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The 4th International workshop on "Innovation and Production Management in the Process Industries" will be convened at Provadis School of International Management and Technology in collaboration with the University of Münster in May 2022 in Frankfurt, Germany. Further information will be announced soon on our website.

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The Journal of Business Chemistry (JoBC) focuses on current developments and insights at the intersection of management and chemistry, biotechnology or pharmacy.

The JoBC provides an international forum for researchers and practitioners in companies, research institutes, public authorities, consultancies or NGOs to present and discuss current challenges as well as potential solutions in an interdisciplinary manner. Thus, the JoBC aims to foster the dialog between science and business, to support management practice in the chemical and pharmaceutical industry and to indicate where further research from academia is needed. The JoBC offers high quality publications with academic standards, a fast publishing process and global reach. With this multidisciplinary and boundary-spanning approach, the JoBC intends to become the leading journal for decision makers in the chemical and pharmaceutical industry.

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Letter from the Editors

Doughnuts not only for eating

In the last issues, many articles revolved around the topic of sustainability. In this issue, in fact, all articles touch the topic of sustainability. The sheer abundance of aspects to consider and their interconnections make the topic of sustainability exciting but also challenging not to mention the urgent need for radical changes. What models exist to give us some orientation? There is the widely known three pillars model but there exist also newer models like the doughnut economics (Raworth, 2017). It describes a safe and just operating space for humanity located between social boundaries as the foundation and planetary boundaries as the ceiling – thus visualizing a doughnut. The idea is to address social shortfalls while preventing overconsumption of resources and too much pollution. The ecological aspects namely, climate change, ocean acidification, chemical pollution, nitrogen and phosphorus loading, freshwater withdrawals, land conversion, biodiversity loss, air pollution, and ozone layer depletion are adopted from Johan Rockström. The considered social aspects are food security, health, education, income and work, peace and justice, political voice, social equity, gender equality, housing, networks, energy, and water.

The research paper "Carbon Capture and Utilization – A new building block for Circular Economy?" by Florian Frieden first introduces some CCU processes before exploring the hurdles and potentials of CCU based on expert interviews. The article thus sheds light on a technology that is still in its infancy but could make important contributions to climate protection as well as circular economy. The recognition of CCU in the EU ETS, costs, entrepreneurial risk, the efficiency of CCU processes, and the high energy demand are identified as main hurdles. On the contrary, the large field of application, rising CO_2 prices and higher margins through sustainably labeled products present the potentials of CCU.

The first contribution to our commentary section comes from Jutta Paulus. Her article "Is the EU Green Deal channeling a transition towards a sustainable chemical industry?" picks up a ten-point action plan for the green transition of the chemical industry that she developed together with her colleague Sven Giegold. In the following, she explains each of these points in more detail, highlights progress and, above all, points out what still needs to be done.

Nabila Rabanizada´s and Monica Harting Pfeifer´s article "Disruption of the role model closed loop mechanical recycling of PET" deals with a challenge in the recycling of PET bottles used for e.g. juice: The coating inside the bottle. They raise awareness of this topic and call for exchange of knowledge and cooperation in the supply-chain to achieve true circularity.

Please enjoy reading the third issue of the eighteenth volume of the Journal of Business Chemistry. We are grateful for all the support from authors and reviewers. If you have any comments or suggestions, please do not hesitate to contact us at janine.heck@businesschemistry.org. For more updates and insights on management issues in the chemical industry, follow us on LinkedIn: www.linkedin.com/company/jobc/ and subscribe to our newsletter: https://www.businesschemistry.org/

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Raworth, K. (2017): *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*, Random House.

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Research Paper

Florian Frieden*

Carbon Capture and Utilization – A new building block for Circular Economy?

Reducing the emissions of greenhouse gases is a great challenge for today's industry. Besides using efficiency improvements and CO_2 free processes, the utilization of CO_2 as a raw material could be an important technology on the way to a greenhouse gas neutral world. Especially in the chemical industry these processes could help to implement a fully circular economy. For now, Carbon Capture and Utilization (CCU) is in its infancy and just a few demonstration plants are already running. After introducing some CCU processes, this article shows the hurdles and potentials of CCU in general. Knowing the hurdles of this new technology is important to accelerate the implementation in an efficient way. The potentials demonstrate how influential CCU could be towards a circular economy for the chemical industry. The basis for this work is the content analysis of expert interviews. The interviews were held with professionals from the chemical industry.

1 Introduction

Climate change is one of the greatest threats to humanity. To avert this crisis, the Intergovernmental Panel on Climate Change (IPCC) has set the target to stay below a 2 °C increase of the global temperature (United Nations, 2015). Following the recommendation of the IPCC, governments and companies worldwide have set their own CO_2 reduction targets. The European Union (EU) wants to be climate neutral until 2050. An important milestone is the year 2030, when the EU aims to have lowered the output of CO_2 by 55 % compared to 1990 (European Commission, 2020b).

Today companies are under societal and political pressure to reduce their CO_2 output. By introducing the Emission Trading System (ETS) the EU has set up a monetary incentive for companies to reduce their CO_2 output (Directive 2003/87/EC, 2003). Since modern industries rely on fossil fuels that inevitably produce CO_2, energy intensive companies need innovative solutions to drastically reduce their CO_2 output.
Carbon Capture and Sequestration (CCS) may be a solution, since large amounts of CO_2 could be stored in geological sites (Gibbins & Chalmers, 2008). But stored CO_2 could lead to diffuse leaks, that are hard to handle. Furthermore, the public perception of CCS is negative. Therefore, CCS on an industrial scale is forbidden in the EU (Directive 2009/31/EG, 2009).

A similar technology is Carbon Capture and Utilization (CCU). By using captured CO_2 to manufacture goods it can substitute fossil resources and bind CO_2 in products for a certain duration. Consequently, the output of CO_2 into the atmosphere is lowered (Assen et al., 2013). In contrast to CCS, CCU can produce added value for companies, making it a better alternative economically. Due to the manifold applications of CCU, it is an interesting option for the chemical industry (Baena-Moreno et al., 2019). Substituting fossil resources with CO_2 could decouple the industry from oil and gas imports and therefore pave the way towards circular economy (Kätelhön et al., 2019). As the societal pressure on

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companies rises and fees for CO_2 outputs increase, many companies develop systems to reuse CO_2 to generate a higher added value. Currently, using CO_2 to produce chemical goods is more complex than the conventional alternative. Higher costs and rejection by industry managers is the consequence. Furthermore, there are regulatory barriers. For example, there is no exception for CCU in the EU ETS (Implementing Regulation (EU) 2018/2066, 2018). So, CO_2 that is bound in products counts as emitted and companies need to buy certificates accordingly.

To efficiently implement CCU as technology that promotes circular economy in the chemical industry it is important to identify and understand its potentials concerning economic and technologic issues and aspects of climate protection. On the other side, its hurdles need to be recognized to enable companies to manage them. Both scopes of CCU are significant, as an ideal circular economy has to be sustainable from an economic and a societal point of view (Kirchherr et al., 2017).

In this paper application potentials of CCU will be examined. Therefore, a range of CCU technologies will be discussed. A special focus will be put on applications that have a high impact for circular economy. Relevant hurdles for CCU that prevent an implementation on industrial scales will be reviewed in economic, technologic and regulatory dimensions. To generate a holistic picture of CCU, an analysis of the scientific literature and the knowledge of industry experts is combined.

2 Theoretical Background

2.1 Chemical Industry

The chemical industry is one of the most energy-intensive process industries. In Germany, the sector accounted for 28,6 % of total industrial energy consumption in 2018. However, it is important to note, that more than one third of energy carriers in the chemical industry are used as raw materials for chemical syntheses (Statistisches Bundesamt, 2021). This is a peculiarity of the chemical industry and leads to two problems concerning its CO_2 emissions.

The chemical industry has an intrinsic demand for carbon, as numerous chemical products are based upon the carbon atom. Hence, the chemical industry is forced to use carbonaceous resources. Utilization of fossil resources is established as the major source of the chemical industry, while biomass is only used as a minor resource (European Chemical Industry Council, 2019). Synthesized chemical products based on fossil resources decompose at the end of their product life cycle and release CO_2 into the atmosphere. Therefore, they contribute to climate change. Products that are based on biomass would also release CO_2, but the emissions are balanced by CO_2 sinks.

The chemical industry has a potential to reduce its CO_2 emissions that is special to this industry. Many products can be built out of CO_2 and other renewable resources like H_2. So, CO_2 can be used as a resource for the chemical industry. Production processes can be transformed from today's fossil dependency to a more sustainable alternative. Using CO_2 as major carbonaceous resource can reduce the carbon footprint of chemical products significantly, depending on the CO_2 source (Assen & Bardow, 2014). By using CCU the demand for carbon of the chemical industry could turn into a carbon cycle.

The second problem of the chemical industry is that chemical processes consume a lot of energy. As renewable energy sources do not account for a significant share of used energy carriers in the industry, the high energy consumption leads to high CO_2 emissions. Despite efficiency gains, total CO_2 emissions did not drop in the last years because of rising production volumes (European Chemical Industry Council, 2019). Innovations that reduce the CO_2 intensity of chemical production processes often come with a rising energy intensity. This means that the transformation of the chemical industry towards a lower CO_2 intensity in the production process comes with an even higher energy intensity (Geres et al., 2019).

2.2 Emissions Trading

Following the ambitious goals for climate protection in the EU, there are several mechanisms to reduce CO_2 emissions. The most important instrument is the EU emissions trading system (Directive 2003/87/EC, 2003). It is a “cap and trade” mechanism. Emissions of all plants that are included in the ETS are capped by the EU. To emit a ton of CO_2 a plant has to return certificates. As the certificates are capped, they receive a real exchange value. Certificates can be traded by companies and member states of the EU. But every company and state has to buy enough certificates for their emissions. The total amount of certificates has been reduced by 1,74 % per year until 2020 (Directive 2009/29/EG,

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2009). Since 2021 the reduction rate rises to 2,2 % per year to motivate companies to install sustainable processes even faster (Directive (EU) 2018/410, 2018).

The EU ETS is the world's biggest market for greenhouse gas certificates. It accounts for approximately 45 % of greenhouse gas emissions in the EU. Since 2013 many plants of the chemical industry have been taken into account in the EU ETS. In recent years certificates have been traded for prices between 20 € and 50 € per ton of CO_2 (Ember, 2021). This leads to high costs for the chemical industry as it is dependent on fossil fuels. The emerging economic problem will enlarge in the future given that certificate prices are going to further rise in the future.

To dampen the costs for the European industry, some certificates are allocated to energy intensive plants for free. To be eligible to get free certificates companies have to produce with a low CO_2 intensity. Productions are measured by a benchmark. Top 10 % of the most efficient plants compose the benchmark for their industry sector. Using these benchmark-plants the number of free certificates is calculated. If plants meet the requirements of the benchmark, they get free certificates. But the total number of free certificates decreases over time to promote less CO_2 intense processes in all industry sectors. In 2020 only 30 % of all certificates have been allocated for free. Furthermore, the carbon leakage mechanism has been implemented to prevent the relocation of companies into foreign countries without an ETS. Plants that are entitled to the carbon leakage mechanism still get 100 % of their certificates for free (Delegated Regulation (EU) 2019/331, 2018).

