Framework conditions for the transformation toward a sustainable carbon-based chemical industry – A critical review of existing and potential contributions from the social sciences

Authors

Ellen Matthies, Otto von Guericke University, Magdeburg, Germany

Katrin Beer, Otto von Guericke University, Magdeburg, Germany

Michael Böcher, Otto von Guericke University, Magdeburg, Germany

Kai Sundmacher, Otto von Guericke University, Magdeburg, Germany

Laura König-Mattern, Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany

Julia Arlinghaus, Otto von Guericke University, Magdeburg, Germany

Anke Blöbaum, Otto von Guericke University, Magdeburg, Germany

Melanie Jaeger-Erben, Brandenburg University of Technology Cottbus-Senftenberg, Germany

Florian G. Kaiser, Otto von Guericke University, Magdeburg, Germany

Karolin Schmidt (corresponding author), Otto von Guericke University, Magdeburg, Germany; E-Mail: Karolin.Schmidt@ovgu.de

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Abstract

Due to the urgent need for global climate change mitigation, the use of renewable carbon sources and the application of circular economy principles represent promising ways to implement the necessary fundamental transformation toward a sustainable (i.e., carbon-neutral) carbon-based chemical industry. As this required transformation involves a multitude of stakeholders and requires broad societal support, social sciences have to be involved to inform possible transformation pathways. Although there is a growing body of social sciences research in the field of a circular plastics economy, some processes in the social sciences that have the potential to support the transformation process are still understudied. Based on a reflection of the current circular economy approach, we point out research needs in the following fields: (1) behavioral plasticity of consumer behaviors and potential side effects of mitigation strategies, (2) the dynamics of political framework conditions, and (3) the citizens' literacy as relevant supporters of the transformation. We conclude that social sciences-related circular economy research is just beginning to understand the needs and willingness of actors involved in the transformation toward a sustainable carbon-based chemical industry, clearly implying the need for further contributions from the social sciences.

Keywords

sustainability; chemical industry; circular economy; social sciences; consumers; political framework

1. A sustainable carbon-based chemical industry

In its latest report, the Intergovernmental Panel on Climate Change (6^{th} report; IPCC, 2022) states that the 1.5 °C global warming target requires immediate action and ambitious climate change mitigation policies. Particularly the chemical industry— which, to date, uses the largest amount of fossil energy and 10% of the total energy demand (Lim, 2021)—has so far been spared from carbon pricing and other effective policy measures (IPCC, 2022). Scholars in chemistry and in chemical engineering have therefore sought to realize carbon-neutrality in their vision of an upcoming “green chemistry” or “sustainable chemistry” (e.g., Marion et al., 2017; Bellona Europa, 2019).

Due to its unique features, carbon or organic compounds will continue to dominate the chemical industry in the foreseeable future. CO_2 emissions will continue to originate from using fossil fuel-based energy, but also from the CO_2 that is released when carbon-based products are decomposed at the end of their lives. Because today’s production of carbon compounds depends mainly on virgin fossil feedstock as raw material and fossil-based energy supply, the chemical industry is a net-positive CO_2 sector. Among its different sub-sectors, the production of polymers for plastics is most dependent on carbon-based materials. More than 90% of all new plastics are produced from fossil fuels (CIEL, 2017; Plastics Europe, 2018). As these materials degrade or are combusted after use, the fossil feedstocks originally used to produce the plastics inevitably end up sooner or later in the atmosphere as CO_2 emissions. Today, about 2.7 tons of CO_2 are emitted for every ton of plastic burned (Material Economics, 2018).

Against this background, Marion et al. (2017) identified three aims for a sustainable carbon-based chemical industry: recycling of fossil carbon (e.g., recycling polymers) from end-of-life products, using renewable (i.e., fossil-carbon-free) energy, and feeding renewable carbon sources (biomass, waste, CO_2) into chemical processes. The latest IPCC report goes even further. It asks for a fundamental change in the chemical industry. Specifically, the report points to the need for a sustainable carbon-based chemical industry: that is, an increased circularity of fossil carbon, a more efficient use of biomass feedstock, and direct air capture of CO_2 as a carbon source. Despite the fact that reuse and recycling are not always feasible, the IPCC strongly advocates for a circular economy (CE) with waste avoidance, product reuse, and material recycling as its core measures. The IPCC strategy is mirrored in the key targets for a sustainable carbon-based chemical industry proposed by the German chemical industry (VCI & VDI, 2023):

