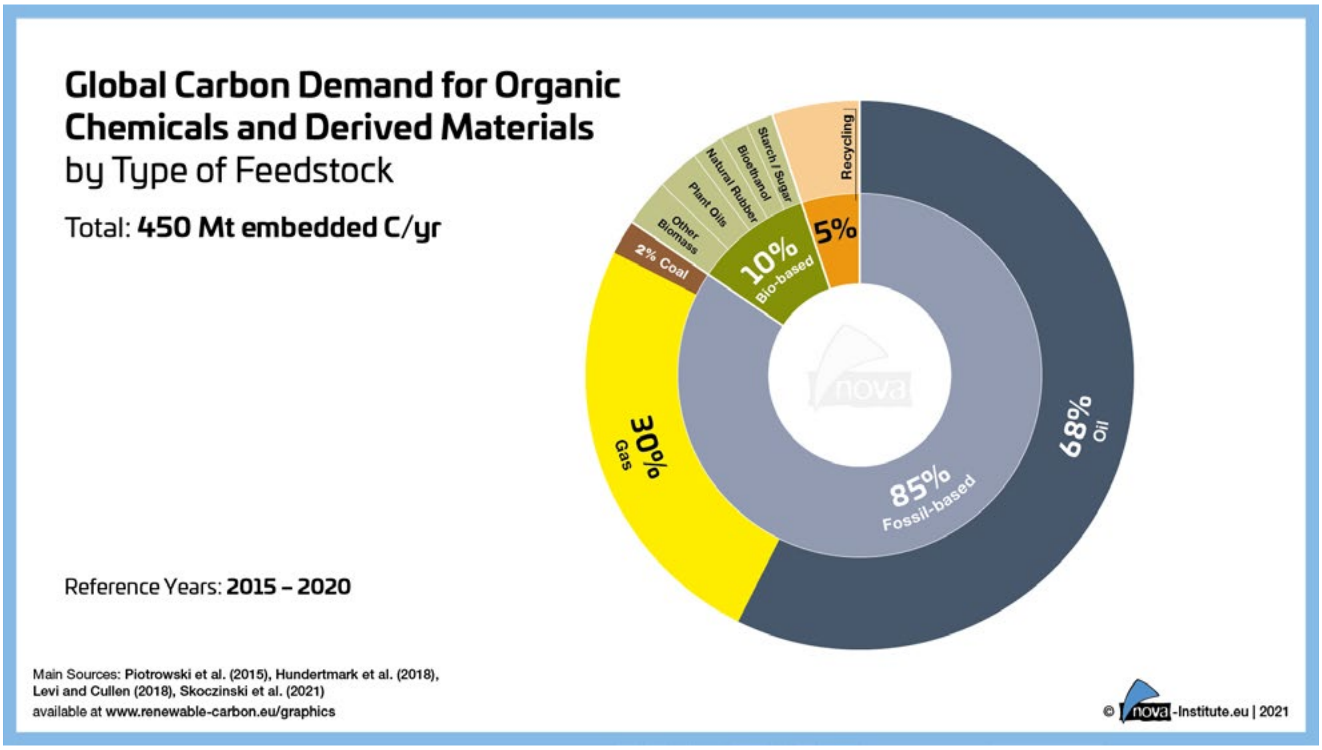
Turning off the Tap for Fossil Carbon

Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon



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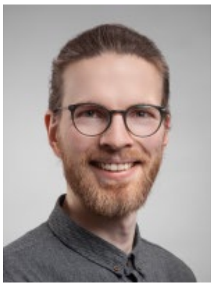
Authors

Ferdinand Kähler



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Physicist, from 1983 to 1994, he worked for the IT industry, environmental institutes and the solar industry. In 1994, he co-founded nova-Institute and has been functioning as owner and Managing Director since then. More 30 years of experience in the field of bio-based economy, including work on biomass feedstocks, industrial biotechnology and all kinds of bio-based materials, and since about 10 years in Carbon Capture and Utilisation (CCU). Main focus of his work are bio- and CO_2-based chemicals and materials with a focus on strategies, technology, markets, policy and sustainability. In 2020, Carus initiated the Renewable Carbon Initiative (RCI).

Christopher vom Berg

Christopher vom Berg is working for nova since 2017. He is deputy head of the policy & economy and member of the sustainability department. He has been involved in various projects about regulatory and sustainability aspects for the chemical industry and on methodological aspects of CCU in life-cycle assessments (LCA). In his daily work, he is contributing to several national and European projects with focus on policy, regulation, sustainability assessment and LCA for bio-based materials, chemicals and renewable CO_2. Since 2020, Christopher strategically supports the development of the RCI.

This study has been carried out on behalf of Unilever plc.

The authors are part of nova-Institute's Economy & Policy and Sustainability expert groups. More reports of expert group members are available at www.renewable-carbon.eu/publications

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renewable carbon strategies

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1 Executive summary

The climate crisis is accelerating at an unprecedented rate, with global warming, greenhouse gas emissions and deforestation causing food insecurity, global health concerns and biodiversity loss.

Greenhouse gas emissions linked to the use of fossil-based energy sources such as oil, coal and natural gas are the main factor contributing to climate change. It has become evident that we can no longer ignore the consequences that our current production methods have on the planet. Increasing pressure from governments, investors and other stakeholders to transition to renewable energy sources has accelerated the development of solar power, windfarms and hydroelectricity, and of new technologies such as electromobility and green hydrogen. These innovations, however, are not being implemented fast enough. To decarbonise the energy sector by 2050, and ensure the achievement of the goals set out under the Paris agreement, it is essential for the industry to completely phase out its use of fossil fuels.

But is that enough? Does it solve the climate problem?

This report provides an analysis of the CO_2 emissions that originate from the carbon embedded in commonly used products and commodities. It also shows how the chemical and material sectors can enact systems change to reduce their environmental footprints. Plastics, rubbers, textile fibres, detergents and personal care solutions are often derived from the basic elements of organic chemistry, which are by definition dependent on carbon. At the end of their lifecycle, today, most of the embedded carbon ends up in the atmosphere in the form of CO_2.

For the first time, the amount of carbon needed annually for the production of chemicals and derived products – broken down to several application areas – has been calculated. This carbon can later be found in the diverse products of our modern-day lives, improving efficiency and comfort. The demand for carbon embedded in organic chemicals and their derived materials is 450 million tonnes (Mt) per year. 85 % of this demand is generated by fossil-fuel-based resources, 10 % by biomass and only 5 % by recycling. To create long-lasting and sustainable change, three sources of renewable carbon have been identified that can substitute the utilisation of fossil carbon that is extracted from the ground: biomass, recycling, and CCU (Carbon Capture and Utilisation; captured CO_2, from industrial processes or the atmosphere).

The demand for embedded carbon is set to rise. Increasing population, higher incomes and a growing middle class will drive the need for products and thus also for carbon. By 2050, nova-Institute estimates that the demand for carbon embedded in organic chemicals and derived materials will increase to 1,000 Mt per year. To achieve this demand sustainably, sharing, reusing and recycling play the main role in keeping carbon in a closed loop, in line with the Circular Economy. Chemical and mechanical recycling industries will be largely responsible for innovating their processes to better reuse and recycle carbon. Since keeping the entire carbon in a cycle is technologically not possible, additional renewable carbon sources such as biomass and CO_2 capture and use become necessary. For both options, sufficient land is available for either cultivation of biomass or the production of the required renewable energy for CCU. With these three renewable carbon sources (recycling, biomass and CCU) combined, it will be possible to keep using all the products we are used to without the need for any additional fossil carbon sourced from under the ground.

For the first time since the beginning of the industrial revolution, which was only possible due to the access to cheap fossil carbon sources, we are able to completely decouple the chemical and derived materials industries from virgin petrochemicals. Technologies, as well as investment capital, are available for the transformation from fossil to renewable carbon of the entire economy.

Contrary to energy, it is not possible to decarbonise chemicals and products. The renewable carbon family is the only pathway to a sustainable future for commonly used materials such as plastics, fibres, surfactants and other materials based on organic chemistry, and the industries that produce them. Adequate carbon management can aid companies in achieving their emission targets and allow them to resolve potential questions such as:

- In a given situation, what is the best choice from the renewable carbon family? Biomass, CO_2 capture or recycling?
- Which renewable carbon source is the most sustainable, efficient and socially acceptable solution for a certain application in a given region?
- Is it biomass from wood, sugar beet or metropolitan biogenic waste?
- Is it captured CO_2 from fossil power plants, from fermentation or from the atmosphere (direct air capture)?
- Or is it recycled carbon from old plastics via mechanical or chemical recycling?

Once the need for transitioning the entire economy towards the use of renewable carbon is established, these are the questions to be addressed on a case-by-case basis taking into account the desired use and available infrastructure.

The exclusive use of renewable carbon as feedstock is a key condition for the chemical industry to achieve climate neutrality. The use of renewable carbon in the chemical and derived material industry is what decarbonisation is in the energy sector. In this report, a comprehensive policy framework for carbon management is discussed, which is necessary to realise the revolutionary transformation of the chemical industry, within a timeline that is in accordance with our climate targets.

As outlined already, the chemical sector uses 67 Mt of renewable carbon annually, covering 15 % of the total demand of embedded carbon (450 Mt). The authors predict that the demand for embedded carbon could reach 1000 Mt by 2050. In other words, renewable carbon production will have to be increased by a factor of 15 by 2050 to cover the needs of the chemical and material sector. This highly laborious task will require cross-sector collaboration: industry, governments and consumers.

This report aims to raise awareness of the need for, and the technical, industrial and political feasibility of, the biggest transformation of the chemical and derived material sector since the industrial revolution.