2.3 Circular Economy

If the global population continues to grow to more than 9 billion people by 2050 and the economy still produces with today's process routines, we would need resources equal to three planets to continue our lifestyle (United Nations, 2020). The consumption of basic resources like biomass, fossil fuels, metals and minerals could double in the next 40 years (OECD, 2019). Using the production routines of a circular economy could help to reduce the consumption of resources.

There is a big difference between an ideal circular economy and today's economy. The conventional economy roughly consists of four processes. Resources are extracted, processed to products, used and disposed as waste after the product lifecycle. The amount of waste this system produces will increase in the next years and could rise up by 70 % by 2050 (Kaza et al.). Figure 1 shows a schematic illustration of today's linear economy combined with the concept of a value level.

Final products have a higher value level than their raw materials, as resources and energy have been used for the production. In developed countries a significant share of waste is recycled, but products of recycling processes

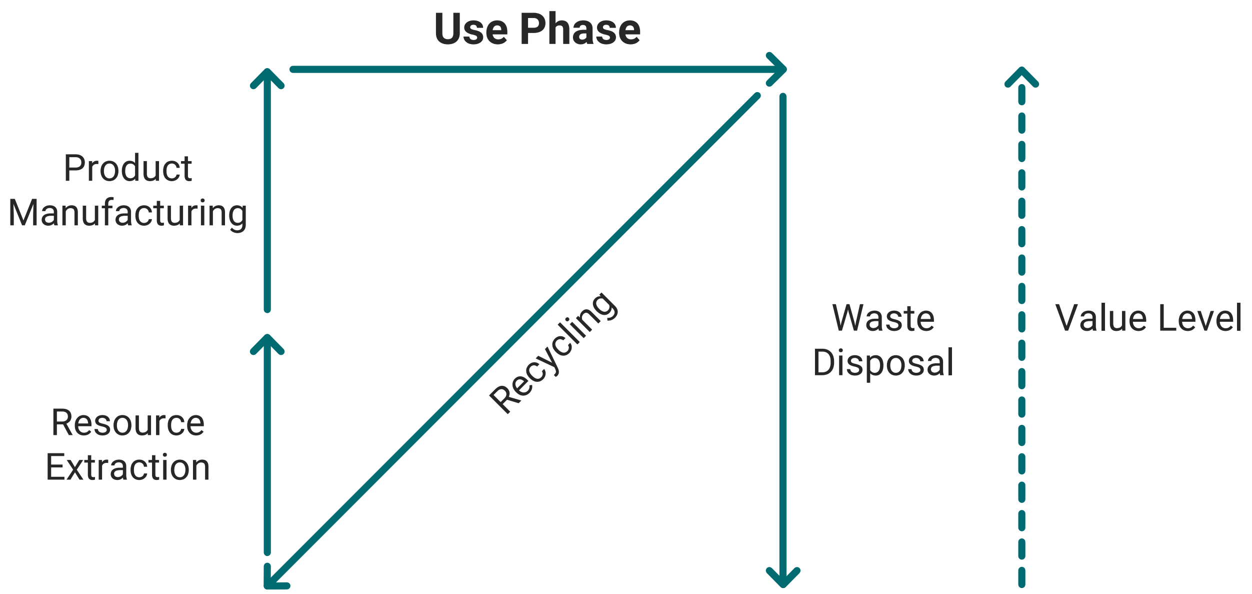

Figure 1: Scheme of a conventional linear economy. Arrows indicate the flow of goods/energy. The dotted arrow indicates the value level.

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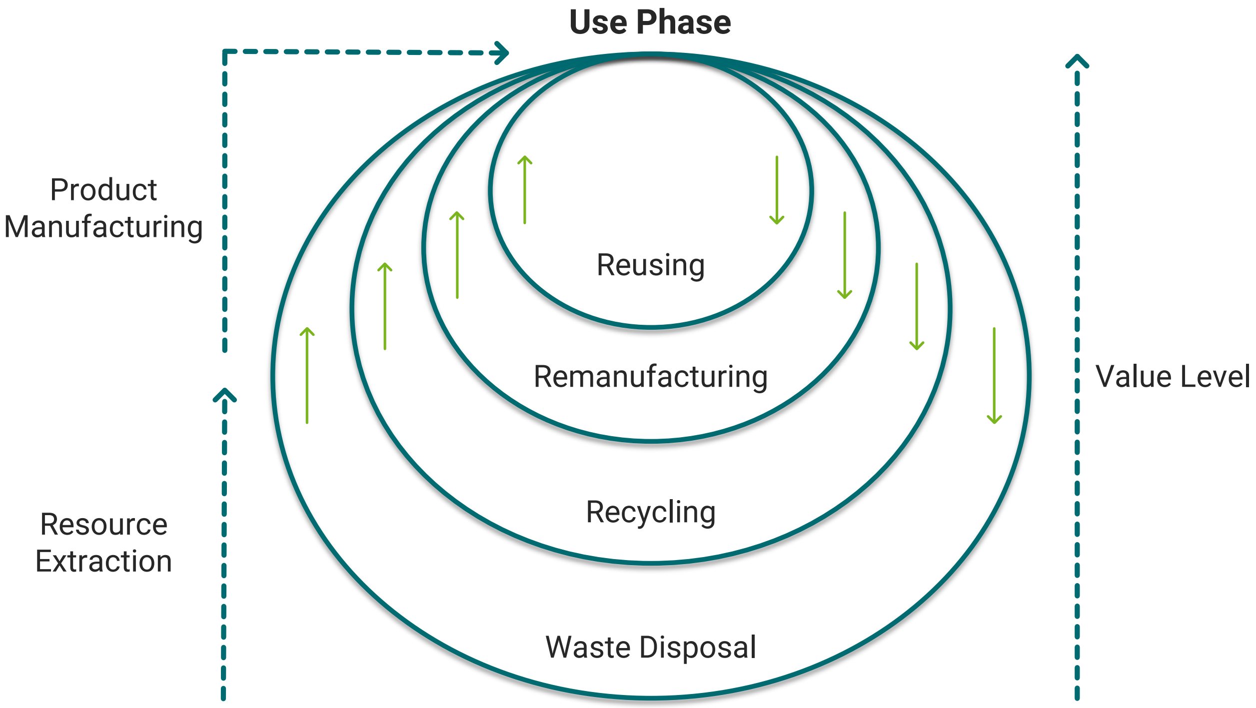

Figure 2: Ideal circular economy with recycling stages at different value levels. Adapted from (Mihelcic et al., 2003). Arrows indicate the low of goods/energy. The dotted arrow indicates the value level.

are often raw materials. Their value level is equally low to raw materials because resources and energy have to be put in to produce final products. So recycling reduces the consumption of primary raw materials, but other resources and energy are still used to produce final goods for consumers (Korhonen et al., 2018).

In contrast to today's recycling circular economy prioritizes the value level. Products are supposed to be recycled on the highest value level possible. Figure 2 shows a schematic illustration of a value level focused circular economy.

All circles in figure 2 recycle products after their life cycle to be used again. Staying on a higher value level means that less energy and resources are needed to get the product back to its use phase (Korhonen et al., 2018). Consequently, a higher economic and ecological efficiency results in the prioritization of the inner circles of figure 2. Outer circles are sorted in descending order according to their value retention. **Reusing** products after their former lifecycle decreases the value level on an interim basis in a small extent. **Remanufacturing** products uses further resources and more energy. When products are **recycled** their raw materials are extracted and large quantities of resources and energy are consumed to reproduce products. **Disposal** of waste leads to a value level of zero, as remaining resources need to be extracted again and are not available in a usable form.

Circular economy has become more popular in the latest years as more politicians recognize the concept. An important module of the European Green Deal is the transition towards a circular economy for Europe (European Commission, 2019). This module is operationalized in the Circular Economy Action Plan of the European Commission, which describes measures to implement circular economy in European value chains (European Commission, 2020a).

2.4 CCU Technologies

There are numerous possibilities to use CO_2 in the chemical industry or adjacent areas. In this chapter only a few applications that have a high impact today or in the future will be described.

2.4.1 Synthesis Gas

Synthesis gas is an important basic product in the chemical industry. The mixture of hydrogen and carbon monoxide can be used to produce a wide range of chemical products

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and synthetic fuels. Because of the numerous secondary products synthesis gas has a high production volume. Hence, producing synthesis gas with a CCU application could cause high emission reductions (Foit et al., 2017).

The H_2/CO mixture can be synthesized directly from CO_2 and H_2O via high temperature co-electrolysis. The process combines CO_2 and H_2 electrolysis. The reduction of CO_2 is slower than the reduction of H_2O. Using the reversed water-gas shift left over CO_2 can be converted to CO. As two different processes are used, it is possible to adjust the H_2/CO ratio by changing the reaction parameters (Foit et al., 2017). The co-electrolysis works with solid oxide electrolysis cells and solid proton conducting electrolysis cells. The latter has the special feature that small amounts of methane are generated in the electrolysis process (Ebbesen et al., 2014).

2.4.2 Urea

Using CO_2 in the production of urea is the standard process today. Ammonia and carbon dioxide are converted to ammonium carbamate under high pressure. The resulting ammonium carbamate produces urea via a dehydration reaction. The process is advantageous for the chemical industry because CO_2 and NH_3 react exothermic. Even though the dehydration reaction of ammonium carbamate is endothermic, the total process remains exothermic (Meessen, 2010). So, chemical companies do not need high energy inputs to produce urea.

Coupling the urea production with the production of ammonia has the advantage that both ammonia and CO_2 that accrues in the production chain prior to the synthesis of ammonia can be used to generate urea. Today the process with the three steps, steam reforming, ammonia synthesis and urea synthesis remains a CO_2 source. In the future hydrogen for the synthesis of ammonia could be generated in electrolysis facilities without CO_2 generation. CO_2 for the urea synthesis could come from other sources, making the process a CO_2 sink (Driver et al., 2019).

2.4.3 Organic carbonates

Producing organic carbonates via CO_2 is interesting as the greenhouse gas can be bound in products and in addition toxic reactants like phosgene and carbon monoxide can be substituted. There are two ways to produce organic carbonates using CO_2. Diols or two mono alcohols and CO_2 can react to corresponding cyclic or acyclic carbonates. The reaction can be used to produce numerous simple cyclic and acyclic carbonates without metal-based catalysts (Lim et al., 2014). The reaction could become more important in the future, as electrolyte components like ethylene carbonate and dimethyl carbonate for lithium ion batteries can be produced with a lower carbon footprint (Xu, 2014). Epoxides or oxetanes and CO_2 can be converted to cyclic carbonates or polycarbonates using metal-based catalysts. The reaction can convert terminal and some internal epoxides and oxetanes (Martín et al., 2015).

Polyether carbonate polyols can be synthesized in a similar way by increasing the stochiometric ratio of epoxides to CO_2. Other than that, the reaction parameters and catalysts have to be adjusted. The exact product is dependent on the starter alcohol (Langanke et al., 2014). This process has been developed by Covestro. A demonstration plant already uses the process to produce "Cardyon" (Covestro AG, 2020). A mass fraction of 20 % of CO_2 is the upper limit but this share already reduces the emission of greenhouse gases of the production of polyether carbonate polyols by up to 19 % (Assen & Bardow, 2014).