- **Circular economy (CE) of plastics:** Plastic waste, a secondary raw material, can cover a large part of the chemical industry's carbon requirements. A change in mentality is required in industry, society and politics. To make sure that the CE of plastics serves the net-zero target and is an industrially viable pathway, life cycle assessment must be combined with technical feasibility and economic viability analysis. A CE of plastics must be realized along the entire value chain and the recyclability of products must already be taken into account during their design and production. A complementary approach is required for mechanical and chemical recycling. In order to establish a functioning recycling market, bureaucratic hurdles concerning the transport and valorization of secondary raw materials must be removed.

- **Use of biomass:** Biomass can make a significant contribution to the supply of raw materials for the chemical industry. Climate protection is the main criterion for the sustainable use of biomass. Regarding competition with biomass use for other purposes (e.g., nutrition), a utilization cascade should be defined. Among the various uses in the chemical industry, the use of biomass for chemical syntheses should be prioritized, while the energetic use of biomass should be prioritized for high-temperature industrial processes, ideally in combination with Carbon Capture and Utilization (CCU) to enable CO_2 utilization in combination with biomass-based energy supply. The authors of the VCI and VDI (2023) study recommend maximizing the use of primary wood and renewable raw materials in the chemical industry.
- **Use of Carbon Dioxide:** CO_2 will need to become the third indispensable carbon source in the chemical industry in order to achieve the net-zero goal. CCU will be a core element of the chemical industry's greenhouse gas neutrality strategy. Thus, the required CO_2 transport infrastructure must be prepared and created.
- **Electricity from renewable energies:** A rapid expansion of renewable energy harvesting and transportation capacities, including an expansion of electricity grids, is a fundamental prerequisite for the successful transformation of the chemical industry. Flexibilization via demand side management must be exploited systematically, and electricity from renewables energies (wind, solar, biomass) must be made available at all times. For this purpose, sufficient energy storage capacity must be provided, as this is a further essential component of the overarching transformation strategy.
- **Hydrogen:** In addition to carbon, hydrogen is another indispensable resource for the chemical production, both as a reactant and as an energy carrier. According to the VCI and VDI (2023) report, as a result of the foreseeable competition in the utilization of H_2 for different purposes, the use of hydrogen should be incentivized where it cannot be substituted (especially in chemical synthesis) and/or where it can be used with high GHG savings. By the target year 2045, using exclusively green hydrogen should be aimed for. The necessary grid-based H_2 transport infrastructure is still to be created and/or existing natural gas grids to be repurposed. The development of hydrogen storage capacities is a key component of the future energy system.
- **Financing the transformation:** According to the study of VCI and VDI (2023), competitively priced electricity from renewables is a fundamental prerequisite for the successful realization of the

transformation toward a sustainable production of chemicals. In addition, a rapid market ramp-up of green hydrogen is needed at internationally competitive prices. The maximization of plastics recycling and use of sustainable biomass should be driven by favorable regulatory framework conditions and support programs, as well as a coherent financial incentive system, designed to limit excessive electricity and hydrogen demand. Climate protection contracts should ensure long-term planning security.

All these targets require fundamental changes not only in the production process technologies used for basic and fine chemicals, but in the entire value chains. This is particularly the case for the plastics industry, which is – as mentioned above – almost completely based on fossil feedstock nowadays and is a fast-growing sector. It is a central task to apply circularity principles and initiate changes in materials and design processes, as well as structural changes (e.g., Ellis et al., 2021; Schüth, 2022). Kaiser and Bringezu (2020) showed in detail that, within the German industry, CCU technologies can enhance the circularity of carbon used as a raw material by creating additional recycling cycles, and it can also compensate for dissipative losses. However, this would require high amounts of energy. The higher energy consumption that is generally associated with the defossilization of the chemical industry (see Gabrielli et al. 2023) varies depending on the transformation pathways (proportion of recycled waste versus biomass use; see Stegmann et al., 2022) and results in a fundamental competition with defossilization strategies in other sectors (Gabrielli et al. 2023).