2 The role of carbon in our daily lives

Climate change is among the most severe problems of our time. 92 % of global warming impacts are caused by carbon-containing greenhouse gas emissions. Out of these, 80 % are of fossil origin[1].In total, 89 % of the carbon extracted from the ground is utilised for energy and fuels, whilst 11 %[2] is employed for cement, chemicals and derived materials. The latter will rise tremendously by 2050, as explained in chapter 4. The process of "decarbonising" the energy sector and expanding the use of renewable energies is ongoing in many countries. However, removing the carbon from the chemical and derived material sector is not an option. These commodities surround us in manifold ways and many of them contain carbon. From the carpet we set our feet on in the morning, the toothbrush in our mouth, the shampoo for our hair, the clothes we wear and the detergents used for our laundry; to the vehicles we use to commute, the electronics we use to communicate, the packaging our cooking ingredients are wrapped in, the dishwasher tabs that help wash our plates, the insulation of our houses and the solar panels on our roofs – all of these products include substances derived from the chemical and derived material sector, see Figure 1. The large variety of properties that allow for such broad application can be traced back to a single element: carbon, the backbone of life on Earth. Together with other elements (e.g. hydrogen, oxygen, etc.), carbon forms chemical compounds processed in the various pathways of the chemical industry into a wide range of industrial and consumer goods. However, most of the carbon

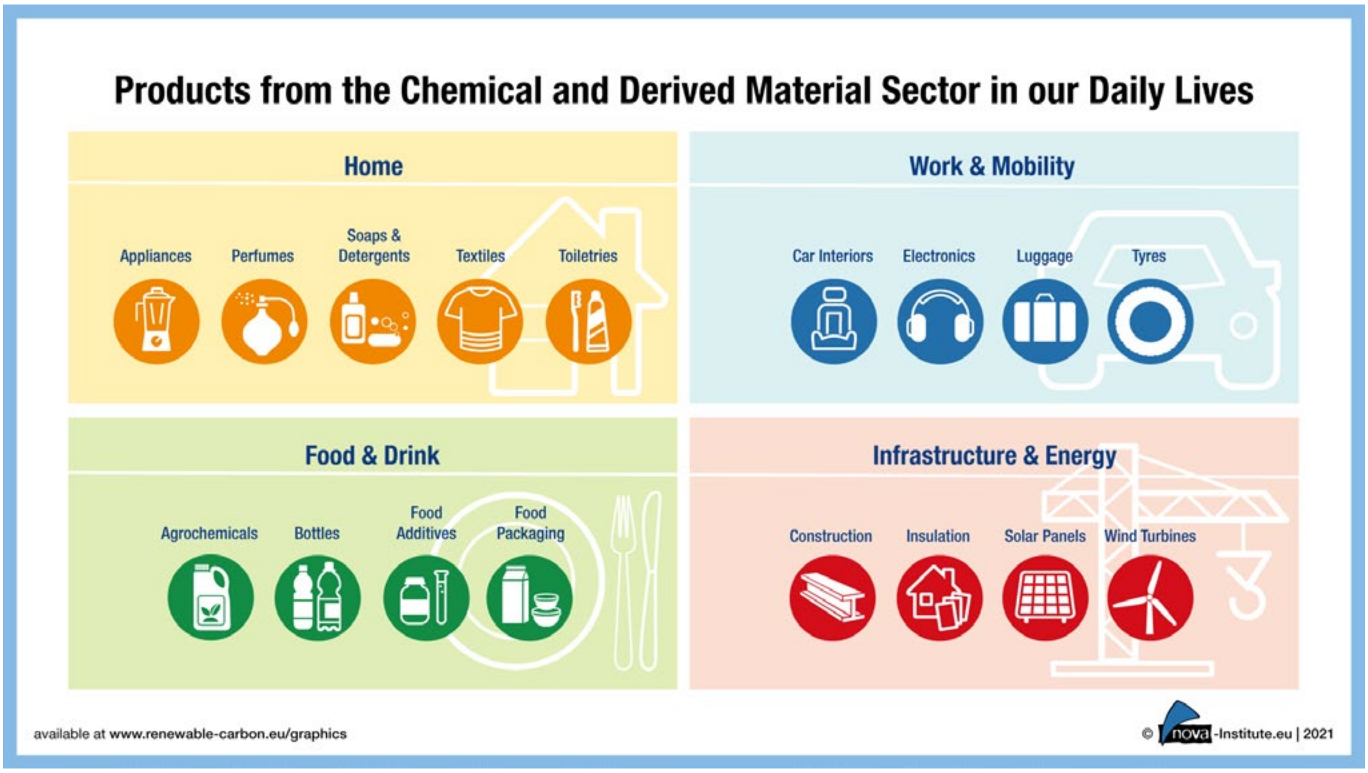

Figure 1: Products from the Chemical and Derived Material Sector in our Daily Lives

1 based on IPCC (2014) and Olivier et al. (2017)

2 10 % of the total final energy consumption used by the chemical sector. Hence, it's the largest industrial energy consumer, ahead of iron and steel, and cement. 90 % of primary oil and natural gas demand occur in "Other industry", "Power", "Transport", "Buildings", and "Others". (Pales and Levi 2018)

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[3]. Renewable carbon circulates between biosphere, atmosphere or technosphere, creating a carbon circular economy."[4]

consumed by the chemical and derived material sector is made from fossil fuels – as is the case for the energy and fuel sectors. This poses a large issue, as the fossil carbon extracted from the ground (oil, gas and coal) eventually ends up in the atmosphere, contributing heavily to global warming. More than 50 % of the extracted fossil carbon is released into the atmosphere as CO_2 within a short amount of time; this includes plastic and rubber products that are incinerated, or detergents and cleaning agents that simply biodegrade. The remaining percentage initially remains in the technosphere in the form of products, and, depending on logistics and infrastructure, will later also be incinerated or biodegrade (in the environment and landfills) over decades to centuries. In the context of the circular economy, ever larger parts will be recycled in the future. Only then will the influx of emissions into the atmosphere end.

Energy

For the energy sector, the strategy to phase-out fossil fuels is called "decarbonisation". Fossil energy sources, namely coal, gas and oil, are replaced by renewable ones: solar power, wind turbines or hydrogen production together with electric cars, direct use of hydrogen and fuel cells. In the long-term, only a limited number of fuel types will continue to require carbon (mainly aviation fuels). For the medium-term, however, this also includes fuels for long-distance shipping and trucks.

Chemicals, plastics, detergents and other products

Currently, the chemical sector consumes 14 % of global oil and 8 % of global natural gas supply, that represents 723 megatons (Mt) of pure carbon (equivalent to 2,655 Mt of CO_2)[5]. The largest share of the chemical manufacturing industry, be it plastics or detergents, is still fed by virgin fossil resources. However, decarbonising chemicals is not possible, as carbon is a key element of many chemical compounds. Therefore, the future share of the global oil and gas demand for carbon-based products will sharply increase. Organic chemistry, by definition, is the branch of chemistry that utilises carbon and carbon-based materials, therefore no feasible replacement exists. Renewable carbon sources include: **carbon from recycling** (technosphere), where it is kept in technical cycles; **carbon from biomass**, which has been taken up from the atmosphere and is bound by plants (biosphere); and **carbon from CO_2** which either comes directly from the atmosphere or is extracted from exhaust gases (technosphere), see Figure 2.

3 Link to RCI glossary to follow

4 For more information see nova-Paper #12 (Carus et al. 2020b) and the Renewable Carbon Initiative (RCI) (nova-Institute 2021)

5 Shares of global oil and gas consumption of for petrochemicals according to Pales and Levi (2018). According to BP's Statistical Review 2019 (Dudley 2019), the global annual consumption of oil was 4,662 million tonnes of oil equivalent (Mtoe) in 2019. 14 % of this corresponds to around 650 Mtoe, which contain an amount of 560 Mt of carbon, equal to 2,050 Mt of CO_2. Also according to BP, global annual consumption of natural gas is 3,309 Mtoe of which 8 % or 265 Mtoe is used for petrochemicals. This corresponds to 226 Mt of natural gas (1 Mtoe = 0.855 Mt natural gas, according to BP) or 165 Mt of carbon (carbon content = 73 % based on own calculations), which corresponds to 605 Mt of CO_2.

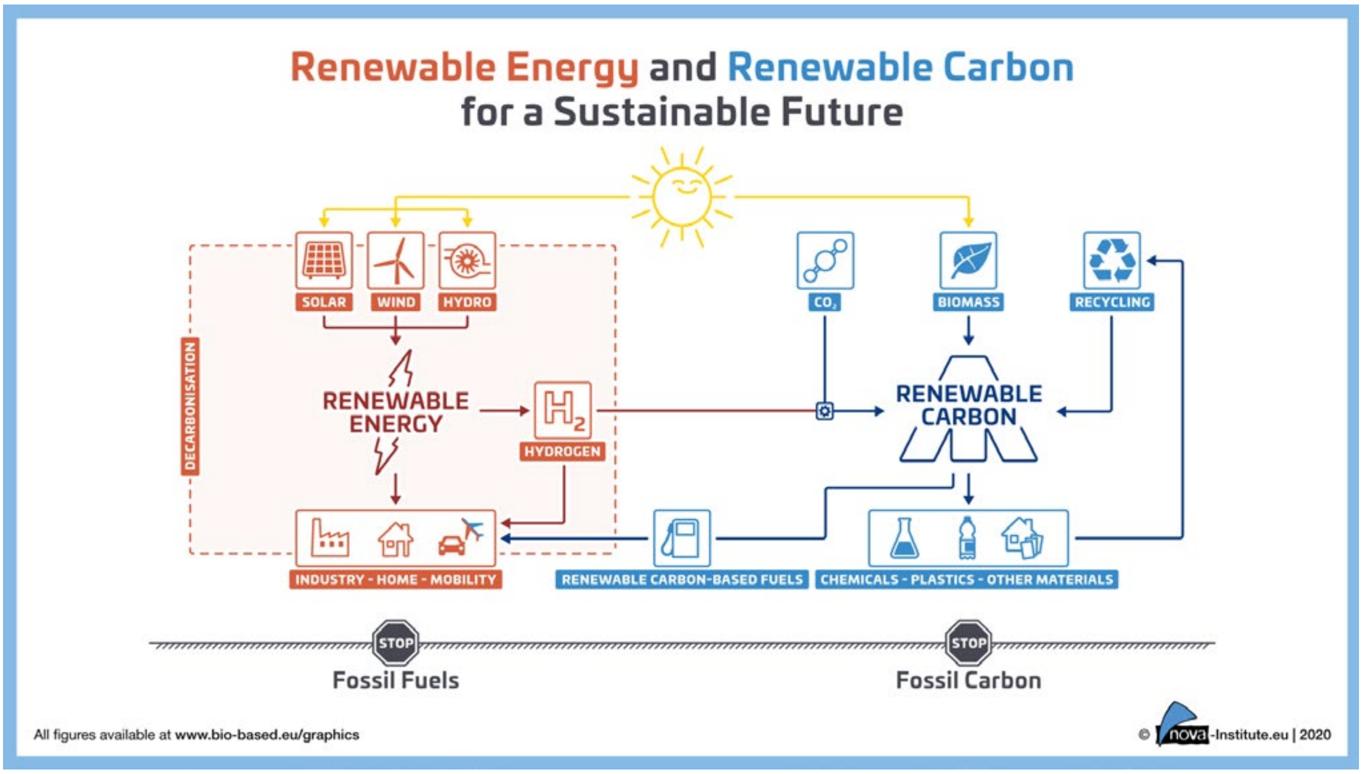

Figure 2: Renewable Energy and Renewable Carbon for a Sustainable Future (nova-Institute 2020)

Scope of the report: Embedded carbon for organic chemicals and derived materials

This report addresses carbon contained in organic chemicals and derived materials that conventionally use high shares of virgin fossil resources. These include:

- Plastics, mainly thermoplastics, but also thermosets and elastomers or rubber;
- Man-made fibres such as polyester; and
- Organic chemical substances such as adhesives, solvents, detergents, paints, etc.