2.4.4 Methanol

Methanol could become very important in the energy and chemical industry. It could function as platform chemical for both sectors. Methanol can be used as energy storage or in the transport sector as fuel. Furthermore, Methanol is a basic chemical that is used to produce other high-volume chemicals like acetic acid and formaldehyde (Nyári et al., 2020). Even alkenes like ethene and propene can be generated from methanol (Chang, 1984). The high number of downstream products results in a high CO_2 reduction potential, if Methanol is produced under incorporation of CO_2.

Hydrogen and carbon dioxide can directly be converted into methanol and water. But the yield is lower than the conventional synthesis of methanol via synthesis gas (Inui, 2002). New catalysts might help to reach higher and more economic yields. So, the research focuses on new catalyst combinations and process technologies (Centi & Perathoner, 2014). Carbon Recycling International already uses this technique to produce 4000 t of methanol per year (Carbon Recycling International, 2021).

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With regard to coming volatilities in the power grid due to the higher share of regenerative electricity generation it could be important to store energy. Excess electric power can be converted to H_2 via water electrolysis. But H_2 is difficult to store and transport. Synthesizing methanol from H_2 and CO_2 could provide a versatile energy carrier, as it is easy to store and transport. The needed CO_2 could be captured locally by Direct Air Capture facilities (Fasihi et al., 2019). Furthermore, as stated above Methanol can be used in numerous applications (Weimer et al., 1996). This could also relieve the problem of the geographic inequality of the production of regenerative energies.

2.4.5 Synthetic fuels

Fuels with a reduced carbon footprint that are usable in conventional combustion engines could be important for the transition time towards fully electric transport systems. Synthetic fuels produced by the Fischer-Tropsch process meet this requirement. The synthesis provides a broad range of hydrocarbons by reacting CO with H_2. Main products of the process are olefins and paraffins besides water as side product, but oxygenated hydrocarbons are also generated. Selectivity and conversion rates towards certain products can be controlled by the catalysts and reaction parameters used (van der Laan & Beenackers, 1999). Coupled with the process to produce synthesis gas from CO_2 and H_2 the Fischer-Tropsch process can generate synthetic diesel or kerosene in a sustainable way. CO_2 could directly be used in the mentioned process via the reversed water-gas shift (Choi et al., 2017).

3 Method

To expand the scientific knowledge about CCU with the knowledge of the chemical industry expert interviews were used. The interviews were structured by a guideline with main questions, so every interview followed the same scheme. The guideline was designed to be open for detailed questions and expert specific questions. This approach allowed to generate usable information without large excurses. Additional information could also be generated using this approach (Gläser & Laudel, 2010). The following catalog of criteria has been used to find qualified experts in the field of investigation. Experts did not have to fulfill all of the criteria mentioned in the catalog, as this is partly impossible.

- Knowledge about CCU
- Knowledge about sustainability
- Knowledge about regulatory affairs
- Deep knowledge about specific companies
- Broad knowledge of the chemical industry
- A suitable position in the organization
- Diversified points of view

Of the 23 experts requested, 13 accepted and participated in an interview. It was possible to conduct interviews with experts from all three requested areas: industry, consulting and public authorities. The lowest proportion of experts came from public authorities. The composition of the experts is shown in table 1.

The interviews have been recorded and transcribed verbatim to avoid losses of information. A qualitative content analysis has been used to analyze the transcripts and derive results. This is particularly suitable for the open conceptualization of investigations and the identification of essential areas (Mayring, 2015). For an easier analysis the software MAXQDA has been used (MAXQDA, 2021). A category system has been constructed to extract information from the transcripts. Following the general conceptualization of the analysis, the category system has been designed in an open manner. This allowed to include aspects that have not been anticipated (Gläser & Laudel, 2010). A schematic representation of the category system is shown in figure 3. After analyzing and aggregating similar aspects, the information was structured and compiled to form the results in the next chapter. The subsequent discussion contextualizes the results of the analysis and the findings from the literature.

Table 1 Composition of interviewed experts.

Overview of Experts	Industry	Consulting	Public Authorities
Request	12	7	3
Consents	5	7	1

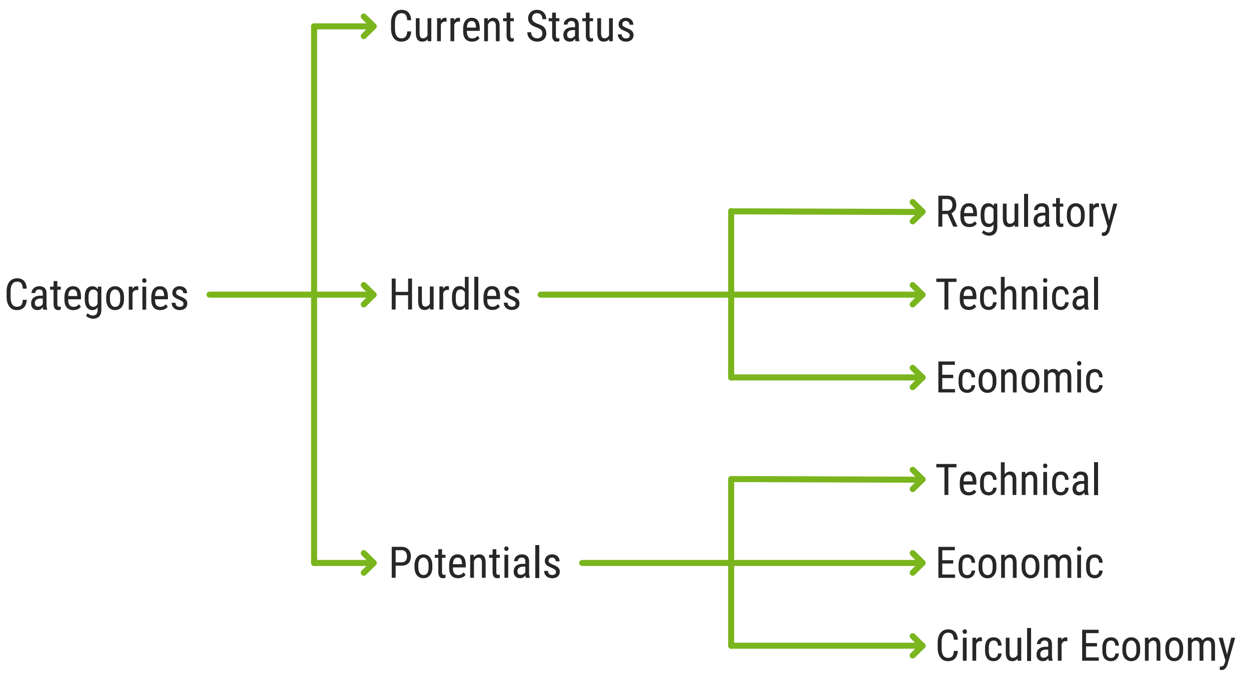

Figure 3: Schematic representation of the used category system.

4 Results

4.1 Current status of CCU

Using CO_2 as a raw material in the chemical industry has so far been based on the idea of using it where it seems energetically viable. Products that are higher in energy terms are obtained from energy-rich raw materials such as natural gas and crude oil. The new idea of CCU is to replace these raw materials and include more energetically expensive processes. With the rising priority of climate change discussions, such projects have received government funding in Germany. A well-known product of these subsidies is "Cardyon", which is produced by Covestro. The synthesis process of "Cardyon" involves high-energy reactants besides the CO_2. Therefore, the use of CO_2 to improve the environmental assessment of the process lends itself. In addition to the energetically overloaded synthesis pathway, the prospect of a margin bonus through the "green" production of premium products is also a driver for the implementation of CCU processes.

The majority of CCU processes, for example the production of highly discussed products such as fuels or plastics, are not commercially viable yet. On the one hand, this is due to the high amounts of energy required to get the inert CO_2 molecule to react. For the carbon footprint of the products to actually be improved by the CCU approach, only renewable electricity must be used. On the other hand, CCU processes are at the beginning of their development and the efficiency can still be significantly increased. Compared to conventional fuels and petroleum-based chemicals, whose production processes have been improved over decades, CCU processes are still at an early stage. Thus, the efficiency of the processes is difficult to compare so far.

4.2 Regulatory Hurdles for CCU

4.2.1 Political perspective

Due to societal pressure, political boards have become strong drivers of climate protection. They initiate large funding programs for projects in the field of sustainability and quotas regulate recycling and the use of fuel additives. Thus, political boards are also a driver for the development of CO_2 utilization processes. Accordingly, developments in this area depend on politics and its decisions.

To get large companies to invest in CCU technologies a clear direction must be set by politics. An example is the handling of CCS. If large amounts of CO_2 are stored by CCS in the future and the economy continues to be based on fossil fuels, then alternative processes such as CCU will have a weak economic position. Similarly, the required duration for CO_2 to be bound in products is a concern. The supposed advantage of CCS is that it can sequester CO_2 indefinitely, whereas most CCU processes can only store CO_2 for a certain duration, from weeks to a few decades. For example, if a sequestration period of several years is required, then the use of synthetic fuels in transport, especially in aviation, is not feasible.

Recently, there have been many serious changes in the political framework in the energy sector, but also in related areas. These short-term changes within one or a few legislative periods make it difficult to calculate the profitability of plants that will only pay off after decades. The political framework must be more stable so that companies can calculate with a certain degree of planning reliability. Investments in CCU technologies must be viable for at least 30 years. The risk for companies to invest in such a technology and the required plants would otherwise be too high. This means that politicians must set up conditions that will last beyond a few legislative periods.

4.2.2 Deductibility of CCU in the EU ETS

The EU ETS is the central instrument in Europe for the mitigation of climate change. Storage of CO_2 in the sense of CCS is deductible in the EU ETS, so no certificates have to be handed in for stored CO_2. Besides one specific exception, this deductibility does not apply for CCU. Although CO_2 can be captured with these processes and, depending on the product type, is not emitted for a long time, companies are not able to take advantage of this cost benefit.

Deductibility of CCU in the EU ETS would enable the greatest CO_2 reduction potential of CCU. By transferring CO_2 from other sectors to chemical companies, the potentially bound amount of CO_2 increases enormously. However, without deductibility, no company would pursue this effort, as it would not be an economic advantage. Power, cement and steel plants, but also other industrial facilities, will continue to emit CO_2 for decades. Especially in developing and emerging countries, the economy is expected to decarbonize more slowly than in the EU. By using CCU the emissions of these industries could be bound in products and a contribution to climate protection could be made before the decarbonization of these industries is finished.

4.2.3 Methodological basics

In order to make the use of CO_2 more transparent and set up the deductibility of CCU in the EU ETS, better methodological basics for the accounting of CO_2 emissions and bindings are needed. There are already problems with possible cases of double charging through the EU-ETS and national CO_2 trading systems. The accounting problems would be exacerbated by CCU, where the boundaries between emissions, reductions and avoidance can quickly become blurred. The following example will exemplify the problem.

If CO_2 from a cement plant is converted to synthetic fuels by the chemical industry, to whom is this CO_2 reduction credited? How high is the reduction of CO_2 emissions compared to conventional fuel? Theoretically, the CO_2 reduction would be exactly 50%, due to the substitution of fossil fuels. Consequently, who pays for the EU ETS allowances for the other 50 % of CO_2?

These questions highlight the challenges of implementing CCU in the regulatory context. They need to be clarified through life cycle assessments and implemented in legal frameworks to provide certainty for companies and consumers. On the other hand, a clear regulatory framework in this area is also important for states, as CCU together with sector coupling and globalized companies could open loopholes to remove CO_2 from a company's balance sheet, even though it is actually emitted.