It is therefore often claimed that sufficiency, i.e., the reduction of demand, must be an essential part of the necessary transformation of the chemical industry (IPCC, 2022). Thus, another way to address the resource and energy problem is to focus on the multiple possible loops that occur before recycling (treating recycling as the last resort when all else fails). This broader perspective integrates the debate of a circular economy (CE) into the 10R framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover; Cramer, 2017). Research on the CE addresses the multiple challenges of a circularity-oriented system instead of linear processes of production and consumption. The CE represents the fundamental basis for appropriate utilization of scarce resources (e.g., biomass) in a future sustainable carbon-based chemical industry.

Most of the analyses and studies published to date have attempted to develop/identify measures to achieve an economic system with net-zero CO_2 emissions by the middle of this century. E.g., Meys and colleagues (2021) showed that net-zero emission plastics can be achieved by combining biomass and CCU with an effective recycling rate of 70%, while saving 34 to 53% of energy. In addition, the question can be raised as to the conditions under which even net-negative CO_2 emissions could possibly be achieved. Stegmann and coauthors (Stegmann et al., 2022) showed in a detailed comparative analysis of the plastics production sector that focusing on CE targets alone can reduce the potential for negative emissions in the long term. By pursuing a circular bioeconomy (CBE) approach, a synergy between climate and CE targets can be achieved, ultimately turning the plastics sector into a net carbon sink while reducing the demand for raw materials. However, a fully recycling-based plastics sector will be impossible as long as the demand for plastics continues to grow. Future approaches and policies must therefore be geared toward initiating behavioral and societal changes that help to significantly reduce the currently rapidly growing demand for plastics.

2. The circular economy (CE) approach—does it cover all relevant aspects of the upcoming transformation of the carbon-based chemical industry?

2.1 Overview of previous CE research

CE has been becoming a more and more popular concept, prominently promoted by the EU. The European Commission adopted the new circular economy action plan (see the European Commission, 2020, for details) in March 2020 as one of the main elements of the European Green Deal (see European Commission, 2019a for an overview).

However, Kirchherr et al. (2017) claimed that "[the CE] means many different things to different people" (p. 229). In an analysis of 114 definitions, they found that the CE is most frequently depicted as a combination of reduce, reuse, and recycle activities but often does not scale up to a systemic level or relate to the concept of sustainable development.

On a fundamental level, all elements of the CE including resources, material and energy flows, chemical processes, as well as humans themselves are subject to the laws of physics. Thermodynamics were identified as a limiting factor for CE (Korhonen et al.,2018; Londoño & Cabezas, 2021) i.e., high energy demand, entropy increase, and exergy loss. The first law of thermodynamics implicates that in recycling processes, energy is neither created nor destroyed but only transformed. According to the second law, a recycling process can never be 100% energy-efficient due to inevitable entropy generation due to process-internal dissipation, resulting in a loss of exergy (energy of a system available to perform work). While new technologies are continuously developed to reduce exergy losses, there will always be unavoidable inefficiencies due to entropy generation. Hence, independent of the applied technology, new exergy input is required in each cycle to make up for inefficiencies, leading to resource consumption. To evaluate the thermodynamic efficiency of CE processes, input-output analyses (Cooper et al., 2017; Parchomenko et al., 2019), material and energy flow analyses (Parchomenko et al., 2019), and exergy analyses are commonly applied. Furthermore, the analysis of emergy (Londoño & Cabezas, 2021), a term introduced by Odum (1988) defining the amount of solar energy required to generate a product or service, is used to calculate the environmental work necessary to replace the consumed resources. In statistical entropy analyses, thermodynamic principles have been adopted to estimate the resource-efficiency of recycling processes in a CE (Parchomenko et al., 2020; Compart & Gräbner, 2024).

Georgescu-Roegen, an environmental economist, recognized the interdependence between economic productivity and the laws of thermodynamics (Georgescu-Roegen, 1971). In his notion, human welfare is based on economic production, requiring sufficient material and energy supply (in particular exergy). Due to recycling limits imposed by the second law of thermodynamics, in his opinion also CE would lead to unsustainable levels of resource consumption if the overall growth of the economic system is not limited. His theories have sparked vivid discussions about systems boundaries (Ayres, 1999 from Korhonen et al., 2018), technological innovation (Mayumi et al., 1998), and the relevance of policies limiting economic growth (Levallois, 2010), highlighting the need for interdisciplinary research between the natural sciences, engineering, and social sciences (see Section 3 for an overview).