Inorganic chemicals are not in the scope of the study, even though they provide a large share of chemicals and derivatives. Important inorganic chemicals include nitrogen-based fertilisers, which are indispensable for providing secure food supply; phosphates, which are essential for many food additives; and sulfuric acid, that is used in many applications. In regard to materials, metal extraction and processing provide a class of materials with extraordinary properties. However, those groups of substances are out of scope because they are generally not based on and do not include carbon. It should be noted that a large share of the energy required for their processing today is fossil-based but will be replaced by renewable energy in the course of decarbonisation of the energy sector.

Furthermore, only the carbon-based materials whose precursors originate from the chemical industry ("derived" materials) were considered. Accordingly, wood used for construction and furniture is excluded as well as cotton fibres. Chemically processed wood is included, e.g. a wide range of chemicals from wood chemistry as well as cellulose fibres.

The CO_2 emissions associated with chemistry and derived materials come from two main sources. Firstly, emissions from production, resulting directly from the energy use of fossil carbon, that are often quite visible and well recorded. Secondly, embedded carbon[6], as many organic chemicals and their derived products consist largely of carbon. The embedded carbon becomes relevant at the end of products' lifecycles, as sooner or later most of it ends up in the atmosphere. However, as we edge closer to 2050, by applying the Renewable Carbon strategy outlined in this study, more and more of the embedded carbon can be kept in a circular loop, avoiding its release into the atmosphere.

Figure 3 shows the distribution between the embedded carbon and the production-energy related carbon for six major chemicals and materials. More than two thirds of the carbon footprint of these products is composed of embedded carbon. Moreover, the share of carbon related to production will decrease in the future, when fossil fuels are replaced by renewable energies. The amount of carbon required for the product itself, however, will remain constant. In the long-term, the demand for chemicals and derived materials will grow, as shown in the future scenario introduced in chapter 4. Hence, the importance of embedded carbon will increase as well. Industry efforts, therefore, must go beyond energy, and substitute embedded fossil carbon. For this reason, this report focuses on embedded carbon in chemicals and materials, and provides a roadmap for replacing fossil with renewable carbon, an often-ignored aspect of climate change mitigation.

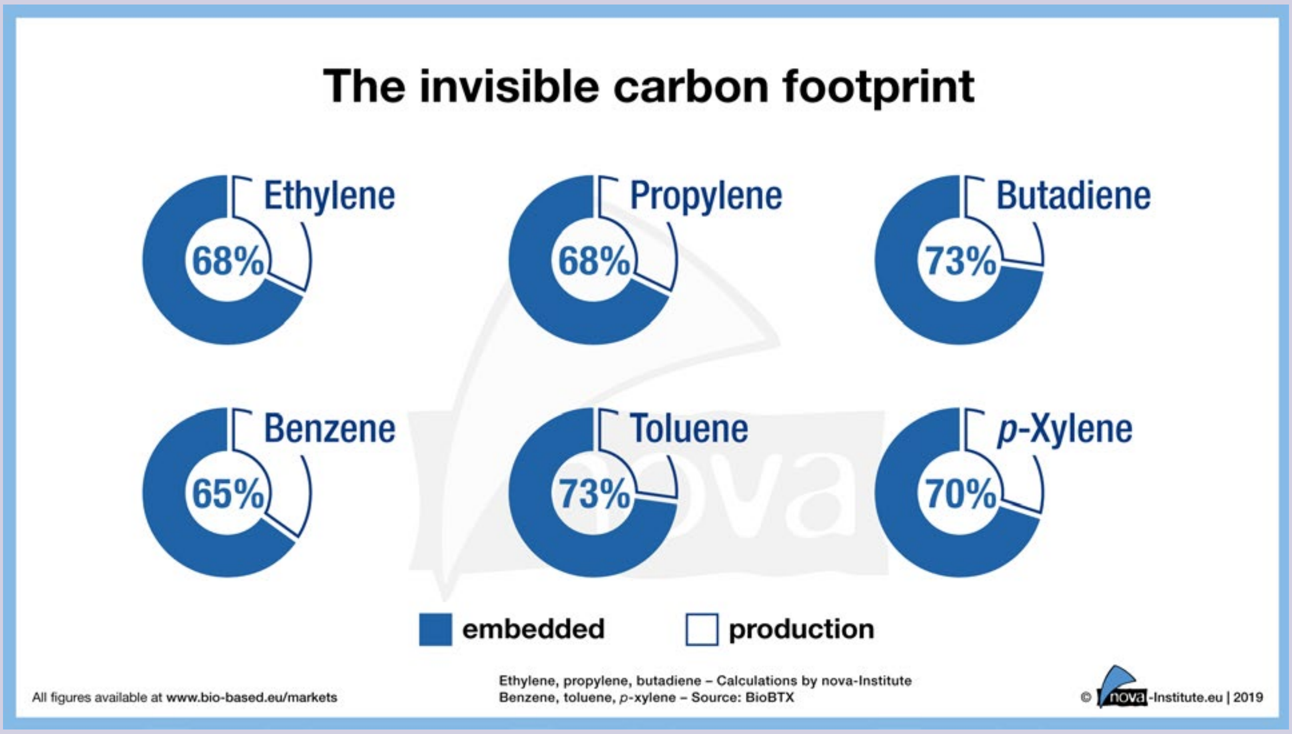

Figure 3: The role of embedded carbon in the overall carbon footprint (nova-Institute 2019)

6 The "embedded carbon" is also called "hidden carbon", because the related potential CO_2 emissions at end-of-life of the product are only barely visible.

3 The use of carbon in today's Chemical and Derived Material sector

The amount and type of feedstocks currently used as embedded carbon in products of the organic chemical and derived materials sector is shown in Figure 4. The figure displays only the amount of carbon actually contained in the products ("embedded carbon"), measured in million tons of carbon (Mt C). This is in contrast to the often-cited carbon footprint, which quantifies greenhouse gas emissions from production to disposal in CO_2 equivalents.

In order to determine the amount and composition of embedded carbon in organic chemicals and derived materials, a comprehensive list of petrochemicals was analysed for their carbon contents. Furthermore, several studies have been evaluated to determine carbon flows from biomass and recycling. This allows us to quantify the amount of embedded carbon in organic chemicals and derived materials for the first time ever, which amounts to 450 Mt of carbon per year.

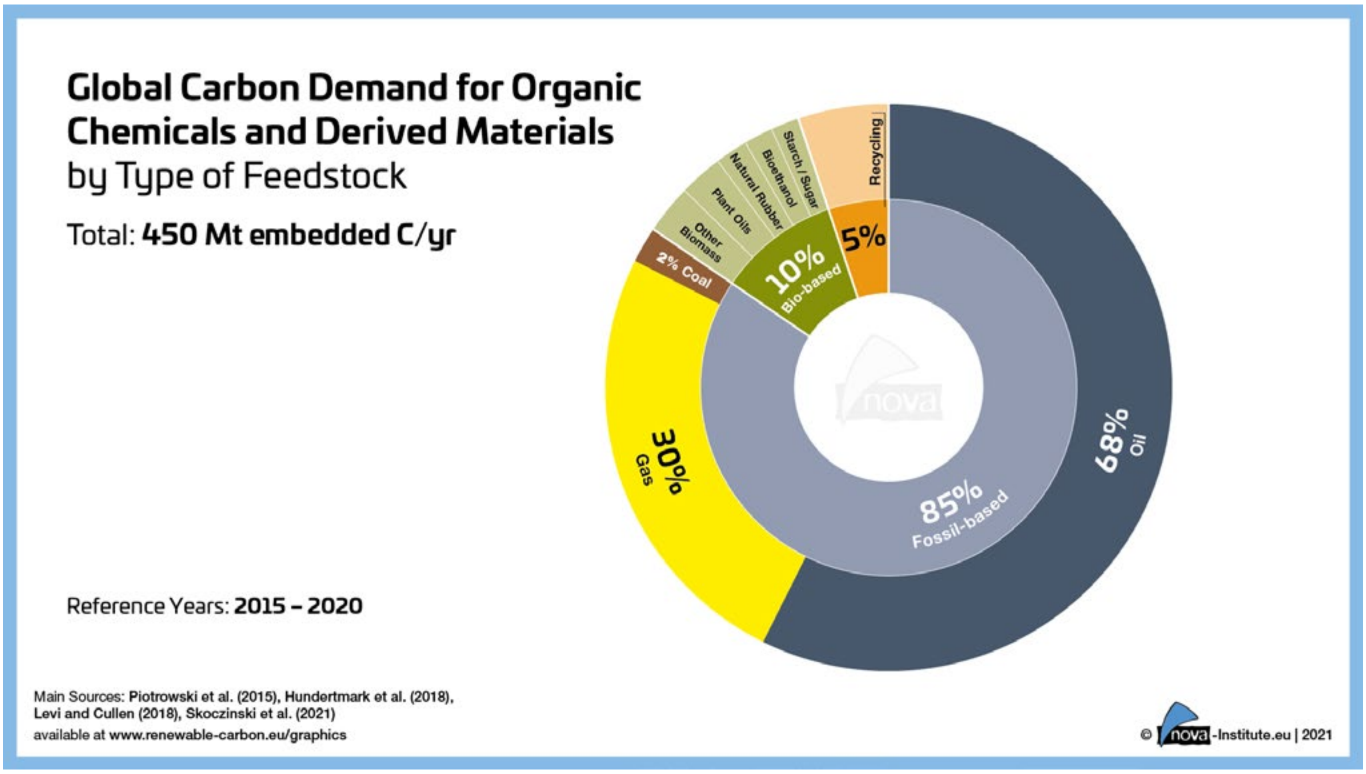

Figure 4: Current global demand for carbon embedded in organic chemicals and derived materials by type of carbon feedstock (nova-Institute 2021, based on various sources[7])

7 The composition of fossil resources (share of oil, gas and coal used in the chemical industry excluding the production of ammonium), absolute figures for fossil-based thermoplastics, thermosets, solvents, additives & explosives, and other chemicals for the year 2013 are based on Levi and Cullen (2018). Figures for bio-based thermoplastics, thermosets, and solvents and additives, figures for rubber products, total man-made fibres, and bio-based man-made fibres for the year 2020 are based on Skoczinski et al. (2021). The composition of bio-based feedstocks and the amount of other bio-based chemicals for the year 2010 is based on Piotrowski et al. (2015). Figures for total recycling are based on Hundertmark et al. (2018). Figures for recycled man-made fibres are based on Textile Exchange (2020). Carbon content of each substance is determined by experts from nova-Institute, using weighted averages, based on production volumes stated in the mentioned publications.