4.3 Technical Hurdles for CCU

4.3.1 Efficiency and Effectivity

An important technological hurdle is the low efficiency of CCU processes. This depends on the level of technological maturity and the associated scaling effects. The efficiency is expected to increase with a growing plant fleet and experience effects.

However, some processes such as the co-electrolysis also have process-related drawbacks. Most conventional chemical processes operate in a solvent or gaseous state. This makes it much easier to create scaling effects with conventional processes. Electrolysis processes are bound to the surface of the electrodes. Increasing the surface area of a system is more challenging and thus more costly than its volume. This is also true for water electrolysis, which is an important prerequisite for many CCU processes.

Another issue is the effectivity of CCU. CCU can presumably help to save CO_2 emissions and substitute fossil raw materials. However, the question arises to what extent this

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is possible. If the example above of synthetic fuel based on CO_2 from a cement plant is used again, then the theoretical reduction of the total CO_2 emissions would be 50 %. This is because no fossil oil is needed to produce the fuel. In practical comparison, the reduction would be less than 50 %, because the transport and conversion processes have to be included. In addition, there is the important question of whether a 50 % reduction is sufficient to meet climate goals. As things stand, a 50 % reduction will not be sufficient. Thus, it is questionable whether more long-term binding methods like CCU based chemicals can withstand the requirements to achieve the climate targets.

4.3.2 Balance of Energy

An inherent problem of CCU is the energy balance of most processes. Efficient chemical processes are preferably designed to move from a high-energy feedstock to a lower-energy product, to reduce the amount of input energy required. Now, CO_2 is a very stable and low-energy molecule. In the case of CCU, a low-energy molecule is used and higher-energy products are produced. It thus contradicts an energetically efficient chemical process. Most of the chemical products can be generated with moderate energy input using CCU processes. However, the production of synthetic fuels poses an even greater problem. These materials are used in particular because of their high energy density and represent a significant market potential for CCU. The desired energy density for the production of synthetic fuels from CO_2 must be supplied by large amounts of renewable energy. This problem, which arises directly from consideration of the desired reactants and products, is one of the main drawbacks of CCU and will not be solvable due to its intrinsic nature.

4.3.3 Electricity and Hydrogen Demand

The decarbonization of the economy is accompanied by its electrification. Electrifying the entire economy will require large amounts of "green" electricity, which is not yet available. Renewable energy expansion is accelerating, but current expansion targets cannot keep up with the economy's electrification goals. Thus, renewable energy could become the bottleneck of the economic transformation.

Manufacturing chemical and petrochemical products with CCU processes would require large amounts of "green" electricity. On the other hand, for climate protection reasons, it also makes sense not to use renewable electricity in CCU processes with high priority. This is because other measures to reduce CO_2 emissions, such as the use of heat pumps or the electrification of transport vehicles, more efficiently convert the electricity used into CO_2 reductions.

Hydrogen is often needed to manufacture products through CCU. However, it will also reach a greater demand in the future in other sectors of the economy, such as the steel industry. The supply of "green" hydrogen is likely to lag behind demand in the next few years. Thus, CCU processes with a high hydrogen demand, such as synthetic fuel synthesis or co-electrolysis, are in strong competition for this raw material.

4.3.4 Carbon Capture

CO_2 capture from point sources is the only economic option to avoid CO_2 emissions through carbon capture in the short and medium term. Contrary to the common belief that CO_2 is a waste material and therefore free, carbon capture is energy intensive and expensive. In addition, depending on the flue gas captured and the desired synthesis pathway, capture is complex because impurities and trace substances have to be filtered out. The concentration of impurities in the exhaust gas of waste incineration plants, which could serve as a suitable CO_2 source in the long term, is particularly high. Thus, not only the technical maturity of CO_2 utilization needs to make great progress, but also the preceding process for raw material extraction for CCU.

While Direct Air Capture is an ideal solution for today's economy and would significantly improve the long-term environmental assessment of CCU technologies, the concentration of CO_2 in the atmosphere must be considered. The concentration of 0.04 % CO_2 in the atmosphere is hardly sufficient for technical purposes. Even though there are initial pilot projects, the capture of CO_2 from ambient air on a large scale is not yet economically viable. The volume flows alone, which would have to be moved to capture several tons of CO_2 per day, would be enormous. This would further increase the energy input of CCU processes. Coupled with the general scarcity of renewable energy described above, it is more economical to tap point sources while they still exist.

4.4 Economic Hurdles for CCU

4.4.1 Costs

As the chapter on CO_2 capture already shows, the raw material CO_2 is an expensive basic product. Compared to crude oil, which is a high energy raw material, the price is not

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competitive. This increases the cost of all CCU processes. Depending on the origin of the CO_2, costs can vary widely, but cheap sources such as natural gas production sites are not in the spirit of the circular economy and contradict the principle behind CCU.

In addition, CCU processes require the addition of energy, which crude oil or natural gas already provide. This means that large amounts of energy are required. These energy quantities must come from renewable sources as described above, otherwise one of the core ideas behind CCU is invalidated. As the demand for "green" electricity increases in the future, the price is also likely to rise. Thus, operational costs of CCU will not decrease in the short and medium term.

This is a particular problem for the economic viability of CCU, as operational costs make up a large part of total costs. That is due to the target size of production facilities for CCU products. In order to utilize economies of scale as efficiently as possible, very large plants are planned. As a result, the investment costs are high, but in comparison, the operating costs are disproportionately higher due to the high scaling of the plants. Hence they dominate investment decisions of participating companies.

4.4.2 Entrepreneurial Risk

Companies constantly have to take certain risks in order to develop innovations. As the following aspects show, the risks surrounding CCU they are very high. So many chemical companies do not invest in the new technology. There is little planning security, which makes companies tend to act conservatively. This is because there have hardly been any economic success stories in this area to date. There are also foreseeable organizational problems, as new supplier relationships will have to be created. While there have been hardly any relationships between industrial sectors in the past, CCU would have to rely on these intersectoral supply networks. For example, steel plants would have to become suppliers for chemical plants. However, there is a risk that these steel plants or other suppliers will be decarbonized in the long term and thus no longer be able to act as suppliers.

On the other hand, CCU is very dependent on the political perspective. As long as CCU is in competition with the use of fossil raw materials, real economic viability cannot be achieved. It can only be achieved through government levies or quotas. As a result, companies are more strongly influenced in their decisions by the government than in other technologies and business areas.

4.4.3 Margin

The costs addressed above have a direct impact on the achievable margins of CCU products. A significant proportion of the population is interested in sustainably produced goods and is slowly becoming more willing to pay for these products. However, the higher prices are not enough to absorb the increase in production costs due to CCU. This is because these higher margins have largely been achieved by companies at the end of the value chain. These companies still claim low purchasing costs for their products from the upstream value chain. Since the chemical industry rarely sells directly to the end consumer, but mostly bears the additional costs for the use of CCU processes, the margins at this point in the value chain are lower.

4.5 Technical Potentials of CCU

4.5.1 Technical Maturity

The current technical level of CCU is not yet high enough to build large industrial plants, but some demonstration plants for selected processes are already in operation. Since many CCU processes have already been tested in an industrial environment, the number of demonstration plants can be increased significantly in the next few years. By 2030, many demonstration phases could be completed and the construction of industrial plants could start. Due to the role model function of pioneer companies, like Covestro, the overall development speed could increase and more companies could start the implementation of CCU technologies. This is also due to the feasibility of CO_2 utilization, because there are no scientific rules opposing it. One example is the production of synthetic fuels via Fischer-Tropsch synthesis. The principle has been known for a long time, but it has only recently been tested for large-scale production and applied industrially.

The rapid development of adjacent technologies such as water electrolysis is another positive aspect for CCU. This is because most CCU processes can only be performed with large amounts of "green" hydrogen. Due to the rapid development, the high hydrogen demand of CCU could be covered more easily in the future.

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4.5.2 Large field of application

A variety of possible applications of CCU have already been shown. Modern chemistry makes it possible to use CO_2 in various processes and to produce diverse chemical end products. This dimension of possibilities opens up great potential for CCU, as it makes the technology interesting for many companies. From basic chemistry to specialty chemistry and in the pharmaceutical and cosmetics industry, CCU can be used in almost all areas of organic chemistry. In the construction industry, mineral carbonation can also be used to bind CO_2 and improve the performance of materials.

While classical chemical conversion still accounts for the majority of CCU processes, more and more electrochemical processes are also being developed to utilize CO_2. In addition, biotechnological processes are being researched in the CCU sphere, like the Rheticus project by Evonik and Siemens. This project uses bacteria to produce butanol and hexanol. The project is particularly interesting because C4 and C6 molecules can be produced directly from CO_2. Overall, CCU processes can be used to produce almost all relevant products in the organic chemical sector via various intermediate stages.

4.5.3 Platform chemicals

The wide range of applications of CCU is mainly due to the possibility of sustainable production of basic materials such as methanol, but also other important basic products such as alcohols and carboxylic acids. Since large parts of today's chemistry are built up from these basic chemicals, the CO_2 footprints of downstream products are also reduced.

Methanol in particular could be used as a platform chemical in the future, which can be produced directly from CO_2 and H_2 and serve as a basis for a variety of chemical end products. This is due to the chemical structure which can easily be converted into various products and the possible scalability of the production process of methanol. Since methanol can be used directly in fuels as a blending component or converted via some intermediate steps to polyoxymethylene dimethyl ether, which serves as an additive for diesel, the large automotive market can also be addressed.

Furthermore, methanol could be used as a chemical energy storage, so that surplus renewable energy is converted into methanol on site and can be stored and transported more easily. This would be a great advantage for remote locations that can efficiently produce solar or wind power. Methanol can be easily converted back into electricity during times of high energy demand.

4.6 Economic Potentials of CCU

4.6.1 Scaling effects

An important factor in reducing the costs and increasing the economic viability of CCU is scaling. So far, the largest projects are still in the demonstration phase and industrially relevant quantities are not being produced yet. The processes studied are scalable, because companies examine the scalability before investing in a technology. Only by using high scaling effects plants can reach production costs that are competitive in the international competition. As soon as the first industrial plants are built in the future, production costs will also fall due to natural economies of scale. Due to technical drawbacks mentioned above, this effect could be lower for electrolysis processes than generally assumed. Nevertheless, the costs of this type of CCU process will also decrease due to scaling. In addition, there are experience effects that increase the efficiency of a process the more it is used. To date, this effect is very small for CCU technologies. But in the future it could contribute to cost reductions.

4.6.2 Increasing margins

Companies that use CCU processes can exploit premium products or sustainably labeled products to economically serve the market. In the case of premium products, the price increase due to the use of CCU is less significant for the overall price of the product. Therefore, consumers are not discouraged to buy the product as much. This can be explained using a car as an example. If the conventional car costs 100 % and all the plastics in the car account for 5 % of the cost, then doubling the manufacturing cost of the CCU-based plastics would only result in a total price of 105 % for the car. This means that a price premium would be lower in proportion and demand for the car would fall less. This effect could be exploited with many premium products that are close to the customer or products that have a low material cost share in the total costs.