In addition to thermodynamic implications on processes and economic systems, Korhonen et al. (2018) identified several challenges that must be addressed for the CE to be able to contribute to global sustainability. As described above, thermodynamics (i.e., a high energy demand), and associated conflicts of use regarding renewable energies are central challenges for both the transformation of a carbon-based chemical industry and also for a CE in general (see also the overview Kyriakopoulos et al., 2019). Another challenge is to reflect on and widen the system boundaries, so as to also enable the consideration of socio-economic side effects or ecological implications

Corvellec et al. (2022) stated that the CE "is based on an ideological agenda dominated by technical and economic accounts, which brings uncertain contributions to sustainability and depoliticizes sustainable growth" (p. 421). Aguilar-Hernandez et al. (2021) identified particular conditions under which the implementation of CE business models could lead to substantial reductions in CO_2 emissions. They reviewed more than 300 CE scenarios, compared them with business-as-usual scenarios and examined how both scenario types would evolve in the 2030-2050 period. They were able to demonstrate that the implementation of ambitious CE scenarios could reduce CO_2 emissions substantially with only marginal or incremental changes in GDP and employment (Aguilar-Hernandez et al., 2021).

It seems crucial to distinguish between the depth and breadth of the impact of different circular economy strategies. Potting et al. (2017) focused on the potential to reduce resource consumption by developing a cascade system of circularity. This systemic analysis includes higher levels of circularity than mere recycling, e.g., through (1) smarter product use and manufacture, for example by making a product redundant by offering the same function with a radically different product (R0 - Refuse), by making product use more intensive (e.g., through sharing; R1 - Rethink), or by increasing efficiency in product manufacture or use by consuming fewer natural resources and materials (R2 - Reduce).

Medium levels of circularity are expected for (2) the extension of the lifespan of products and its parts, by reusing discarded products that are still in good condition (R3 – Re-use), by repairing (R4 – Repair) or refurbishing them (i.e., by restoring an old product and bringing it up to date; R5 – Refurbish), by using parts of discarded products in a new product with the same (R6 – Remanufacture) or with a different function (R7 – Repurpose). Only if the two options of a higher/ medium circularity have been fully utilized, the lowest circularity level, (3) the useful application of materials, e.g., recycling (R8) or recovering (R9) of materials, come into view.

These different levels of circularity, their implications for actor networks or circular econosystems, and potential socio-economic effects make the task to assess CE and its contribution to a sustainable development even more complex and bear a variety of implications to the role of consumers/users of products. Besides the appropriation of new products and services, a variety of alternative practices of acquiring, using, and disposing of products need to be learned whereas other consumer practices need to be unlearned (see e.g., Rabiu & Jaeger-Erben, 2024). Only within the framework of an improved CE can a transformed chemical industry based on renewable carbon make the best possible contribution to a climate neutral society.

2.2 Relevant actors for the implementation of a CE

The transformation toward a sustainable carbon-based chemical industry combined with CE comes with implications for various actors. The transformation can only be achieved through well-designed joint efforts of all relevant actors and has to be based on a supportive policy framework. To be able to provide a comprehensive overview of all relevant actors and their specific contributions to this transformation (which depends on highly specific features of each production cycle) we will illustrate these joint efforts between relevant actors in the transformation toward a sustainable carbon-based chemical industry for the German plastics industry and relevant EU policies (see Figure 1 for an overview). We chose this example of application for two reasons: On the one hand, not only from a German, but also from a global perspective, plastics represent the most demanded and commercially marketable material, with production levels increasing during the past decades. Following several estimations, the current worldwide annual production of plastics ranges from 275 to 299 million metric tons (Zobkov et a., 2018).

On the other hand – but in conjunction with the extremely widespread use of plastic materials in a wide variety of applications – plastics are only rarely biodegradable and they are commonly fragmented into huge amounts of macro-, micro-, and nanoparticles through different processes and under natural conditions, making them ubiquitously harmful pollutants to the global environment. Microplastics represent the most notable type of plastic degradation and pollution, and were identified as threats against natural environmental and wildlife habitats, particularly in marine environments, seawater, and surface waters (see e.g., Kyriakopoulos et al., 2022 for an overview). Against this background, it becomes clear that the transformation toward a sustainable carbon-based chemical industry is of high relevance especially with regard to the plastic production sector.