Table 1: Current global demand for carbon embedded in organic chemicals and derived materials by type of carbon feedstock (nova-Institute 2021, based on various sources)

Carbon Feedstock	Annual amount of carbon	Share
Fossil	380 Mt C	84.5 %
Crude Oil	257 Mt C	57.3 %
Natural Gas	114 Mt C	25.1 %
Coal	9 Mt C	2.1 %
Biomass	47 Mt C	10.4 %
Plant Oils	11 Mt C	2.5 %
Natural rubber	9 Mt C	2.0 %
Starch / sugar	7 Mt C	1.6 %
Bioethanol	7 Mt C	1.6 %
Other biomass	13 Mt C	2.8 %
Recycling	23 Mt C	5.1 %
Total	**450 Mt C**	**100 %**

The vast majority of this embedded carbon (378 Mt C or 85 %) is derived from fossil resources, see Table 1. Crude oil is the most important feedstock (257 Mt C), followed by natural gas (113 Mt C) and coal (8 Mt C). Of the remaining 15 %, 10 % or 45 Mt of carbon is given by biomass and 5 % or 22 Mt is derived from recycling. The amount of embedded carbon from CO_2-based resources is currently negligible, but is expected to rapidly grow in the coming years.

To highlight the importance of carbon in our daily lives, the use of products based on organic carbon from the chemical and derived materials sector is classified by end-user application in Figure 5.

Around two thirds of the annual demand for embedded carbon for chemicals and derived materials is used for polymers and rubber (291 Mt C). The remaining share is used for organic chemicals (155 Mt C). Thermoplastics are the most sought after group of plastics with an annual demand of 189 Mt of carbon. These are mainly used in packaging, that accounts for 45 % of all thermoplastics use. Man-made fibres (including synthetic and cellulosic) are the second largest group in plastics with an annual carbon demand of 53 Mt C. Rubber accounts for 26 Mt C, and thermosets for approximately 23 Mt C. Within organic chemicals, solvents, adhesives and explosives together make up for 59 % of embedded

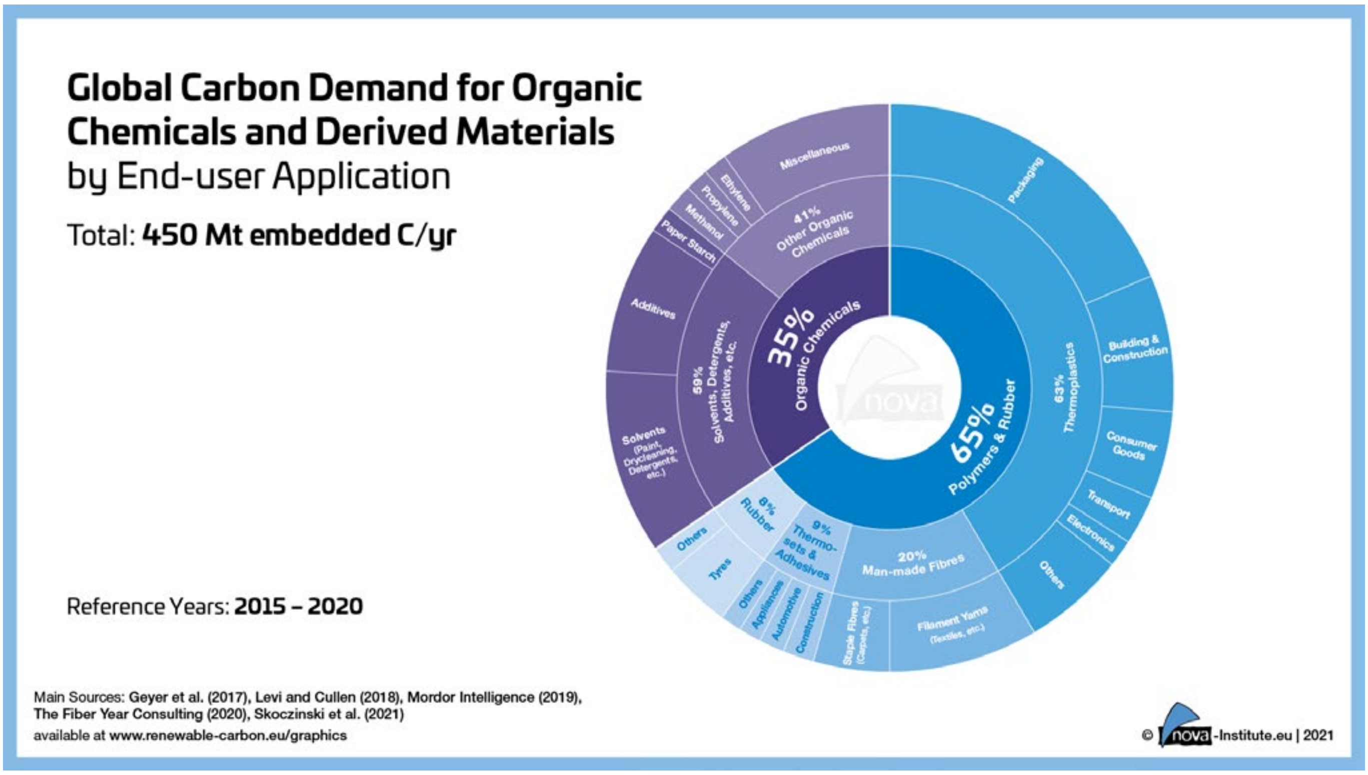

Figure 5: Amount of carbon embedded in products from the global organic chemicals and derived materials (nova-Institute 2021, based on various sources[8])

carbon demand or 94 Mt C respectively. From this group, solvents (e.g. used for paint, dry-cleaners or detergents) account for 50 Mt C, and additives (e.g. found in fuels, tires, plastics etc.) for 39 Mt C.

To phase-out fossil resources in the chemical and derived materials sector, the technological pathways can differ depending on the unique requirements for each product group. The type of feedstock required for each product group is shown in Figure 6.

The share of virgin fossil-based carbon resources for chemicals and derived plastics is dominant and comparable (83 % and 85 % respectively). This share varies widely within product groups, with some groups such as "other organic chemicals" and thermosets depending heavily on fossil resources (respectively 96 % and 97 %), whilst others have significantly lower fossil shares (e.g. rubber with 52 %). The share of bio-based carbon is significant for "organic chemicals" (17 %), but lower for polymers (7 %). Product groups that largely use bio-based carbon as feedstock include rubber (48 %), and solvents & adhesives (26 %). Recycling is important for polymers and rubber (8 % of embedded carbon), and higher than the bio-based carbon share (7 % of embedded carbon), but currently does not play a significant role as a feedstock for chemicals (amount of chemical recycling negligible thus far). Product groups with high shares of feedstock from recycling are in particular man-made fibres (10 %) and thermoplastics (9 %).

The findings disclosed above give an unprecedented view on carbon supply for the chemicals and derived

8 Figures based on the sources stated in Figure 4. End-user applications for thermoplastics based on Geyer et al. (2017). End-user applications for thermosets based on Mordor Intelligence (2019). Applications of man-made fibres based on The Fiber Year Consulting (2020)

Product groups explained

Polymers are chemical compounds consisting of repeating structural units (monomers) synthesised through the process of polymerisation or fermentation. **Plastic** materials are composed of a blend of polymers, additives and fillers, whose granulates are ready for industry use. Polymers can be subdivided based on their chemical and physical properties. **Thermoplastics** become mouldable when heated and are commonly used for everyday objects. They can generally be recycled efficiently. **Man-made fibres** are used to produce textiles such as clothing or carpets. This group includes synthetic and cellulosic fibres. Natural fibres, including cotton or flax, are excluded. **Thermosets** tend to be used in more specialised materials and resins, but can also be found in everyday objects like worktop surfaces, car parts or boats. These cannot yet be efficiently recycled. **Adhesives** consist of thermosetting polymers, among others. High-performance adhesives based on epoxy or polyurethane are used in aircrafts, automobiles, bicycles, boats, etc. **Rubber** (or elastomers) polymers can be subdivided into natural and synthetic rubber. Large amounts of rubber are used for tyres; however, it is also used for gloves, dampeners or gaskets.

Organic Chemicals are an important output of the chemical sector. **Solvents and additives represent the largest group among these**. **Solvents** are used for a variety of applications, such as paints and coatings, manufacturing of pharmaceuticals, household care, cosmetics, adhesives, printing inks, polymer manufacturing, industrial cleaning, agrochemicals and lubricants. The umbrella term **additive** refers to substances that are added in small quantities to other materials to alter their specific properties. Additives can be used in fuels, tyres, plastics, paper, and many more. Within **other organic chemicals**, methanol, propylene and ethylene have the largest production volumes. These also have very broad application fields, including agrochemicals, pharmaceuticals, cosmetics, organic dyes or surfactants (for soaps/detergents).

materials sector. However, for some applications, the data available lacks detail. The wide diversity of "organic chemicals," and their broad range of potential uses, make it difficult to determine clear end-user applications. In an attempt to tackle this issue, a closer look at organic chemicals is provided in the following section.

The European Union's market can be examined in further detail due to increased data availability. Detailed statistics are available from the Prodcom statistics that use the "Statistical Classification of Economic Activities in the European Community" (referred to as NACE classes) for the accounting of several manufacturing industries. Organic chemicals are included in NACE class C20: "Manufacture of chemicals and chemical products." The corresponding production value in the EU-27 + UK in 2018 is depicted in Figure 7. Double counting is avoided for intermediates produced by the chemical industry that are later processed to end-user products.

The figures prove that the production of organic chemicals has a large economic value of € 162 billion annually. Within this group, "paints & varnishes" form the largest subset, followed by cosmetics applications in "perfumes & toilet preparations" and "soaps & detergents".