Higher margins can also be achieved with sustainably labeled products. Today many customers are willing to pay a price premium for "green" products. So far, this purchase behavior has been limited mainly to certain customer groups, but the customer base appears to be growing in the next years. As more and more companies recognize this potential, the

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range of products that could be marked with such a "green" label is growing. This perspective is particularly interesting for companies at the end of the value chain, but the aspect is slowly penetrating higher levels of the value chain as well. This is motivated by the increasing awareness of sustainability along the entire value chain and by companies demanding better product carbon footprints from their suppliers. In addition, margins for "green" products could rise sharply in the short and medium term due to increasing demand, for example if public procurement procedures are linked to sustainability criteria. Demand could then grow rapidly, while the supply can only rise up slowly due to newly built plants.

4.6.3 Prices

CO_2 taxes and levies will rise continuously in the coming years. In the EU, the expected price increase in the EU ETS, even if CCU is not counted in the system so far, will lead to an increase in the price of fossil-based alternative processes. CCU will thus benefit indirectly. With the foreseeable levy increasing and other coming governmental subsidies, many CCU processes could become economically competitive with their conventional alternative processes in a relatively short time. Some projects are already close to an economic break-even and could be operating on an industrial scale before 2030. The cost increase of conventional processes could then lead to more companies turning to alternative processes.

If CCU becomes deductible through allowances in the EU ETS in the next few years, the industrial implementation of CCU could make a leap forward. Because companies would receive money for processing the raw material CO_2 through CCU. In addition, chemical companies could convert their own CO_2 emissions into products and thus reduce their costs. Also, CO_2 from other industries could be used and a market for CO_2 could be emerge. This would make CO_2 a commodity with a financial value. The deductibility of CCU in the EU ETS would significantly increase the profitability of many CCU applications and could encourage companies to invest in this area. With a price of 50-100 € per ton of CO_2 in the EU ETS, which is expected in the coming decades, many CCU processes would be economically viable and could be rolled out more quickly due to greater interest by investors.

4.7 Contribution to the Circular Economy

There will be a carbon demand in the chemical industry in the future, even if the society acts more sustainably and tries to reduce the use of corresponding products. If fossil raw materials are no longer allowed to be used as a carbon source in the future, only three major sources will be available to meet the industry's demand for carbon.

There is the recycling of plastics, where a distinction must be made between mechanical and chemical recycling. The former is highly efficient in terms of energy, since plastics can be reused without requiring a high amount of energy. Chemical recycling is on the verge of a major breakthrough and the processes developed are very promising. It will lead to a reduction in the amount of residual waste incinerated. Both recycling methods can open up usable carbonaceous waste streams for the chemical industry.

The second source is biomass. Apart from the processing operations, the use of biomass to manufacture products is always carbon neutral and therefore attractive. Even high-energy biofuels can be obtained from energy-rich bioproducts such as vegetable oil or sugar. However, the industrial use of plants always comes with the disadvantage that these agricultural areas cannot be used for food. This problem will increase with a rising world population und climate change. In addition, food production is likely to be prioritized over industrial use of biomass, so the latter may be curtailed in the future.

CCU represents a third option to meet the demand for carbon. In theory, CCU could supply carbon to the entire chemical industry. This would mean a significant additional effort for the industry, since all products would have to be built up from a C_1 molecule, but in modern chemistry it would be possible with just a few exceptions. In terms of quantity, there should also be sufficient CO_2 available. At least in the medium term it is unconceivable to assume that the major CO_2 emitters such as power plants and industrial plants will be electrified worldwide. If there is a long-term shortage of efficient CO_2 point sources, capture of CO_2 from ambient air could be used. CCU with Direct Air Capture as a CO_2 source would also create a fully closed carbon cycle within the chemical industry. However, since this technique is more inefficient than using point sources, it would only be used if point sources were not available. Or if this separation method is required by customers.

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Practically, CCU will probably not have to meet all the demand for carbon on its own. Nevertheless, CCU can bridge the gap between the supply through mechanical and chemical recycling, the bioeconomy and the demand of the chemical industry. Thus, CCU can contribute to a fossil-free economy. In the chemical industry, the use of CO_2 could have a double positive effect because it can produce its own products from CO_2, which are thus managed in a circular way. On the other hand, by using CO_2 from external point sources, it can also help other sectors to advance the circular economy and contribute to climate protection. In many sectors, this could only be a transitional solution, for example in the steel sector, which will switch to direct reduction with hydrogen in the long term. In other industries, which have unavoidable CO_2 emissions, this industrial symbiosis could be of a long-term nature. So, CCU results in a high contribution to the circular economy for the chemical industry.

5 Discussion

With regard to regulatory hurdles, the recognition of CCU in the EU ETS presents itself as one of the main problems. This problem could be addressed by the EU in the near future, as the EU's Circular Economy Action Plan will also establish a regulatory framework to certify the removal of CO_2 from the atmosphere. However, the extent of deductibility of CCU in the EU ETS in the sense of the chemical industry is still an open question. It must be taken into account that there are other CO_2 reducing technologies that are more effective for climate protection and are therefore given higher priority by policymakers. Examples include the installation of heat pumps in buildings and electromobility. Thus, it may be that CCU is deliberately promoted less to steer companies directly towards these alternative technologies. Nevertheless, there is a political will to focus on sustainable technologies in the EU in the long term. So regulatory hurdles in this sector could be reduced in the future.

The big problem from a technical and economic perspective is the efficiency of CCU processes. Even the most sophisticated technology will not be able to change the energy level of CO_2. However, modern catalysts can significantly simplify the conversion of CO_2 in terms of energy and thus improve the overall energy balance. The efficiency of CCU with regard to the use of renewable energy and also hydrogen will probably be the biggest issue in the coming years. This is because many industrial sectors will require these resources and the supply can only grow at a limited rate. For example, the chemical industry alone could use as much renewable electricity after the electrification as Germany currently produces in total.

Companies investing in CCU today are taking a risk by doing so, as they will have to invest a lot of research work and money in the processes before they can be used commercially. In addition, the processes are highly dependent on the regulatory framework. Therefore, it is difficult for many companies to approve investments in CCU processes. This high entrepreneurial risk can be reduced by some support measures, but the currently high and uncompetitive costs remain for the time being. In addition to the risks of the technology itself, new supplier relationships for CO_2 from point sources will need to be formed. However, chemical companies must accept the risk if they want to be among the pioneers and thus among the winners of the technology if it becomes permanently established. Tesla is a good example for an early adoption of a sustainable technology and demonstrates the economic advantage of such investments. The development of CCU processes, which are not profitable today, could therefore be seen as an investment in the future.

The scalability of CCU is an important criterion for the cost degression of the technology. This relates to both the production processes and the sales markets. The production of methanol by CCU could play an important role, since this market is already large and the process is known and easily scalable. The advantage of fuels based on methanol or other synthetic fuels is that they can be used without major modifications to conventional systems. This applies to cars, but also to aircrafts and ships. Particularly in the area of long-distance transport, i.e. in the area of aircraft, ships and also trucks, these fuels have great potential due to their high energy density. A chemical economy based on methanol is also a possible future scenario and could significantly increase the market potential of sustainably produced methanol.

Undeniably, CCU is a way to establish a circular economy for the chemical industry. It can be built up in cooperation with other industries by using point sources or within a closed loop by capturing CO_2 from ambient air. Since the first alternative would provide a transitional solution for many industries and is more efficient, it should be prioritized. In the long term, a switch could be made to Direct Air Capture once point sources are decarbonized. The advantage of

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this circular economy for the chemical industry is not only the sustainable and climate-friendly production of its products, but also the increasing independence from oil and gas imports. Decoupling from fossil resources and using sustainable processes could also improve the image of the chemical industry in the long term.

The use of CO_2 as a raw material can reduce the emissions of the chemical industry and even emissions of other industries. In contrast to many other emission reduction options, it is possible to create value in the process. However, the absolute reduction potential strongly depends on the products manufactured and there are many other technologies, that have a higher CO_2 reduction potential per amount of renewable energy used. Nevertheless, CCU is becoming an important technology on the way to a carbon-neutral economy. In certain sectors, carbon-containing products will be used forever and a complete mechanical and chemical recycling will not be possible. To meet the residual carbon demand, only CCU remains. The bioeconomy will probably only be able to contribute a small part due to population growth and the reduction of agricultural land due to climate change. Moreover, unlike almost all other approaches, CCU can recapture CO_2 already emitted while contributing to value creation. This will likely be necessary in the future due to already high concentrations of CO_2 in the atmosphere that have to be reduced to an acceptable level. So CCU will not be the universal solution. But the technology can make an important contribution to climate protection and the circular economy.

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Commentary

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Is the EU Green Deal channelling a transition towards a sustainable chemical industry?

1 Action Plan for the Green Transition of the Chemical Industry – Transformation for People and Planet

In our everyday life, chemicals play an important role. The renewable energy sector, the healthcare sector, the telecommunication sector, the food sector - no industrialised country could do without the supply of chemicals of a wide variance. Therefore, it is all the more important that production, use and disposal of chemicals are managed in a sustainable way.

To strengthen Europe's chemical industry, we need a policy that connects economic and industrial policies with the conservation of human health and nature. Safe and sustainable chemicals "Made in Europe" should be the new standard. This vision would contribute to the accomplishment of our climate goals and ensure that everyone is living well within our planetary boundaries. To achieve this, the EU needs a holistic policy framework. It is of key importance that all services of the European Commission (COM) effectively implement the EU Action Plan: "Towards a Zero Pollution for Air, Water and Soil" (Zero Pollution Action Plan, ZPAP) of the European Green Deal. We need this paradigm shift in order to make sure that production, use, and disposal of chemicals and the use of products containing chemicals do not harm human health nor human rights nor ecosystems. This cannot be achieved by pleas alone. Producers must take responsibility for the entire value chain of their products, from downstream users to safe end-of-life procedures. The existing legislative framework has to be complemented and strengthened. Building on the do-no-harm principle enshrined in the EU's Green Deal, we published a ten-point action plan for the Green Transition of the chemical industry (Paulus and Giegold 2020a), followed by an extensive debate with the European Commission, the European Chemical Agency ECHA, and the chemical industry (Paulus and Giegold 2020b). In the following section, I briefly present this plan, going into detail for some of the actions needed for the transition.