To provide a comprehensive overview of the relevant actors and their specific contributions to the transformation of the German plastics industry, various actors and their interactions have to be considered (see VDI, 2022 for an overview):

The implementation of a CE in the German plastics industry would require profound changes in the industrial systems themselves. The relevant actors able to implement such changes are (1) the chemical industry itself, (2) plastic producers, or (3) processors. The chemical industry has to solve the task of covering the demand for raw materials in the transformation process by using recycled materials and thereby considering sustainability issues, for example by exploiting the potential of chemical recycling or by tapping into the potentials of CO_2 utilization (e.g., CCU) or renewable raw materials (bioeconomy).

This implies several structural and process-oriented challenges. Production locations, production organization, supply chain management including material sources and logistics require adaptations. Alternative/ new strategies and methods have to be developed to collect and reintegrate products and raw materials after use to reduce the total amount of raw materials needed. Significant changes and adaptations are necessary in several aspects of (4) the supply chain structure and management:

Chemical production is typically organized in the form of industry parks. Facilities and companies in close proximity follow the logic of the so-called *dome production* (the very close coupling of processes) (Casciano et al., 2019; Chen et al., 2019) and divergent product structures (not one, but several products are the result of one process chain; Machado-Ramos et al., 2023, Chen & Reniers, 2020). These energy-intensive systems not only require a large number of highly skilled workers, but depend on a stable supply of feedstocks and affordable (electric) energy. Depending on the type of feedstock, experts expect a greater distribution of material sources and a higher share of renewable energies to enable a chemical production with smaller and more local clusters. Creating closed-loop material flows would consequently create fluctuations and uncertainties on the supply of various materials both in terms of quality and of quantity. This again may require the development and implementation of technological solutions to evaluate and alter the quality of the feedstock (e.g., by means of sensorics and pre-processing). Moreover, the procurement systems and sourcing strategies would have to be more flexible. Finally, an accordingly flexible reverse logistics system has to be established, e.g., similar to the systems established for polyethylene-terephthalate (PET) bottles for beverages (Pinter et al., 2021). For these systems, reverse logistics are significant cost factors requiring multilevel logistics systems (see, for instance, Landi et al., 2018). Similarly, planning and controlling methods for production, procurement, logistics, and value network management have to be advanced in order to meet the new requirements and the associated increased demand for more specific and more real-time information along the entire value network (Benecke et al., 2023).

Building on changes in the chemical industry and in the value chain structure and management, plastic producers can subsequently contribute to the CE by providing alternative and highly qualified plastics that can be used for longer and more flexibly, and if all else fails, be recycled. Plastics processors are relevant actors, for example, with regard to the design for circularity (at the component/module level), to ensure the longevity, reusability, repairability, and the technical suitability and processability of newly developed alternative plastics.

In addition to these changes in industrial systems, the implementation of a CE in the German plastics industry also calls for profound changes in products and services, requiring joint efforts and the cooperation of further relevant actors: (5) original equipment manufacturers (OEMs)/users are highly relevant, for example by conceiving, developing, and establishing circular product service systems in the market, by providing new business models for the CE (e.g., the sharing economy), and by creating acceptance among customers through transparent communication. Furthermore, (6) (stationary) commerce serves a key function in a CE by representing the interface to consumers, the market, and logistics and disposal, for example by including circular products in the product range (and slowly fading out unsustainable and linear products) and by providing the necessary infrastructure (e.g., sorting and collection points). Additionally, (7) logistics/waste disposal also represent necessary actors for CE implementation, for example by optimizing the collection as well as pre- and end-sorting systems, which allow for larger volumes, a low degree of contamination, and a higher grade of purity of disposed materials, which are then used by (8) recycling companies, which are needed as new raw material suppliers in the CE.