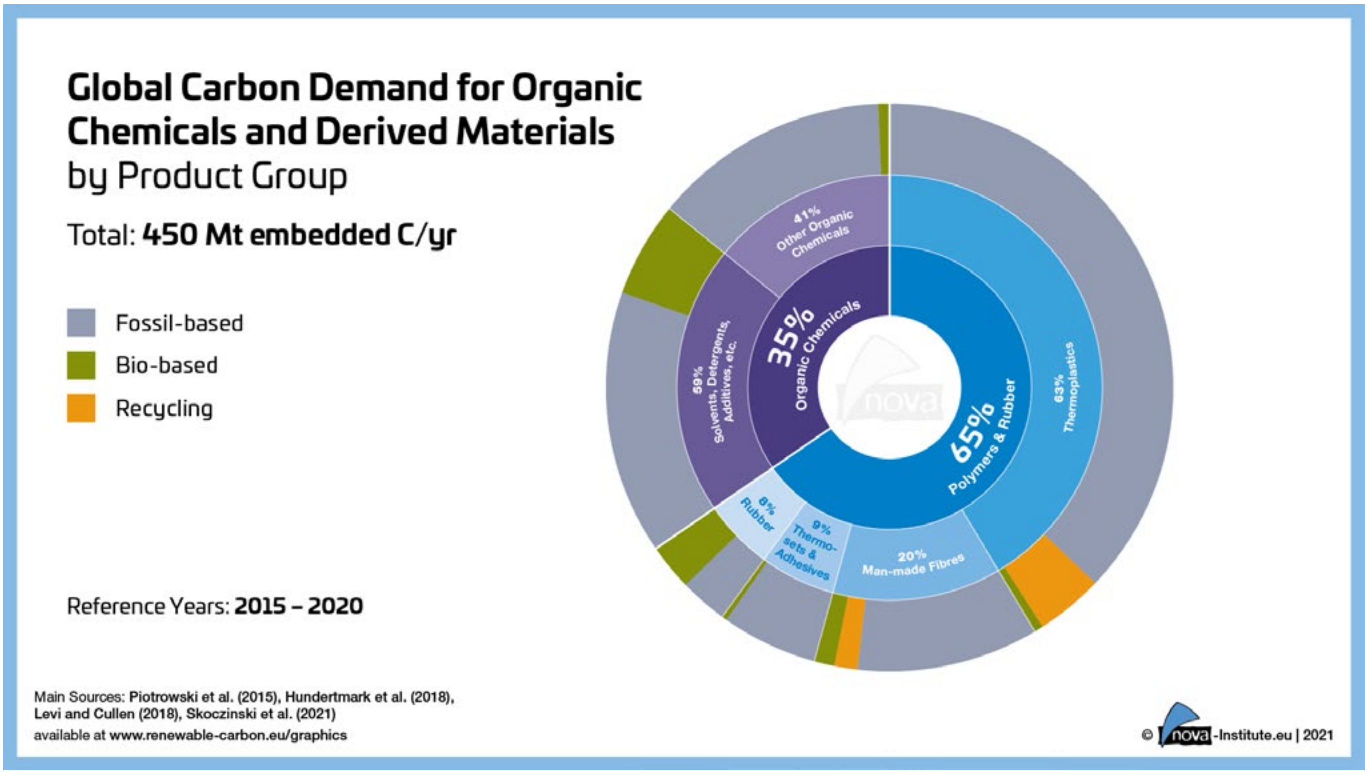

Figure 6: Type of feedstock for embedded carbon in each product group (nova-Institute 2021, based on various sources[9])

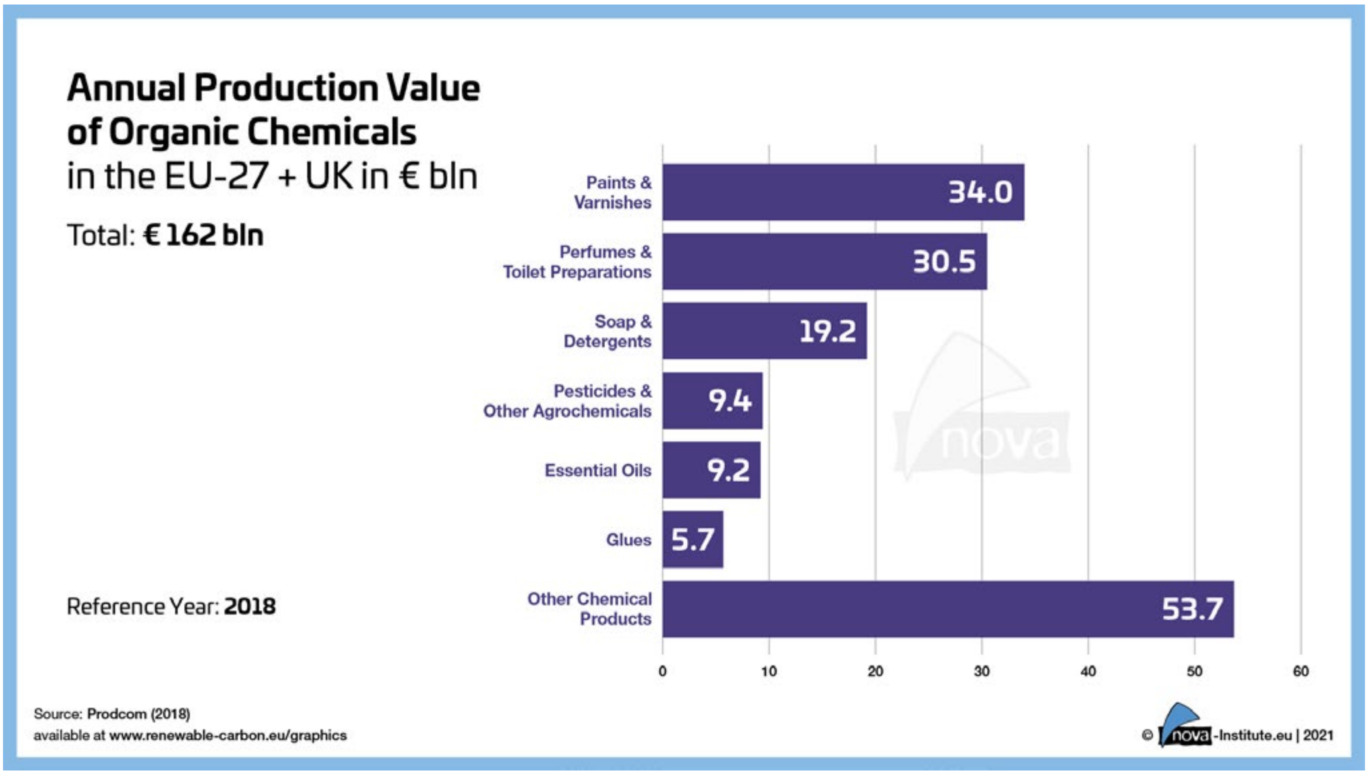

Figure 7: Production value of organic chemicals in the EU-27 + UK in 2018 by end-user application[10] (nova-Institute 2021, based on Prodcom 2018)

9 Figures based on the sources stated for Figure 4

10 NACE class C20 "Manufacture of chemicals and chemical products", except for sub-class C20.6 "Manufacture of man-made fibres". "Other chemical products" include additives, animal & vegetable fats/oils, biofuels, etc.

Conclusion

The data gathered in this chapter provides an overview of the types of feedstocks used for embedded carbon in products from the chemical and derived material sector. The predominant type of feedstock is of virgin fossil origin (85 %), see Figure 4. The determination of carbon in different end-user applications (see Figure 5 and Figure 7) shows that these products are prominent in endless areas of life. Hence, a reliable supply of carbon is crucial for society and for the economy. Many of these applications, however, only use marginal amounts of renewable carbon, and most rely heavily on fossil feedstocks. The available data clearly shows that there is still a long way to go for achieving a fully renewable-based chemical and derived material sector. The next chapters will provide further detail on how the path towards a systemic transformation could be achieved.

4 Carbon demand from the Chemical and Derived Material sector in 2050

The previous section shows the strong dependency on fossil carbon feedstocks in the global chemical and derived materials sector. A future pathway towards a more sustainable supply of feedstocks is examined in the following section. A scenario for 2050 that includes the total phase-out of additional fossil carbon resources is outlined, and a possible future composition of carbon supply is determined. Subsequently, the consequences of such a transformation are discussed.

The total global demand for carbon from the chemical and derived material sector is influenced by a multitude of factors. Some of the most relevant parameters are: projected population growth and projected wealth increase in population-rich countries. The global population is estimated to reach 9.7 billion by 2050, with particularly large population growth expected in Sub-Sahara Africa, Northern Africa and Western Asia[11]. This corresponds to an annual growth rate of +0.75 %. In regard to wealth increase, a growth of the global middle-class is expected. In their latest projections[12], the company BP approximates an income growth of +1.9 % p.a. These income increases for the growing global middle-class will lead to a higher demand for chemicals and products

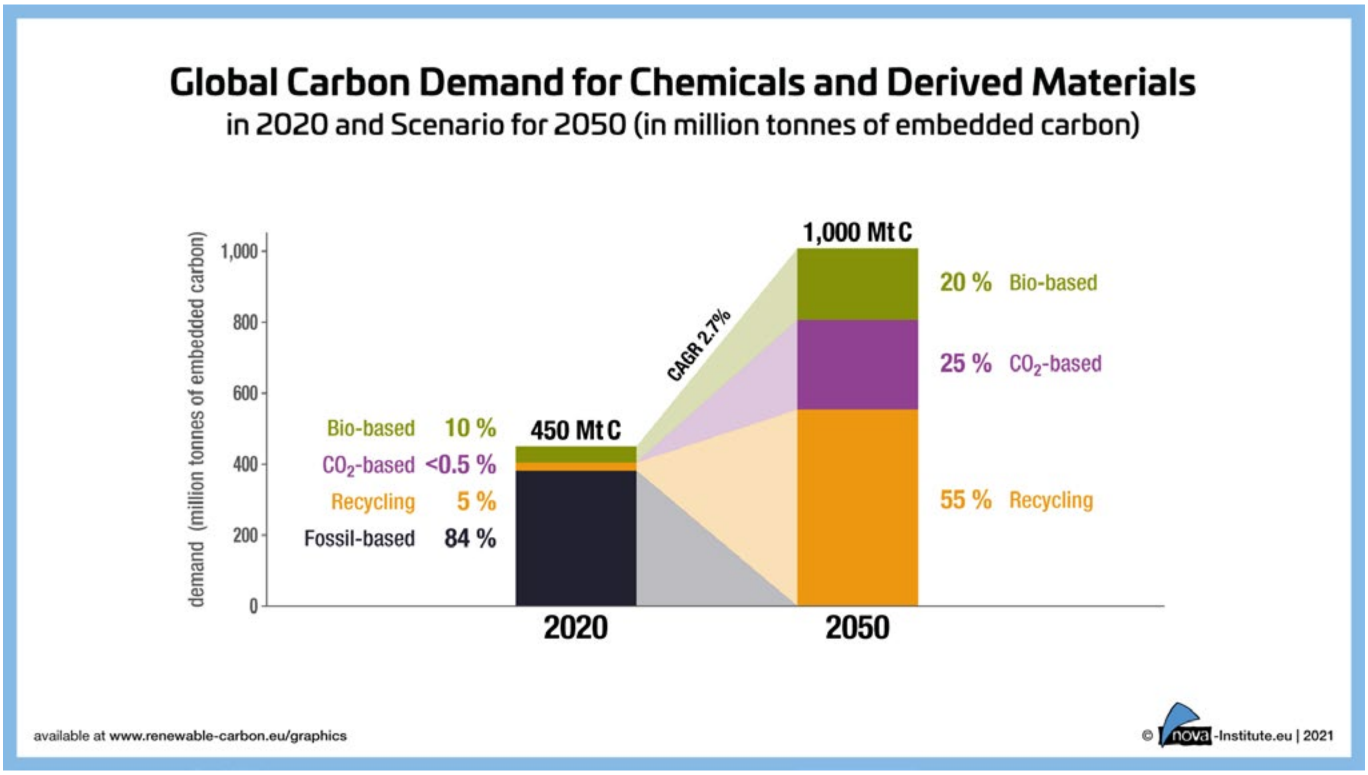

Figure 8: Scenario for the future global demand of embedded carbon for chemicals and derived materials in 2050 (nova-Institute 2021)

11 According to UN DESA (2019)

12 According to BP (2020)

derived from them. Forecasts for the future growth rates for the chemical and derived materials sector range from +1.1 % over 2.7 % up to 4.2 % per year[13].