1. **Apply and enforce EU law rigorously.** REACH is our best legislative framework to reach the ZPAP. Nevertheless, more than 10 years of experience with REACH show, that implementation and enforcement must be improved. To successfully protect human health, including that of workers, animal health and the environment, we must refine the principle of "no data, no market" towards "no proper data, no market". Today, a much too high share of the data delivered is not adequate. For some chemicals, material safety data sheets (MSDSs) don't even exist at all. The larger part of industry invests considerable time and money in fulfilling their duties though; therefore, not acting on incompliance gives laggards a free ride and distorts the level playing field. Member States should consequently apply substantial penalties for non-compliance with chemical laws. The continued occurrence of banned phthalates in children's toys or of harmful chemicals like PFAS (per- and polyfluoroalkyl substances) in food contact materials is intolerable. Up to now, the ECHA has not been able to fulfil all its tasks in a timely manner, due to lacking sufficient and predictable funding. For example, the NGO ChemSec has compiled a SIN ("substitute it now") list (ChemSec, 2021) of hazardous chemicals, building on REACH data. Only a fraction of these substances is found on the REACH SVHC (substances of very high concern) candidate list (ECHA, 2021a) yet. The fast-

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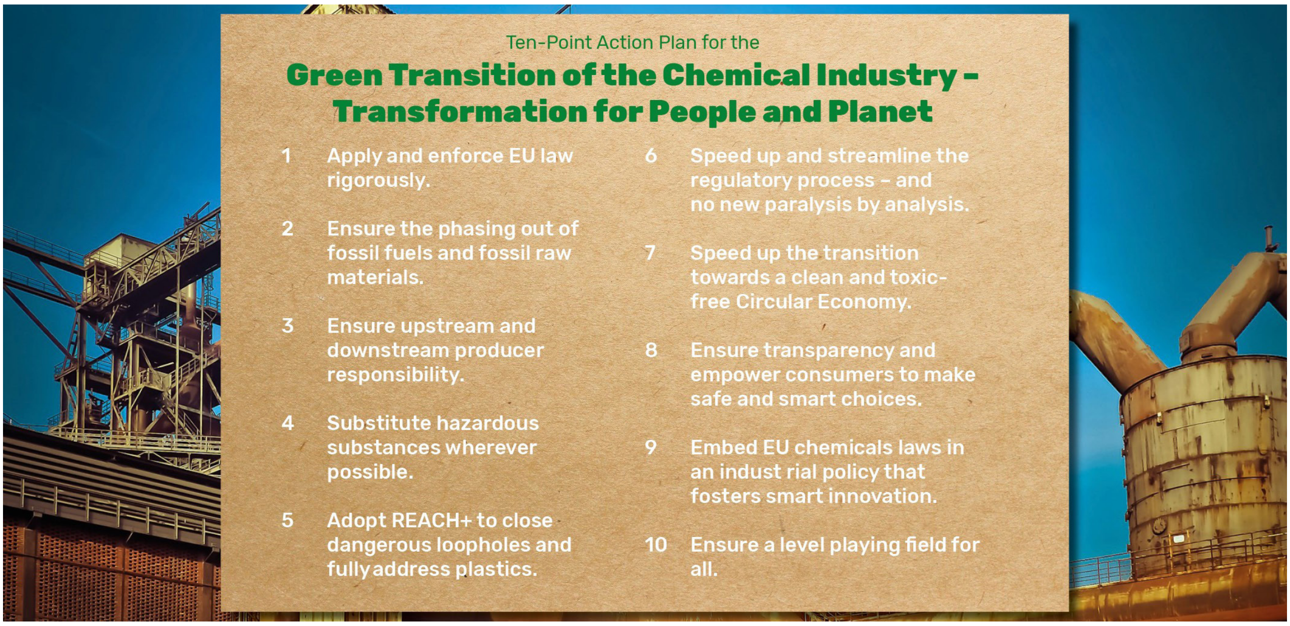

Ten-Point Action Plan for the

Green Transition of the Chemical Industry – Transformation for People and Planet

1. Apply and enforce EU law rigorously.
2. Ensure the phasing out of fossil fuels and fossil raw materials.
3. Ensure upstream and downstream producer responsibility.
4. Substitute hazardous substances wherever possible.
5. Adopt REACH+ to close dangerous loopholes and fully address plastics.
6. Speed up and streamline the regulatory process – and no new paralysis by analysis.
7. Speed up the transition towards a clean and toxic-free Circular Economy.
8. Ensure transparency and empower consumers to make safe and smart choices.
9. Embed EU chemicals laws in an industrial policy that fosters smart innovation.
10. Ensure a level playing field for all.

Figure 1 Ten-Point Action Plan for the Green Transition of the Chemical Industry proposed by MEPs Jutta Paulus and Sven Giegold.

track procedure for consumer use has to be extended to all SVHCs. Also, national enforcement bodies of the Member States need sufficient capacities to ensure the enforcement of EU chemicals legislation. The EU Commission as guardian of the treaties must not tolerate Member States neglecting their duties and has to open obvious cases of infringements without delay. The same is true for other environmental laws such as the *Water Framework Directive* or the *Industrial Emissions Directive*. Finally, the COM should withdraw its appeal to the judgement in case T-837/16[1] and fully apply it. The continuous use of pigments that are carcinogenic and toxic for reproduction in paintings of bridges and road marking has to stop immediately.

2. **Ensure the phasing out of fossil fuels and fossil raw materials.** The chemical industry must contribute its fair share to the EU's goal of reaching climate neutrality by 2050 at the latest. This requires enormous investment in renewable energy and electrification. Similar to the "efficiency first" principle in sectors related to energy, it is "electrification first" when it comes to replacing fossil fuels in industrial applications. Electricity from wind and solar is cost competitive today, but it is highly necessary to remove bureaucratic and fiscal barriers for its use. The guardrails for a climate neutral chemical industry have to be set today, as new production plants will run for thirty years and more. Therefore, it is crucial that no new investment into fossil infrastructure is made in the next years, and the EU and the Member States should make effective use of economic instruments to

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[1] Judgement T-837/16 (General Court, 2019) was a case ended on the 7th of March 2019 in which Sweden, Denmark, Finland and the European Parliament went to court against the European Commission and the European Chemical Agency ECHA concerning the Commission Decision authorising the use of the carcinogenic and toxic for reproduction pigments lead sulfochromate yellow $Pb(Cr,S)O_4$ and of lead chromate molybdate sulfate red $Pb(Cr,Mo,S)O_4$ for some uses like the painting of bridges or road markings under Regulation (EC) No 1907/2006. The court annulled the Commission Implementing Decision C(2016) 5644 final of 7 September 2016 granting an authorisation for some uses of lead sulfochromate yellow and of lead chromate molybdate sulfate red under Regulation (EC) No 1907/2006 and also dismissed the request to maintain the effects of Regulation (EC) No 1907/2006 until the Commission is able to review the application for authorisation. On the 20th of May 2019 the European Commission appealed against the judgement and opened the new case C-389/19 P (Court, 2021) which was decided on the 25th of February 2021. The court renewed its decision to annul the Commission Implementing Decision granting an authorisation for some uses of lead sulfochromate yellow and of lead chromate molybdate sulfate red. But in the second part the Court had to approve the request to maintain the effects of Regulation (EC) No 1907/2006 until the Commission is able to review the application for authorisation. The REACH Regulation allows the continued use of authorised uses after the expiry of their authorisation until a decision has been taken on the new application for authorisation. Therefore, the annulment of the contested decision with immediate effect recalled into force the previous authorisation for the substances.

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incentivise climate-neutral and sustainable products and clean production (e.g. fees, environmental taxes). All processes, all appliances using fossil fuels have to be put to test: is electrification in principle possible? If not, what other options exist? Only for those processes where neither electrification nor the use of thermal solar or geothermal heat is possible, hydrogen - produced from renewable energy - should be chosen. The cost gap of roughly 3 €/kg between green hydrogen and grey hydrogen produced from fossil sources like gas or coal should be bridged with state-backed contracts for difference (cost for hydrogen 2020: grey hydrogen 0.59–2.11 €/kg, blue hydrogen 1.77–2.20 €/kg, green hydrogen 2.7–6,5 €/kg, (IEA, 2020)). The International Energy Agency (IEA) estimates the cost of green hydrogen in 2060 with 1,1–2.79 €/kg. Today, many stakeholders promote so-called "blue" (steam reforming methane with CO_2 capture) or "turquoise" (methane pyrolysis with solid carbon residues) hydrogen, where the cost gap would allegedly be lower. But the methane leakages during extraction and transport of fossil gas have to be taken into account. A study from 2020 showed that extraction in the Permian Basin in the U.S., which is one of the biggest oil-producing regions and contributes > 30 % to the total U.S. oil production (Zhang et al., 2020) has a leakage rate of 3.7 %. With methane being a strong greenhouse gas, 82 times as powerful as CO_2 over a period of 20 years, methane emissions must be curbed as fast as possible. The United Nations Environment Programme (UNEP, 2021) highlighted this in their Global Methane Assessment in May. In addition to mitigation measures such as leak repair and a ban on venting and flaring, the demand for fossil gas and oil must decrease substantially. Of course, the task to phase out fossil fuels in the chemical industry is huge. In 2019, the German Chemical Industry Association (VCI) published a "Roadmap towards a greenhouse gas neutral chemical industry in Germany", modelling that the electricity demand of the chemical industry would rise from 52 TWh (Internetchemie, 2017) in 2013 to 628 TWh per year in 2050 (VCI, 2019), which is higher than the total electricity demand in Germany in 2020 (UBA, 2021). Coming on top of the increase in electricity demand in other sectors like heat and transport, these numbers are alarmingly high. It is obvious that business as usual with electrification of existing processes only is not sufficient. We need new approaches in the chemical industry. A useful tool would be the development of "renewable building blocks" that can be assembled in many ways serving different purposes and fully recovered at the end of the use phase. Today, we are using tremendous amounts of energy to crack fossil feedstock, synthesize and purify compounds, then create inseparable mixtures of polymers which in their majority are not recycled but end up in the furnace (at best) or in the ocean (at worst). To put it into perspective: German chemical industry used 20.8 Mio t carbon feedstock in 2017, 13 % of which were renewable feedstock (VCI, 2017). 18.1 Mio t of fossil feedstock to be replaced in Germany alone shows the imminent danger of depleting natural resources when fossil raw materials are substituted by bio-based feedstock. Therefore, in addition to a life-cycle analysis to ensure sustainability, we need new benchmarks for efficient production to implement the best available techniques. Polymers have become more and more complex in the last decades, making recycling more difficult. Rethinking polymer production by reducing complexity and limiting additives would boost recyclability and reduce demand for virgin feedstock.

3. **Ensure upstream and downstream producer responsibility.** The EU will adopt a *European Due Diligence Law* (EPRS, 2020) to cover supply chain management within the next years. Commissioner Reynders announced this law in 2020, the European Parliament adopted an initiative report in March 2021. Along the supply chain, producers will be accountable for violations of human rights, environmental standards and labour standards. This would put an end to hazardous substances prohibited in Europe being exported to third countries or hazardous waste being exported to the Global South for "recycling" without environmental or social standards. And on the supply side, this would ensure that the resource basis for all chemicals produced and used in Europe is ecologically sound and production respects human rights. Implementing an *Extended Producer Responsibility* (EPR) to products, product groups and waste streams would strengthen waste prevention, discourage the use of hazardous substances and improve recycling.

4. **Substitute hazardous substances wherever possible.** Regarding the journey from neurotoxic substances (lead) being added to fuel and thus widely distributed in the environment or highly bio-accumulative insecticides

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applied freely all over the world (DDT), no one would claim that nothing has changed in our judgement of hazardous chemicals. But still, problematic substances are present in toys, cosmetics, textiles, leather, and food contact materials. It is paramount to establish a toxic-free hierarchy of measures that follows the principle of safe and sustainable by design. By minimising the exposure and effectively substitute hazardous chemicals with safer alternatives, including non-chemical alternatives, the safe and sustainable by design principle would avoid production and use of hazardous substances where not essential. It is often claimed that cocktail effects of chemicals can hardly be precisely assessed. But this must not serve as an excuse for inaction! Instead, these effects should be addressed by implementing a mixture allocation factor in Annex I of REACH (European Parliament and European Council, 2006). And the upcoming revision of the *EU Toy Safety Directive* (European Parliament and European Council, 2009) can ensure that children are better protected from all hazardous substances.