Finally, (9) consumers play a key role in the implementation of CE in the German plastics industry. In the terminology of categories of mitigation strategies at the interface of technology development and behavior change (IPCC, 2022), consumers can contribute to the CE of the plastics industry by (a) ***shifting*** their purchasing behavior toward new services and products, such as refurbished products or products made from recycled materials, and by accepting higher prices for these new services/products.[1]

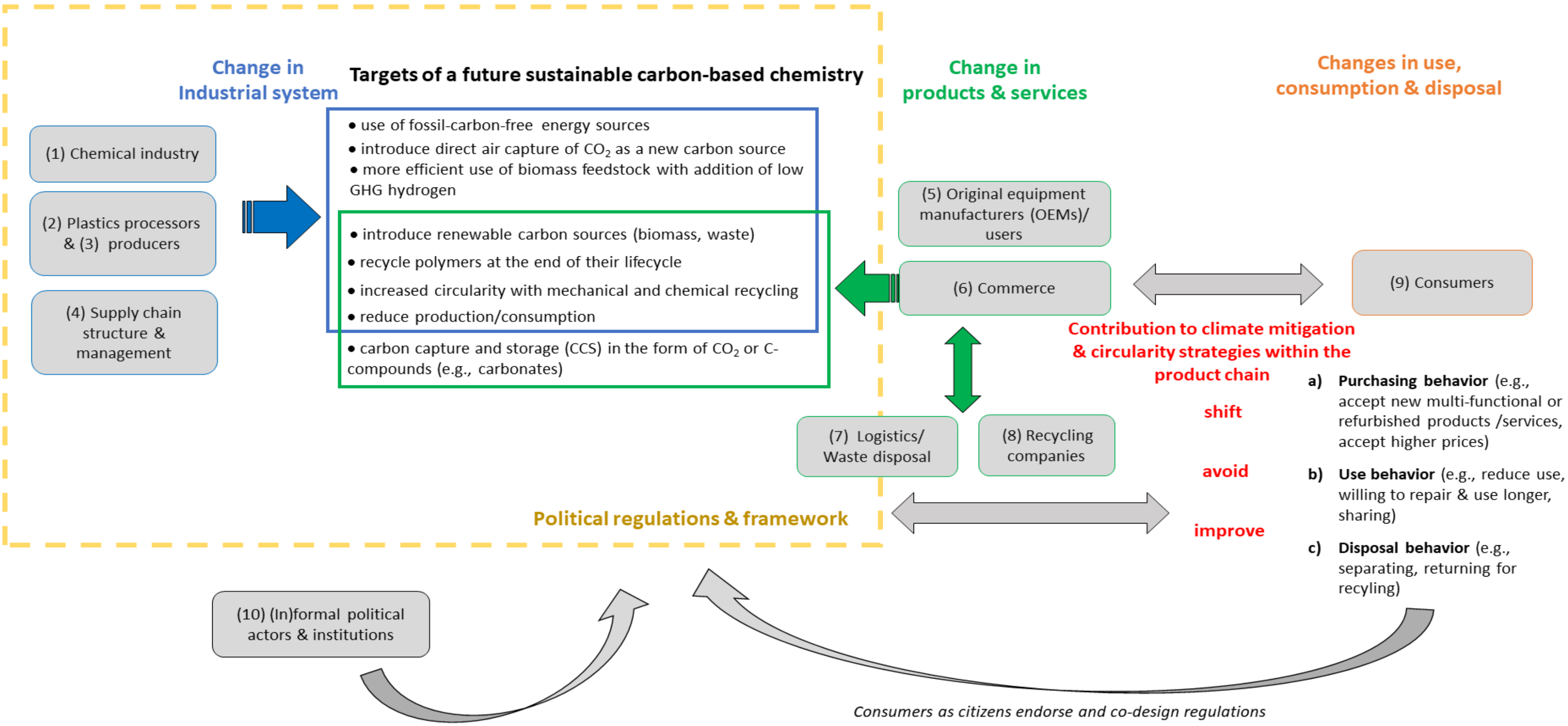
Consumers also contribute to the CE implementation by (b) ***avoiding*** and reducing the use of certain products, in combination with being willing to repair (resulting in longer periods of use) and share

[1] Since not everyone has the means to pay more for the new services/products, it is the task of policy measures and regulations to make the new materials as affordable as possible and to facilitate access.

products with other consumers. Finally, consumers contribute to the implementation of the CE in the German plastics industry by (c) ***improving*** the refurbish, recover, and recycling loops through their disposal behavior, for example by sorting waste and returning materials.

Alongside (10) (in)formal political actors and institutions, consumers can shape and co-design the political framework and production processes in their role as citizens through their political/deliberate consumption behavior (see Section 3.1 for details).