While these figures clearly forecast a strong growth in material demand, the amount of carbon required to meet this demand can be partly mitigated through increases in **efficiency and effectiveness**. A sharing economy with digitalisation and artificial intelligence can play a large role in this, as well as more ambitious repair and re-use commitments, process optimisation, and new technologies that emit less carbon compared to established alternatives. These changes could advance the process of decoupling income and carbon consumption.

Taking the above considerations into account, an annual growth rate of +2.7 % of the chemical industry until 2050 is assumed for our scenario. With the data compiled in the previous chapters, this growth rate leads to an annual demand of 1,000 Mt of carbon as a feedstock for the global chemical and derived material sector. Figure 8 shows the feedstock used for embedded carbon for chemicals and derived materials as well as the example 2050 scenario we have developed. It is assumed that fossil fuels are totally phased out and that supply of carbon is met 55 % by recycling, 25 % through carbon based on captured CO_2, and 20 % with bio-based carbon.

The total phase-out of virgin fossil carbon requires a wide-ranging shift towards renewable carbon sources. The most important source is **recycling**. Globally, waste collection systems are being rolled out or improved, so that landfilling is prevented and incineration of waste is reduced to a minimum. Mechanical recycling processes and upstream separation processes are being further enhanced, and applied to valorise a variety of different waste streams. Waste fractions, that today are incinerated, are made available to chemical recycling in the 2050 scenario. Advances in these technologies lead to a highly improved circularity rate in the chemical and derived materials sector.

But even an optimised use, collection and recycling system can never keep carbon fully in the cycle, due to losses, emissions and low-quality fractions. In addition, there are stock effects due to long-lasting products. Therefore, even in a highly developed recycling economy, additional sources of carbon will be required.

Biomass provides an important share of carbon supply for chemicals and derived materials in our 2050 scenario. Today, the worldwide annual supply of biomass is 12.3 billion tonnes.[14] Biopolymers (excluding rubber) only use 0.034 % of this worldwide biomass supply. All bio-based chemicals and derived materials use 0.86 % of the annual bio-based carbon supply[15]. In the 2050 scenario depicted above, the demand for bio-based carbon would rise from 50 to 200 Mt C. This corresponds to a share of 3.4 % of today's biomass supply. However, the global supply as well as the production chain is expected to change. Global biomass supply could rise from today's 12.3 billion tonnes to 18 or even 25 billion tonnes, based on different scenarios that all act

13 The reference scenario provided by IEA (2018) predicts a doubling of the demand of thermoplastics per capita until 2050, which corresponds to +1.3 % p.a. BP (2020) foresees an increase in the non-combusted use of fossil fuels of +1.1 % p.a. in the business-as-usual scenario and +2.7 % if the trends of the past 20 years are extrapolated. Roland Berger (2015) estimates a growth of +3.6 to 4.2 % p.a. for 2011 to 2035 for the global chemical sector.

14 The demand is dominated by feed (60 %) and food (12 %), followed by bioenergy and -fuels (16 % and 2 % respectively) and materials (10 %, mainly wood), according to Carus et al. (2020a).

15 The amount of bio-based carbon for organic chemicals and derived materials is 50 Mt C p.a., see Figure 4. Assuming a carbon content of 47.5 %, the worldwide supply of bio-based carbon is 5.8 bln tonnes C. Hence, 50 Mt C correspond to 0.86 % of global supply.

within a sustainable framework[16]. The share of bio-based carbon needed for chemicals and derived materials would correspondingly end up between 1.7 and 2.3 % of the global biomass supply. With growing efficiency (e.g. in the process chain of converting biomass to biopolymers), higher utilisation of agricultural side-streams (e.g. wheat straws) and waste-streams (biowaste and wastewater sludge) for bio-based products, the demand for primary biomass for chemicals could be further reduced. Hence, a share of 1 to 1.5 % of global primary biomass supply for bio-based chemicals and derived materials is expected. Improvements in yields, efficiency and technology are realised through new breeds, precision agriculture, and the use of gene editing and GMOs (e.g. for organisms in bio-industrial process lines). Furthermore, through the shift in transport from internal combustion engines to electric vehicles and hydrogen, significant agricultural areas will become available that are today used for biofuels.

Another renewable source of carbon, presented in the 2050 model is captured **CO_2** as a feedstock (Carbon Capture and Utilisation, CCU). With the use of green hydrogen (from renewable sources), the carbon in CO_2 can be converted into valuable substances. CO_2 can either be sourced from direct air capture (DAC) or from industrial point sources[17]. To replace fossil-based hydrocarbons, hydrogen is produced in large-scale electrolysers that are powered by renewable solar and wind power. In the 2050 scenario depicted above, 250 Mt C are sourced annually from CO_2 as a feedstock. To replace this amount of fossil-based carbon with carbon from CO_2, around 15 PWh of electricity are necessary[18]. If this electricity was produced with photovoltaics in deserts, it would require an area of 62.000 km^2, which would translate to roughly 0.4 % of the total subtropical desert area.

In the future, the decision of which renewable carbon source to use in a specific situation can be decided through effective carbon management. Policy should support a general market shift towards renewable carbon, without regulating individual renewable carbon streams as this would lead to undesirable consequences such as non-level playing fields, incentives for non-optimal solutions and barriers for unsupported options. Which renewable carbon source is best suited for a particular case should be decided based on feedstock availability, technology and market conditions, as well as specific environmental issues. This depends on regional factors, concrete applications and production pathways.

There is no one-size-fits-all or universal solution. Whichever source used, however, must be renewable carbon. The renewable carbon source that is most cost-efficient and sustainable in a given situation depends on many regional and product-specific factors. To transform the chemical industry, it will be necessary to consider renewable carbon on a global scale, but on a local level, an understanding of context will be necessary to identify the best source of carbon for a particular application. Sharing, re-using and recycling carbon should be a priority everywhere, even if this is easier to achieve in highly industrialised metropolitan areas than in rural areas. Sustainable wood use will remain an important

16 Different scenarios deployed by Piotrowski et al. (2015). In the 2050 "Business-as-usual" scenario, global biomass supply is 18.17 Gt (dry matter) annually, in the "High" scenario 25.15 Gt.

17 In light of the decarbonisation of the energy sector, point sources of CO_2 like fossil powered plants will not be available anymore in the future. However, some point sources will still be available like industrial fermentation facilities or other industrial processes like calcination.

18 In a recent study, Kätelhön et al. (2019) describe a scenario for 2030, where 22 important chemicals have a production volume of 1000 Mt. This results in 520 Mt of carbon (own calculation). To replace fossil-based feedstock only with technologies that have a high TRL today, 32.0 PWh of electricity are required or 0.06 PWh per Mt C. This results in 15 PWh, if chemicals containing 250 Mt C were produced. Assuming a typical PV-yield of 250 GWh / km^2 / yr, this corresponds to 62.000 km^2 of desert land.

renewable carbon source in Nordic countries (e.g. Northern Europe), but only to a lesser extent in the South (e.g. Northern Africa or Brazil). Agricultural improvements like precision farming, regenerative agricultural practices and fertility enhancements, as well as GMOs (where appropriate and allowed), will help harvest more biomass from less land, and do so even more sustainably. This creates space for industrial crop cultivation without having to expand arable land. Where solar and wind power is often produced in surplus, it is possible to produce green hydrogen, that can be used both for energy and for the production of basic chemicals such as methane, methanol, formic acid, and even naphtha and waxes.

The shift towards the exclusive use of renewable carbon sources from virgin fossil carbon requires advances in each of the following fields: sharing, re-using, collecting, recycling, biomass and CO_2 Utilisation. To support this transformation, political and societal openness in regard to science and technology is needed, supported by R&D funds, private sector innovations and investment, and various other support schemes. Furthermore, for the acceptance of many novel technologies by the public, consumers appeal and a strong market demand are crucial. The following sections explore the potential technological and political challenges.

5 The material value chain of fossil carbon – and how to replace it with renewable carbon

The chemical industry is the backbone of the modern world. Almost all everyday products largely derive from chemistry. As shown in the previous chapters, the chemical industry today relies almost entirely (85 %) on virgin fossil carbon as a building block for its products. Fossil carbon comes from oil, natural gas or coal, and eventually ends up in the atmosphere, contributing heavily to climate change. As mentioned previously, the largest challenge for the chemical industry is to convert its feedstocks from virgin fossil-based to renewable-carbon-based.

The use of renewable carbon in the chemical and derived material industry is what decarbonisation is in the energy sector: a key to climate change mitigation. But how can we ensure this change happens? Are the technologies that can enable this change already developed and mature? Is there enough arable land for biomass? Can we really harvest CO_2 from the air? Can recycling turn old plastics into food packaging and detergents?

Before looking at these issues in more detail, let‘s first look at the major challenges in this fundamental transformation. The chemical industry is a key for a variety of other industries and products. It is a highly interconnected, integrated industry and has been optimised in many ways over decades. Figure 9 gives a depiction of a variety of chemicals and the industries that use them to optimise their products (e.g. energy efficiency or even special properties of the products). If this system is to be fundamentally changed, well-considered strategies are required. Comprehensive carbon management needs to take full account of the structure of today‘s chemical industry, preserve or repurpose industrial assets where possible, and replace those that have no future in a renewable carbon world.

There are therefore two different strategies for replacing virgin fossil-based products, both of which are important for the transformation and should be developed in parallel.

Strategy 1: Drop-in

The drop-in strategy uses existing structures of the chemical industry, such as refineries and chemical parks, to initiate the raw material transformation at the feedstock level. Instead of naphtha, methane, ethane, propane methanol (see Figure 9) from fossil sources such as oil, natural gas and coal, the raw materials could be obtained from biomass, CO_2 and chemical recycling. The end product stays the same, while the feedstock becomes renewable, and the existing processes and infrastructure largely remain in place. In this case, large amounts of virgin fossil carbon can be substituted quickly.

Strategy 2: Dedicated

The dedicated strategy cares little for existing structures of the large-scale chemical industry. Instead, it builds entirely new structures with new processes to create new raw materials, through biotechnology, wood or electro chemistry. These products often use biomass or CO_2 more efficiently and show properties that are not found in any petrochemical counterpart. However, this would require a large amount of time and resources for building up production capacities, and place the products on the market. Dedicated strategies include replacing petrochemical plastic packaging with paper, cellulose or natural fibre packaging.