5. **Adopt REACH+ to close dangerous loopholes and fully address plastics.** Amending REACH to include the registration of polymers is urgently needed. Although this is bound to be difficult due to the nature of polymers as mixtures of varying molecular weight, known adverse effects on the environment show that exemption is no longer an option. But not only polymers have escaped regulatory action for too long. Far too many substances that are persistent, mobile and toxic or very persistent and very mobile are still on the market, putting people's health and environmental integrity at risk. The legacy of DDT and PCBs which can be found in the Arctic and the deep sea should guide our action on harmful substances. Taking the precautionary principle seriously would require an early warning system to protect us from emerging issues, as well as a monitoring and reporting mechanism for unwanted effects of chemicals. Finally, the addition of energy and resource efficiency to assessment criteria for chemicals used for a specific purpose would make REACH fit for the Green Deal.

6. **Speed up and streamline the regulatory process – and no new paralysis by analysis.** "One substance – one hazard assessment" can avoid duplication of work. Risks, however, must be assessed and managed depending on the respective use and exposure. Formalising the *regulatory management option analysis* (RMOA) (ECHA, 2013) would lead to "paralysis by analysis" as a complicated process would have to be completed, where each and every use of the substance would have to be assessed separately, evaluating options to mitigate the risks of the respective use, before any action could be taken. Until finalisation of the RMOA process, the substance in question would remain on the market with no restrictions at all. Therefore, the hazard assessment should be done only once, and the substance should be put on the candidate list following the result. Essential uses can then be authorised if the risks are properly addressed and mitigated. Chemicals should be grouped both for assessment and for subsequent regulatory action in order to reduce avoidable bureaucracy, to speed up the regulatory process, to avoid regrettable substitution and to reduce animal testing. As a priority, the COM should adopt an action plan for PFAS, with the goal to phase out the general use of all 4700+ PFAS "forever chemicals", allowing only essential uses. Another striking example for missing regulatory action are *endocrine-disrupting chemicals* (EDCs). For these highly effective molecules which can lead to health problems at blood levels far below thresholds for toxicity, common hazard-based criteria should be defined and adopted across all relevant pieces of legislation as a basis for effective action to minimize exposure. Of course, this must include a ban for all consumer products such as toys, cosmetics, food contact materials, and textiles. And the Classification, Labelling and Packaging regulation (CLP) needs new hazard classes for EDCs and PBT (persistent, bio-accumulative and toxic) substances which must eventually be included in the Globally Harmonised System (GHS) on the global scale.

7. **Speed up the transition towards a clean and toxic-free circular economy.** The old model of "dig out – make - use - throw away" has to be transformed to a circular economy where waste is minimised and the bigger part of material and energy are recovered. Neither our environmental nor our climate goals will be achieved if we do not re-use precious - and limited - resources. This approach has positive side effects, such as reduction of the dependency on imports, or reduction of extraction and transport cost. Of course, high recycling rates are only possible with non-toxic material cycles. Consumers are rightfully demanding the same chemical safety

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standards for products made from recycled materials as compared to virgin materials. Therefore, the COM has to develop criteria for safe and sustainable chemicals which should not be limited to (eco-) toxicological properties, but include efficiency benchmarks (e.g. for energy use and waste) for production and processing of chemical products. The overarching principle can be summarised as “safe and sustainable by design”. But it will only become effective if we set targets to reduce resource consumption which can in turn to develop economic instruments to incentivise resource-efficient and circular products. Prioritising waste reduction over recycling in the waste sector only leaves the potential of benign-by-design untapped.

8. **Ensure transparency and empower consumers to make safe and smart choices.** A demand for toxic-free and low-resource chemicals can only be created if their advantages are known and communicable. An user-friendly public information system on hazardous substances present in materials and articles, e.g. via a mobile application, enables consumers to make sustainable choices. This could be based on existing information, such as the SCIP (ECHA, 2021b) database, which could be expanded to include information about recyclability as well as content of recycled materials, energy demand in production and adherence to labour standards. Transparency is also needed for scientific information. For far too long, inconvenient results of studies have ended up hidden in drawers. To prevent this, all studies performed for registration purposes should be reported to the ECHA upon commissioning. All toxicological and ecotoxicological studies that are submitted by registrants and applicants should be made publicly available by ECHA.

9. **Embed EU chemicals laws in an industrial policy that fosters smart innovation.** The Great Transition will not be possible by safeguarding the status quo. The EU should therefore act to bring forward the future champions in industry. Instead of extending the lifetime of the fossil economy, we should embrace the opportunity to boost investment in future-proof technologies. This is the only way to secure the 1.2 million jobs in the European chemical industry. Energy and resource efficiency in production is key for being a front runner tomorrow. Japan’s strict energy efficiency legislation which pushed industry to develop efficient technologies is a good example of achieving innovation by regulation. But while regulation is indispensable, research and education must not be neglected. Europe is not in the lead on digitalisation today and must catch up as soon as possible. But it is home to innovative SMEs, whose potential must be strengthened to develop new business models, incentivising safe and sustainable chemicals "Made in Europe".

10. **Ensure a level playing field for all.** EU manufactured products must fulfil high chemical safety standards; therefore, the same standards must also be in force for imported products. This is not only paramount to protect EU citizens against low-standard products from other places in the world. It is also vital to keep our producers competitive who have substituted hazardous, but cheap chemicals against more sustainable alternatives. To eliminate unsafe products from the market, more tests are necessary. The EU Commission can ensure this by making use of the powers granted under the *Market Surveillance Regulation* (European Commission, 2019c). Under this regulation, minimum standards for the number of samples, frequency, and conditions of the checks performed by the national authorities can be set. Testing alone will not solve the problem, of course. Considerable fines must be imposed on the producer and/or importer, when products are found in breach of EU rules. These measures are indispensable to ensure that REACH’s leading role for ambitious chemicals legislation is not subverted.

2 The European Green Deal and the chemical industry

The main focus areas of the ***European Green Deal*** can be divided in eleven different parts (Figure 2). Most of them are directly or indirectly connected to the chemical industry.

One part is the ***Sustainable Products Initiative*** (European Commission, 2020a), which will revise the existing ***Ecodesign Directive.*** The *Ecodesign Directive* itself applies only on energy-related products today. In order to channel the transition of the chemical industry towards a circular economy, an overhaul and adaptation to include environmental aspects besides energy is paramount. The COM adoption of the *Sustainable Products Initiative* is planned for Q4 2021.

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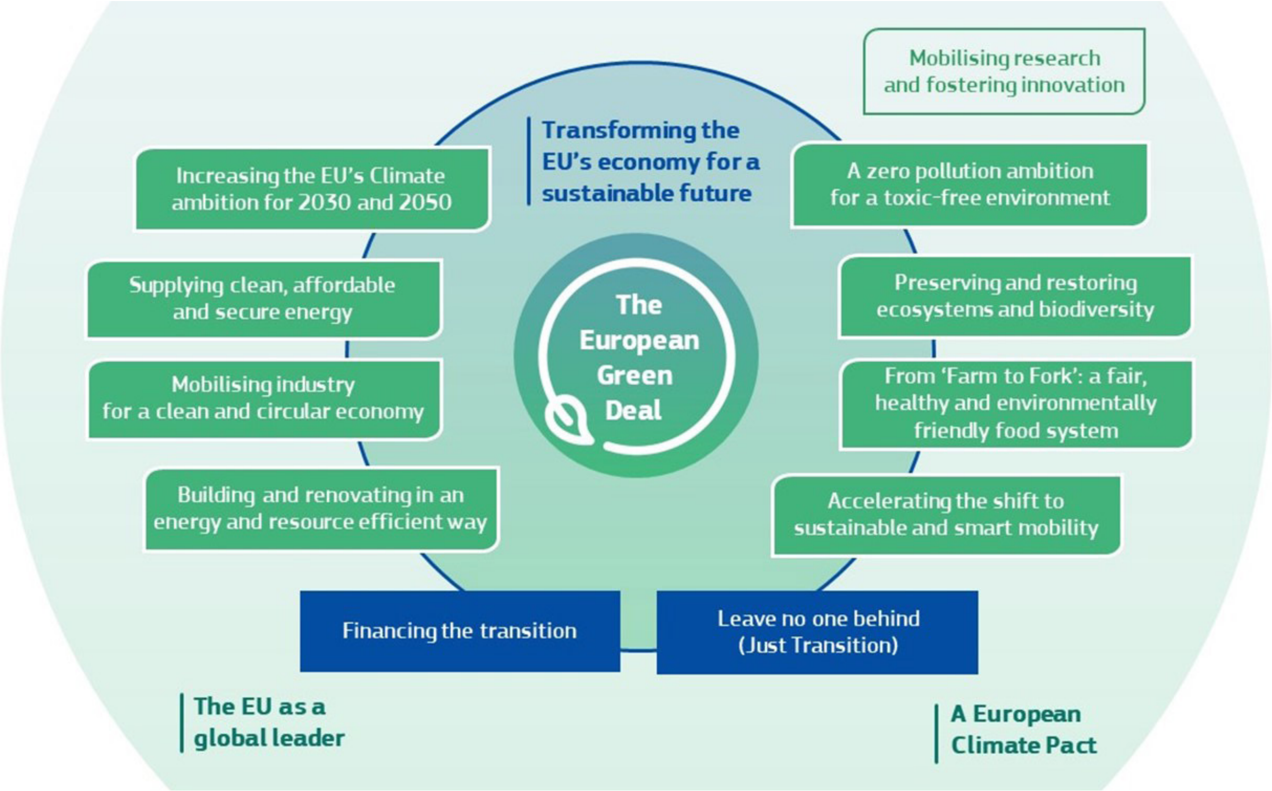

Figure 2 The European Green Deal (European Commission, 2019a).

On March 11th 2019, the COM adopted a ***Strategic Approach to Pharmaceuticals in the Environment*** (European Commission, 2019b). All phases of the lifecycle of pharmaceuticals as design, production, use and disposal are covered in this approach, unfortunately missing the opportunity to lay the main focus on the design phase. More than 20 years ago, Anastas and Warner (1998, 2021) published the "Twelve Principles of Green Chemistry" and promoted the importance of the active prevention of pollution through the innovative design of production processes and technologies instead of inefficient and extremely expensive end-of-pipe solutions. Today, even the most advanced wastewater treatment plants are not able to remove all pharmaceuticals from their effluent and most cities cannot afford to upgrade their existing plants to the so called fourth treatment stage. For production sites outside the EU, this is even more relevant. This is why we should focus on the **"benign by design" approach** (Laber-Warren, 2010) in which chemicals are designed smartly with the goal to reach the same activity with a lower impact on health and environment. Quantitative Structure-Activity Relationship (QSAR) analysis can be a great tool to design new pharmaceutically-active compounds (PhACs) or plant protection products which show better degradability leading to lower or no accumulation in the environment.

On November 25th 2020, the ***Pharmaceutical Strategy for Europe*** was adopted (European Commission, 2020b). A main goal is security of supply in the EU, but research and development for treatments for rare diseases and new antibiotics are also addressed. Sustainability of the pharmaceutical industry and the design of greener pharmaceuticals are mentioned in the strategy, but no regulatory action is announced as of today. A very effective tool to combat pollution through production of pharmaceuticals would be the inclusion of environmental standards like wastewater treatment in the principles of Good Manufacturing Practices (GMP), the minimum standard that medicines manufacturers must meet in their production processes regardless where they are taking place. These principles are monitored and audited in over 100 countries worldwide and are constantly refined by the International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use (ICH). Taking up environmental standards in GMP would ensure protection and a level playing field worldwide.