Despite consumers' key role in implementing CE in the German plastics industry, social scientists have criticized CE research for not adequately addressing consumer behavior in the CE context. Recently, King and Locock (2022) systematically analyzed the focus of the CE literature from the past 21 years and showed that only 9% of publications focused on the consumer. Hobson et al. (2021) proposed five interrelated, critical issues that a CE research agenda must address, including questions about who undertakes consumption work, to what ends, and how its multiple forms are coordinated within and beyond the household. Although research on consumer behavior has increased significantly (Rabiu & Jaeger-Erben, 2024), the question still arises as to whether the potential of social sciences research is being sufficiently utilized to inform the transformation processes of the carbon-based production and consumption system.



322 ***Figure 1.*** *Targets, actors, and a framework for the transformation toward a sustainable carbon-based chemical industry – applied to the example of the German plastics industry (extended/ adjusted illustration, based on VDI, 2022).*

3. Toward a broader understanding of potential social sciences contributions for the transition to a circular and sustainable carbon-based chemical industry

3.1 The need for systematic research on effects and side effects of mitigation initiatives

In a systematic literature review, Camacho-Otero et al. (2018) reported a growing number of studies on consumer behavior in the context of the CE (111 papers from 2005 - 2018). Rabiu and Jaeger-Erben (2022) reported 24 papers since 2018 (44 since 2009) on the topic of circular consumer practices. Another recent review by Halog and Anieke (2021) showed that research on the CE seems to focus mainly on case studies (29 of 70) or takes only a theoretical or conceptual perspective (19 of 70).

This dominance of case studies may reflect a preference for a *transformative research approach*. Transformative science can be defined as a type of science that not only observes and describes societal transformation processes but actively initiates and catalyzes them and thus helps to build scientific and practical knowledge. Transformative science often involves real-world experiments with actors from different sectors of society (see Schneidewind et al., 2016). It thus seems to be an appropriate approach for initiating and observing change processes on the local level (e.g., co-designing new recycle and waste management practices on the urban/municipal level). This conclusion is consistent the finding that 13 of the 70 papers reviewed by Halog and Anieke (2021) focused on the urban/municipality sector in which transformative research strategies (e.g., living lab approaches) are popular (e.g., Cuomo et al., 2021).

Change processes also require an empirically based understanding of consumer behaviors to assess the potential for mitigation and to inform integrated modeling (IPCC, 2022; Creutzig et al., 2018). Approaches from environmental science (e.g., life cycle assessment; LCA) have identified a multitude of mitigation opportunities inherent to societal changes or sociotechnical innovations. However, little is known about how or to what extent the theoretically identified potential can actually be exploited. A helpful concept in this context is the one of *behavioral plasticity*. Stern et al. (2022) defined behavioral plasticity as the “extent to which a mitigation initiative, as implemented, yields the intended responses by the intended responder” (p. 4). For the domain of recycling, Varotto and Spagnolliet (2017) found that waste separation interventions generally yield only small or medium effects, indicating rather low plasticity in recycling behavior under the respective conditions. The concept of behavioral plasticity helps to structure the research that is needed here. In line with the definition by Stern et al. (2022), behavioral plasticity depends not only on the attributes of the responder (e.g., motivational or financial resources), but also on behavioral contexts (e.g., infrastructural factors) and the way in which mitigation initiatives are designed and implemented.

Social sciences in the CE context have yet to focus on ***the assessment of behavioral plasticity*** (i.e., on estimating the actual potential of possible mitigation initiatives based on responder attributes) and possible contexts. In their systematic analysis of consumer studies, Camacho-Otero et al. (2018) stated that out of 111 papers on consumer behavior, only eleven actually analyzed *change processes*. Nine papers aimed to explain how the process of consumption will change in the context of circular solutions, and only two studies looked into external strategies that could help improve the acceptance and adoption of circular solutions.