Both strategies are necessary to achieve the transformation. While the first is mainly suitable for bulk chemicals, the second could be deployed for small-volume special applications. The first strategy

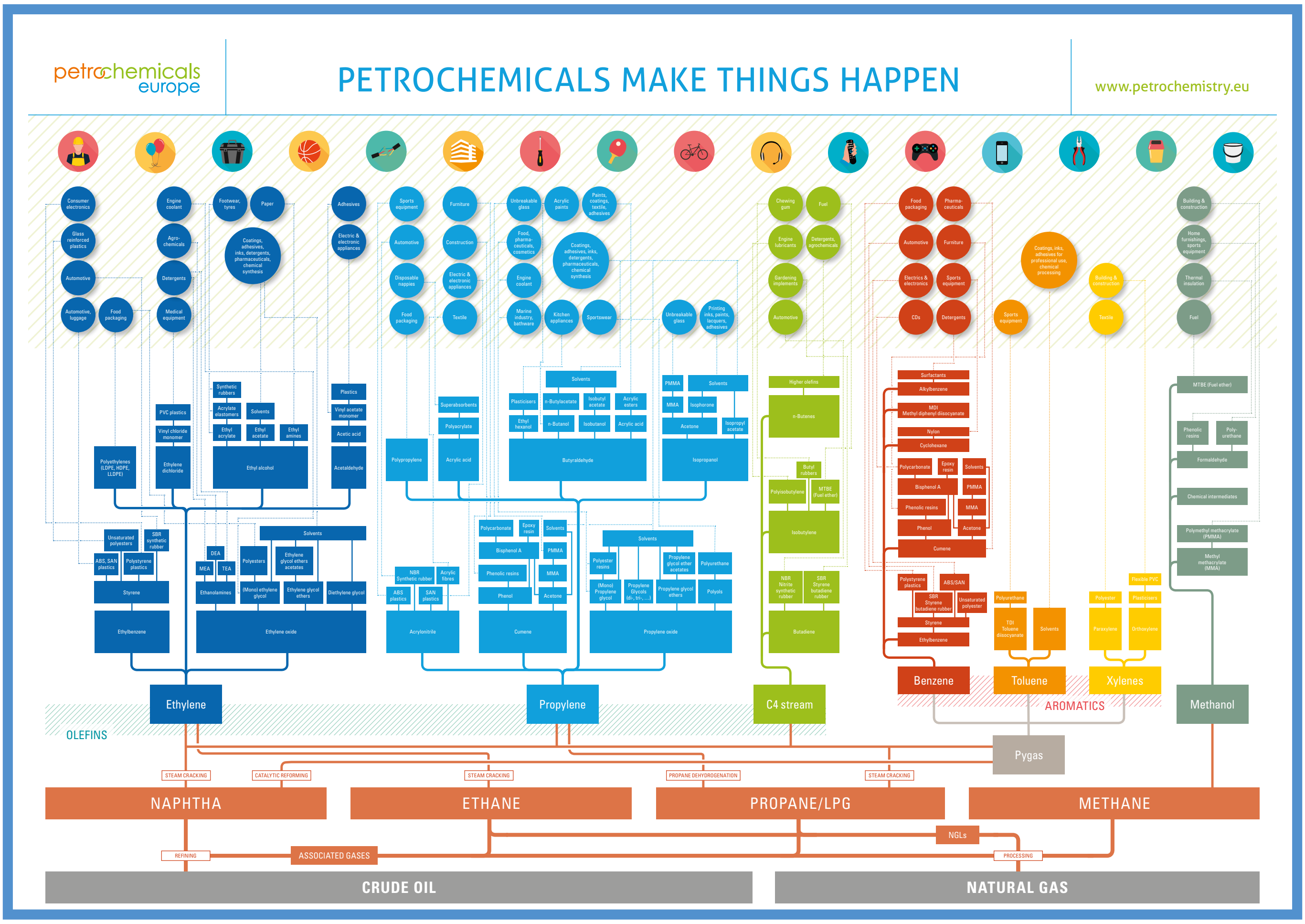

Figure 9: Selection of main steps from raw materials and feedstocks through to petrochemical products, their derivatives and everyday products (Petrochemicals Europe 2018)

would entail adapting the plants of the large-scale chemical industry, chemical parks, integrated sites and oil refineries, that have been optimised over decades, to the new raw materials and intermediate products of renewable carbon. This requires considerable investment in structural changes, as well as the development and integration of new technologies (e.g. electrochemistry).

The second scenario is heavily influenced by research and innovation, as it often involves the creation of production routes (e.g. biotechnology) for products with different new, and improved properties. This is especially true for fine chemicals with lower volume, but that allow for higher quality products.

While chemical recycling and large-volume CO_2 utilisation are usually more suited to the first pathway, biomass (e.g. for fermentation) is often predestined for the second pathway. The reality, however, is not as black and white as it seems, and one can find any combination between renewable carbon source, process and application that makes sense under certain conditions.

Only together

What is clear is that this transformation must be worked upon and implemented with high levels of collaboration, all along the value chain: from renewable raw materials via new processes and intermediate products, to final outputs and how to treat them at the end of their lifecycle. From the raw material supplier to the brand manufacturer and trader, the entire value-added chain must be implemented, physically, but also on a political, social and economic level, and supported by marketing. It should be noted that the renewable products will be more expensive. Carbon will never be as cheap as it was in the fossil fuel age, as fossil carbon did not have to bear its external costs. Carbon products will increase in value, meaning that it will be worthwhile to use them for longer time frames; share and re-use them where possible; and to collect and recycle them where not.

Recycling

Developing technologies to share, re-use and recycle products will be essential to keep carbon in the loop. Today, mechanical processes are predominant in recycling. However, these have limitations in terms of what types of waste-streams they can recycle and the quality of the recyclates. The full potential of recycling can only be unlocked with additional innovative processes such as chemical recycling. In this way, practically all waste fractions, especially mixed ones, can be recycled and turned into high-quality feedstock. First, however, large investments need to be made to implement the necessary capacities of chemical recycling plants. In Europe, investors are waiting for politicians to give the go-ahead with clear framework conditions.

With mechanical and chemical recycling, large parts of the carbon (but not all) remains in the cycle. In addition to recycling, other sources of renewable carbon are needed to close gaps in the cycle and minimize the losses. These sources are biomass and direct CO_2 use.

Biomass

The biomass breaks down into either primary biomass from fields and forests, or secondary 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, and private households). Utilising this kind of “organic waste” will be key in transitioning to a bio-based circular economy.

The utilisation of biomass makes particular sense wherever functional and complex molecular units of the biomass 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 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 regards to health and environmental benefits. Additionally, industrial biotechnology may aid in manufacturing complex molecules, using short and gentle processes and made-to-measure production organisms. Lignin, for instance, a by-product of wood processing, has been little used to date, however, in the future it could be used in the production of aromatic compounds and asphalt.

Already today, significant quantities of chemicals – between 10 and 15 % depending on the world region – are produced on the basis of biomass. Of course, any further expansion of biomass production must pay strict attention to food security and biodiversity loss. Still, experts see potential for sustainable expansion and, above all, prospective yield, efficiency and storage improvements. Despite sometimes unfavourable public perception, food crops are often a good choice for industrial utilisation. This is due to the fact that they produce very high yields per hectare, and often provide protein-rich by-products, therefore, they make for highly efficient and potentially sustainable land-use solutions. Another option is to use the land and facilities that are currently used for biofuel production, as the demand for liquid fuels is set to dwindle over the next few decades due to the rise of electric cars and hydrogen drives. Advanced biodiesel (HVO) is almost identical to naphtha and ethanol, and can easily be used to produce ethylene, a building block for PE and PET.

There are also some promising approaches for the use of marine biomass, such as micro and macro algae. These have not yet penetrated mass markets, however, they are used for products such as cosmetics and food supplements. Today, the total volume of marine biomass lags far behind agricultural and forestry systems.

Overall, biomass will not be sufficient to provide enough renewable carbon on its own. Therefore, it is a good thing that biomass is not alone. Which brings us to the third source of renewable carbon: CO_2.

Direct utilisation of CO_2

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

The field of Carbon Capture and Utilisation offers a wide range of applications, where CO_2 can be used as feedstock for chemicals, polymers, fuels, minerals and even proteins. By combining CO_2 with green hydrogen, several intermediates and end-products can be produced, such as methane and methanol. In combination with CO_2-based formic acid, these can be used as a base feedstock for all kinds of chemicals, polymers and fuels. Synthetic naphtha, for example, can directly replace crude oil naphtha in existing refineries, and can be produced from CO_2 and hydrogen through the Fischer-Tropsch reaction. 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 levels and value. Some chemicals are by default directly synthesised from CO_2, such as urea and other diverse polymers (e.g. polyurethanes and polycarbonates).

In order to make the carbon contained in CO_2 re-usable, it must be chemically reduced, which requires large amounts of energy, mostly in the form of hydrogen. From an ecological standpoint, this means that only renewable energies or existing process energy can be used for CCU processes to ensure they are sustainable. For this reason, looking ahead, there must be massive, worldwide growth in renewable energies such as solar and wind energy, hydropower and geothermal energy. Based on current trends it is possible to say that this transition is achievable, as many energy systems around the world are already shifting towards renewable options. As shown in the previous chapter, only 0.4 % of the area of all subtropical deserts would be needed to provide photovoltaic energy for the carbon supply in the depicted 2050 scenario.

The big advantage of CCU technologies over biomass is their high land efficiency and ability to utilize inarable land types like deserts. Disadvantages of CCU include: high investment costs; energy requirements; and the need for construction of new infrastructure. On one hand, the right incentive systems must be created and, on the other, awareness should be fostered that CO_2 utilisation, while principally feasible for any application, is especially suitable for the production of bulk chemicals.

Conclusion

Since the beginning of the industrial revolution, humanity has almost exclusively relied on cheap virgin fossil carbon sources such as coal and crude oil for its development. Today, for the first time, we can now decouple the production of chemicals and derived materials from the use of virgin fossil carbon. All of today‘s chemicals and derived products can be made with renewable carbon from biomass, captured CO_2 or recycling. Technologies and investment capital are available for the transformation from fossil to renewable carbon for the entire industry.

The renewable carbon family is the only pathway to a truly sustainable future for the chemical industry. Skilful carbon management systems can help find potential solutions to questions such as:

- In a given scenario, what is the most fitting carbon source from the renewable carbon family? Is it Biomass, CO_2 or recycling?
- Which renewable carbon source is the most sustainable, efficient and socially acceptable for a particular application and in a given region?
- Is it biomass from wood, sugar beet or metropolitan biogenic waste?

- Is it captured CO_2 from fossil power plants, from fermentation or direct air capture from the atmosphere?
- Or is it recycled carbon from plastics via mechanical, chemical or enzymatic recycling?

In a future where renewable carbon is prevalent, these are relevant questions that can only be answered on a regional level, based on desired application and available infrastructure.

The exclusive use of renewable carbon as feedstock is a key condition for the chemical industry and all other industries that rely on it, from detergents to technology, to achieve climate neutrality. The use of renewable carbon in the chemical and material industry is what decarbonisation is in the energy sector, a priority of climate change mitigation. A comprehensive policy framework is required to ensure that the chemical industry transforms at a rate that is fast enough to ameliorate the climate crisis.