On May 12th 2021, the COM adopted the ***EU Action Plan: "Towards a Zero Pollution for Air, Water and Soil" (ZPAP)*** (European Commission, 2021). Part of this ambition is also

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the ***Chemical Strategy for Sustainability (CSfS)*** which was published on October 14th 2020 (European Commission, 2020c). PFAS and EDCs will be regulated in the CSfS. But the COM proposal still does not refer to a legally binding framework ensuring adherence to the polluter pays principle. One part of the ZPAP is the goal to reduce the amount of micro-plastic released into the environment by 30 % by 2030.

In total, the EU Green deal is a great toolbox to meet the climate goals, and to show the general direction for a transition towards a sustainable chemical industry. Compared to our "Action Plan for the Green Transition of the Chemical Industry" though, it lacks binding targets and mechanisms for legal enforcement.

3 Closing Remarks

The ubiquity of pollutants, from the deep sea to the Himalaya and the Antarctic ice shelves, should teach us a lesson. Neither the atmosphere nor the oceans are endless. The heritage of living hundreds of thousands of years in the ecological niche of "exploiters", gathering the resources of a landscape and moving on, strikes home on a humanity that has multiplied to staggering eight billion people and spread over the whole globe. And we have not only changed the visible countenance of the planet, loaded the atmosphere with CO_2 to a level not seen for millions of years, changed biogeochemical flows in unprecedented fashion and pushed hundreds of thousands of species to extinction. The long-term impact of manmade substances is impossible to evaluate today. The scientists compiling the concept of Planetary Boundaries (Rockström et al., 2009; Steffen et al. 2015) are not able to define a safe space for humanity concerning "novel entities", which encompass genetically modified organisms and artificial substances. From all what we know today, we leave our children and children's children a toxic legacy of reckless application of scientific knowledge and engineering competence. It may well be that archaeologists of the future will refer to our society as "the plastinizers" - if we succeed in limiting global heating and halting the sixth mass extinction at levels where civilisation as such can survive.

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Commentary

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Disruption of the role model closed loop mechanical recycling of PET[1]

1 Introduction

When we first started recycling plastic some 50 years ago, it was no more than a niche. We believed in saving resources and invested in the development of processes that would allow us to offer secondary raw materials gained from waste streams. Ever since then there has been much change both in regulations and public perception.

The introduction of extended producer responsibility schemes in the 1990's has favourably impacted recycling. The introduction of deposit return system for single use beverage containers in Germany achieved another step jump in collection and recycling rates. As of 2003, Germany created a separate collection of valuable materials such as polyethylene terephthalate (PET), aluminium, steel and glass from a range of single use beverage containers. The system matured and evolved and is now the provider of the largest amount of closed loop material for new food-grade bottle production.

As sustainability became more important in the 2010's, brands became more aware of the necessity of designing their beverage containers in a way that was more conducive to recycling. The colour and the label were adapted to allow better recycling and produce higher quality material following the design for recycling guidelines. Today, it is possible to produce a new bottle from 100% recycled PET as most bottles in the stream are compliant with such rules.

Recent legislation in Germany builds on the success of the past entrusting the separate collection operations with additional material. As of 2022, a wider range of beverage containers will be covered by this obligation as it is extended to juices and nectars among others. Milk and dairy products will follow in 2024. This presents new challenges to the recycling process such as dealing with multilayer structures in technically optimized bottles for the respective contents. This can possibly disrupt the current high quality of the recycled material.

2 The Problem

At first glance, a clear PET, e.g. orange juice container, seems to be equal to similar bottles containing e.g. mineral water. However, due to the requirements of the product, the otherwise perfect transparent PET bottle is often coated on the inside to allow e.g. longer shelf life. These coatings or co-polymerized oxygen barriers cannot be detected by current sorting technology such as Near Infrared Spectroscopy. Chemically, these are either PE-EVOH-copolymers or xylylene diamine-based adipamides. Aldehyde scavengers like anthranilamide may be present, too. It is currently impossible to identify bottles containing these additives and direct them towards designated quality streams for further processing. Some of these barriers may lead to a change in colour during the recycling process as the heat load necessary for recycling triggers a decomposition of the materials in the layer. The consequence of this effect is that a previously perfect transparent bottle is turned into a dark coloured material unsuitable for high end applications.

The method of roasting according to DIN EN 15348:2014 annex C is used to detect residual contamination or in this case specifically non-PET polymers such as polyamide (PA), polyvinyl chloride (PVC), polyolefine (PO), etc. which will decompose while undergoing the specific heat treatment. During one hour at 220°C, the material turns dark depending on the type and amount of the disruptive substance. This

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[1] This paper is based on a presentation by the authors held at an online conference organized by the Association of Chemistry and Economy within the Association of German Chemists and the Institute for Plastics Technology for Small and Medium Enterprises Lüdenscheid, Germany on March 25th, 2021.

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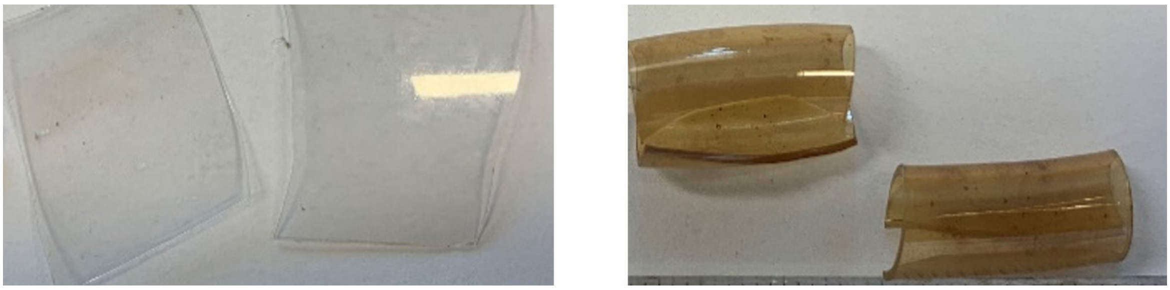

Figure 1 PET bottle sections before and after undergoing roast test.

test can both identify whole flakes out of contaminating alien polymers and coatings or layers of these substances on otherwise valuable PET. The procedure reflects the stress the material undergoes in the PET recycling process. The evaluation of the sample is an optical analysis of the resulting material. Dark coloured flakes are perceived as being contaminated or consisting of undesired polymers. Samples that are still translucid but of a yellowish or brownish colour can be interpreted as coated PET. Opaque pieces are perceived as completely consisting of non-PET material.

Figure 1 shows samples of coated PET before and after undergoing the testing procedure. The brown colour on the translucid flake is interpreted as being a PA coating on a transparent PET piece.

The decomposition of the polymer under these test conditions usually follows the radical mechanism. The trigger of the radical formation can be a trace of oxygen or other oxidising impurities, which are found in all plastics due to their production process. The oxidative degradation involves disintegration of the molecules into their monomers that differ in colour and may influence the PET in further properties.

The main degradation mechanisms can be divided into the following classes with different subsequent or parallel reactions:

- Reconstitution of monomers by depolymerisation of chain ends.
- Statistic split of the polymer chain followed by depolymerisation from the additional radical chain ends.
- Thermolysis of the PET is leading to acetaldehyde and acidic sites that serve as catalysts for further decomposition until they are decomposed by decarboxylation

In consequence, monomers, oligomers and other degradation products are formed.

The proportion of PA-based barrier and the type of barrier have a strong influence on the colouration/yellowing of the PET flakes. Some PET bottles from the same manufacturer can achieve different results in the roast test as the coating is possibly applied in different concentrations. This assumption has been confirmed by the preform manufacturers. When preforms are supplied by different manufacturers with differing production approaches or follow no standardization in the recipe for packaging production, one brand or product can achieve contradicting results with otherwise perceived equal samples. Figure 2 shows a comparison of bottlenecks of the same brand. After undergoing the roast test, it is visible that the chosen bottles have three different coatings. One bottle would be suitable for transparent bottle-to-bottle closed loop application (left), as it shows no significant colouration. The other two samples with severe browning reactions are probably coated with degradation sensitive material. The different shading between the two dark bottlenecks indicates either a non-consistent layer thickness or a variety in layer composition.

The current PET recycling process produces a high quality transparent recycled PET suitable for food grade application without noticeable colour limitations. The few yellowish flakes currently encountered in the material stream are counterbalanced with light blue pigments in lightly coloured flakes, shown in figure 3 (top right). The expected amount and type of additional bottles collected through the deposit return scheme in Germany in 2022 will severely affect the quality of the produced recycled PET as shown in figure 3 (bottom). It is possible that established bottle to bottle processes will be disturbed and customer requirements for new beverage packaging cannot be met.

Figure 2 Bottle necks after thermal load with differing results.

Figure 3 Samples of clear PET flakes after roast test (top left: no coated bottled included, top right: current deposit return scheme material, bottom: material quality expected for 2022).

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3 The Solution

To prevent the setback in quality for established closed material loops or any other high-end application, there are two possible solutions imaginable. Either a sorting procedure is reliably capable of separating coated bottles producing a separate stream for a less (colour) sensitive market. Or the barriers used in such applications are less degrading under recycling process conditions allowing the PET from the newly introduced bottles to be recycled with the current high quality transparent stream.

The first possible solution of identifying and extracting the undesired barrier coated bottles from the transparent PET stream faces two challenges. Currently, there is no technology available to reliably identify the coated bottles among other transparent PET beverage containers. The Near Infrared technology is not able to detect these thin polymer layers on PET. Alternative sorting technology based on innovative approaches such as markings or artificial intelligence is not yet available and may involve high investments for preform or bottle producers and sorting facilities. The optimum allocation of associated costs is both an economic as a societal challenge. For such an approach to be successful all producers or distributors of beverages offered in these bottles would need to make the information about their chosen coating available to waste management and recycling entities.

The long-term disadvantage of this solution is the loss of material for potentially high-end applications as the coated PET would be separated from the transparent stream and processed separately. This material would probably not be suitable for closed loop applications as the colour and amount of degradation residues exceed the requirements of bottle producers. The material would be used in downcycling applications where a return to the PET recycling cycle is not probable.

The more appropriate way forward would be to avoid applying such coatings or co-polymers accepting different product lifetimes while developing barriers that are compatible with closed loop recycling technologies. This is a challenge for all beverage industries, especially for the packaging industries that produce the bottles entering the deposit return scheme.

Looking back, this is a similar challenge like the one the appliance industries faced 30-40 years ago when the CFC refrigerants were found to be destroying the world‘s ozone-layer and had been forbidden. This industry transition of the 1990s has been analysed and could serve as a role model (Albach et al, 1998). When we look at the plastics recycling business today, we see the expectation and responsibility it is entrusted with. What was once a niche became a topic that is debated in parliaments and featured in every media becoming a good example of Amara's law which states that "we tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run". The positive effects of plastic applications are often overshadowed by discussions about littering and marine pollution. We, the whole plastic value chain, need to work together and find solutions for the challenges the world faces in regard to sustainable resource management. We need to accelerate the co-evolution of the design of polymeric materials, in particular for food packaging, the technologies to keep them in closed loop, and the relevant legal framework.

The effects of every new development affecting the material, product, or design should be assessed along the complete product life cycle. The exchange of knowledge and cooperation is a necessity to achieve true circularity. Every link of the value chain needs to be invested in building its part of the foundation for a sustainable plastics industry working for the future.

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