6 What policy framework is needed to phase out fossil carbon?

For the complete shift to renewable carbon to happen by 2050, a variety of technologies are already available, while others still need to be developed, optimised and scaled up. Billions of dollars/euros will have to be invested, meaning that initially quitting fossil carbon will be expensive. The required new infrastructure involves high investments, and carbon from biomass, captured CO_2 and recycling is likely, at least in the near term, to be more costly than extraction of tightly stacked fossil carbon from an oil well.

However, since the complete and rapid switch to renewable carbon is unavoidable to properly tackle climate change and establish a circular and sustainable economy, governments and industry must collaborate to create a roadmap for the transition, and instate the appropriate framework conditions.

In this context, policy-makers are helped by the fact that in recent years fast moving consumer goods manufacturers have been increasingly putting pressure on their supply chains to deliver materials and products that are free from virgin fossil carbon. Unilever has announced that it will phase out all virgin fossil carbon in its cleaning products by 2030. Most recently, L'Oréal announced it will source 95 % of its ingredients from renewable sources by the same date[19]. If policymakers were to support this growing movement with suitable policy framework conditions, the transformation could gain considerable momentum.

Policy makers could make use of the following instruments and measures to promote and speed up the chemical industry's shift to renewable carbon:

Direct financial incentives via e.g. taxes, emission trading system and investment support

Taxation of virgin fossil carbon[20] in chemicals and derived products. To date, the chemical industry does not pay any taxes for their virgin fossil carbon anywhere around the globe. However, it would be quite feasible to introduce a virgin fossil carbon tax – if not globally, then regionally (e.g. in Europe). Imported products would then be taxed, while the tax could be refunded for exports.

Such a virgin **fossil carbon tax** has some systematic advantages over alternative CO_2 tax systems implemented today that mainly target GHG emissions. A virgin fossil carbon tax would be much easier to apply and solves a number of central issues considered a hurdle for the implementation of a CO_2 tax, such as carbon leakage, eligibility to WTO rules or coverage of all sectors in the economy. Last but not least, the virgin fossil carbon tax can be initiated regionally without endangering competitiveness, as subsequent taxation of imports or reimbursement of exports is possible. In that sense, a virgin fossil

19 See https://www.unilever.com/news/press-releases/2020/unilever-to-invest-1-billion-to-eliminate-fossil-fuels-in-cleaning-products-by-2030.html and https://www.loreal.com/en/press-release/group/transparency-security-and-green-sciences-loreal-share-its-vision-of-the-beauty-of-the-future/

20 Note that, according to the renewable carbon concept, fossil carbon becomes renewable carbon through recycling. This means that recyclates, regardless of where their original carbon comes from, are always part of the renewable carbon family and therefore naturally do not fall under the fossil carbon tax, which only concerns additional fossil carbon from the soil.

carbon tax would also work well as a carbon border adjustment mechanism (CBAM), an option that is currently being discussed on a European level.

With a growing population, the demand for embedded carbon for chemistry and materials will continue to rise. To ensure climate mitigation, it is essential that no additional fossil carbon enters the cycle. This is where a virgin fossil carbon tax could play a big role, as it makes additional fossil carbon from under ground more expensive and economically less attractive, steering the economy towards renewable carbon feedstocks. At the same time, declining tax revenues of an increasingly decarbonised energy sector are compensated for by rising revenues from virgin fossil carbon used in the chemical and derived materials sector. That is, at least as long as fossil carbon is still used in these sectors.

Higher costs for fossil CO_2 emissions and an expansion of the emissions trading system (ETS). The European Union Emissions Trading System (EU ETS) is the first large greenhouse gas emissions trading scheme in the world. It is a powerful system for phasing out fossil carbon in the energy sector and traded fossil CO_2 emissions should be more tightly capped to make this instrument more effective and better reflect externalities caused by such emissions. Current trends show signs of prices moving in the right direction, as they have sharply risen to over 40 € per ton. Some calculations, however, have estimated the externality costs of a ton of CO_2 is 200 € or more. Even more importantly, the ETS should be expanded to cover the hidden fossil carbon embedded in chemicals and derived materials. To avoid carbon leakage, this would require proper alignment with the discussed CBAM.

A recent initiative from the European Commission seems promising on this front: **Taxonomy Regulation**. This aims to scale up sustainable investment and support the implementation of the European Green Deal as part of the European Union's response to climate and environmental challenges. It will soon provide harmonised criteria and a "common language" for companies and investors to determine which economic activities can be considered environmentally sustainable, thus aiming to limit the risk of greenwashing and market fragmentation in the classification of green activities and investment projects. For this reason, at the EU level, biomass for the production of biopolymers, as well as chemical recycling, are beginning to receive investment support, given they meet certain sustainability criteria.

Carbon Management

Comprehensive carbon management will be necessary to lead the complex system of the chemical industry sustainably into a future without fossil carbon. How is the carbon demand for the chemical and derived materials industry developing? What renewable carbon sources are available in a given region, a country or even a whole continent? How can the demand be covered as sustainably as possible with renewable carbon? Answering these questions will be a crucial task of governments.

This includes helping **biofuel producers**, who use sustainably sourced, deforestation free biomass, **to become suppliers of the chemical industry**. With the dwindling demand for liquid fuels, biofuel producers will disappear over the coming decades, unless they do not transform their business models. Shifting towards becoming carbon suppliers for the chemical industry, however, should be an easy step for many biofuel producers, and is essential given the predicted demand. By doing so, biofuel plants and their infrastructure could be maintained in the long-term, delivering their carbon to where it is most needed in the future.

The European **Circular Economy Action Plan** and the **European Green Deal** do not delineate specific strategies for carbon management, or a clear vision for the chemical industry. Despite the actions outlined in the Chemicals Strategy for Sustainability, the focus is often solely on safety – which is of course important, but does not go far enough. The substitution of virgin fossil carbon in chemistry is not a high priority in the Green Deal policy agenda, and the concept of renewable carbon has yet to arrive in Brussels. For example, the carbon source of plastics has so far played no role at all in the Plastics Strategy. A properly designed carbon management strategy could significantly accelerate the process of phasing out fossil carbon and its related greenhouse gas emissions. Upcoming policies might provide opportunities to incorporate the concept, e.g. the Sustainable Products Initiative that revises the Ecodesign Directive.

A strong support system for bioenergy, biofuels and now also for CO_2-based fuels has existed for more than ten years with the **Renewable Energy Directive (REDI+II)**. In addition, there is nothing comparable for the chemicals and derived materials sector. Over time, the RED has created a non-level playing field whereby turning renewable raw materials directly into fuels is more attractive than supplying them to the chemical sector first. This not only systematically undermines plans to decouple the chemical industry from crude oil, but it also undercuts the general idea of a circular economy, which intends to keep materials in use for as long as possible. Therefore, for years there have been calls for a "Renewable Energy and Material Directive". Today, it is becoming evident that putting in place a "Renewable **Energy and Carbon Strategy**" or a "**Decarbonisation and Renewable Carbon Strategy**" is necessary to cover and link the shrinking carbon flows in the energy system, and the growing carbon demand for chemicals and derived materials.

Standards and Norms

Another possible action to phase out additional fossil carbon is the development of **certificates and labels** that indicate the **share of renewable carbon** (total share of recycled material, biomass and CO_2) contained in products, in order to inform customers and other actors along the value chain. This would create a market pull by increasing consumer awareness of, and potentially demand for, products manufactured with renewable sources instead of fossil fuels. Such a renewable carbon label is already under development by the Renewable Carbon Initiative (RCI).[21]

A solution that is less specifically geared towards phasing out fossil carbon, but rather focuses on identifying the best solutions within renewable carbon sources, would be to develop **guidance on Life Cycle Assessments standards (LCA)** that considers the circularity of the materials. Such guidance should be based on accepted standards like ISO 14040/14044 and could be comparable to guidance like the ILCD handbook or existing guidance on other specific products or feedstocks. This would enable a fair comparison between different renewable carbon options for a specific application (and region), and aid decision-makers in identifying the best solution for a given situation.

Supporting market access for products based in renewable carbon

To complement existing recycled plastic quotas and broader circular economy mandates for plastic re-use, additional instruments can be used such as **renewable carbon quotas 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 defined with increasing quotas for a later point in time (e.g. 2050).

Another idea would be to require companies in the chemical and plastics industries to issue an annual report on the **percentage of renewable carbon used in their production processes** ("Reporting"), to then create a company ranking based on the share of renewable carbon used in their production.

A third option that aims to support market access, would be the **tightening of environmental requirements for chemicals** (e.g. no hormone-active plasticisers, improved biodegradation behaviour

21 (www.renewable-carbon-initiative.com)

of detergents and solvents etc.). While not directly aimed at reducing fossil carbon, such requirements would lead to a systemic shift favouring renewable carbon-based solutions, in particular those derived from the fermentation of biomass/CO_2.

Other support measures

Discontinuation of any funding programmes in the fossil domain. Every year, the G7 countries spend at least USD 100 billion on the production and consumption of oil, gas, and coal.[22] Just imagine if that investment were redirected to push forward renewable carbon-based solutions and further the decarbonisation of the energy sector!

Systematic acceptance and expansion of mechanical and chemical recycling. Mechanical recycling is limited to well-sorted waste fractions and to certain polymers and applications, but overall volumes can still be further increased. Various chemical recycling processes, on the other hand, can use virtually any mixed biomass and plastic waste stream and convert it into chemical feedstock. This feedstock can then be used again to produce, for example, virgin polymers. Especially in chemical recycling, investors are waiting for political framework conditions and definitions to be clear and stable before building large plants.

Additional and improved financial support is required for **research, development and implementation** of sustainable future-oriented technologies, such as material biomass, chemical recycling and CO_2 technologies used to provide and utilise renewable carbon.

Massive expansion of renewable energies and green hydrogen grids, in combination with CCU as a vehicle for storing energy is needed to provide sustainable renewable carbon to the chemical and plastic industry.

In a wider sense, policymakers should target renewable carbon as a whole and not confine themselves to biomass, direct CO_2 utilisation or recycling – all three paths must be followed simultaneously in order to be able to abandon virgin fossil raw materials entirely as soon as possible. The current 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. The most appropriate technology needed for a certain application, in a determined region, with specific circumstances and networks, must be evaluated by sustainability analyses, from an economic, ecological and social standpoint, not by political dogma. The influence of policy frameworks should never be underestimated. Even small changes in market conditions may cause cascades in innovation.

22 See Simon (2018)

List of acronyms

CBAM	Carbon border adjustment mechanism
CCU	Carbon capture and utilisation
GHG	Greenhouse gas
GMO	Genetically modified organism
HVO	Hydrotreated vegetable oils
LCA	Life cycle assessment
Mt	Megatons
Mt C	Megatons of carbon
PE	Polyethylen
PET	Polyethylene terephthalate
PV	Photovoltaic
REDI+II	Renewable Energy Directive
RCI	Renewable Carbon Initiative

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