In addition to the ongoing transformative research on local, context-specific levels, research on behavioral plasticity is therefore needed to provide a systemic and ***integrated assessment of the potential of circular processes***. Since the transformation toward a sustainable carbon-based chemical industry combined with CE comes with implications for diverse actors (as described in Section 2.2), this transformation process demands many efforts from responders to cope with the requirements of all these new developments. Therefore, a comprehensive concept of behavioral plasticity with regards to responders' attributes not only refers to behavioral specific attributes (e.g., psychological factors determining consumers' waste separation behavior; see Section 4.1 for an example), but also to their general desire for change/ their resistance to change. Thus, research providing an integrated assessment of the potential of circular processes also needs to examine those characteristics, which can affect responders' general desire for change (i.e., their dissatisfaction with the current situation (e.g., referring to economic systems, behavioral practices, policies etc.), their visions about an alternative future (e.g., a sustainable future) and by their confidence in the proposed methods for conducting first steps towards such changes (e.g., the complete implementation of CE in the carbon-based chemistry; Kapsalis & Kapsalis, 2020).In its structured consideration of context and opportunities, the assessment of behavioral plasticity also implies a ***consideration of potential side effects of mitigation initiatives***. These need to be considered in addition to transformative approaches as case studies alone may overlook the danger of creating new problematic behaviors by neglecting potential negative side effects. (Direct and indirect) rebound effects as well as negative spillover effects need to be monitored given their highly relevant (negative) effects on mitigation initiatives' final realized mitigation potential (see e.g., Sorell et al., 2020 or Dreijerink et al., 2023 for an overview).

3.2 The need to investigate the *politics* of transition

Political aspects represent another key issue when researching the transition to a circular and sustainable carbon-based chemical industry. A transition to a circular economy does not happen naturally, but is significantly shaped by the institutional framework (understood as institutional "rules"). These are relevant policies on national, EU, and transnational levels that influence the actions of political actors. Chung et al. (2023) point out that, in addition to technical aspects, political aspects such as institutional rules can enable or hinder transformation processes toward decarbonization. For example, increasing CO_2 prices resulting from the European emissions trading system (EU-ETS), or the prevailing energy policy (e.g., EU Renewable Energy Directives RED I-III), set incentives that sectors like the chemical industry seek for more cost-effective and less CO_2-intensive alternatives such as using more sustainable carbon sources or production processes. However, there are also different interests among the actors. Some parts of the chemical industry might not be willing to look for alternatives, but instead relocate their sites to other regions of the world where, for example, energy is cheaper or there is no emissions trading in the interests of cost efficiency. There are many studies on EU climate and energy policy; however, what has been missing so far, are studies from a public policy analysis perspective that take a cross-sectoral, integrated perspective independent of individual policy areas that examine all politically relevant aspects for a transition of the chemical industry. In addition to traditional industrial policy and innovation dynamics in the chemical sector, it is important that relevant climate and energy, recycling and waste policy aspects as well as relevant bioeconomy and land use policies are integrated into one research approach. This is where chemical policy interacts with land use policies such as agricultural and forest policy and conflicting goals such as the expansion of renewable energies on land and biodiversity conservation. These political perspectives of a sustainable chemical industry go far beyond the need for a classic analysis of sectoral policies. The possibilities and limits of policy coherence and integration must be considered more than ever in policy analysis. Closely linked is the concept of "transversal policy". Transversal policy is a political approach that aims to achieve coherence between two different objectives (Soeparna & Taofiqurohman, 2024), e.g. transformation to sustainable chemistry through greater use of renewable carbon sources and biodiversity objectives on land. A shift from top-down policies to transversal governance (Kapsalis & Kapsalis, 2020) would mean that greater coherence must be established between policies at one level from different policy domains, but also in a transversal way, integrating different vertical levels and sectors (multi-level governance involving e.g. citizens, companies, administrations in all areas). Furthermore, the policy analyses need to focus on the relevant actors, their power resources, and their respective interests. The extent to which political processes hinder or support the transformation of the chemical industry is an open research question. Linked to this is the question of the possibilities of radical political change, which has long been the subject of research in public policy analysis, but has not yet been investigated at all for the transformation of the chemical sector. There is also a scientific discussion that, in addition to top-down policies, bottom-up approaches are also being utilized to a greater extent. Above all, it is important to address and involve citizens with regard to circular economy-oriented solutions at the local level. Through greater participation in such policies, they can take on greater responsibility and become drivers of change at local level (Sondh, et al., 2024).

3.3 The need to consider consumers as *citizens*

Another issue that needs to be given more attention to is the **interaction between consumers and politics, the institutional framework, and future changes** in the chemical industry and products. Consumers' decisions are based on their belief systems and thereby shape the social world they live in. From a political science perspective, it is central to ask questions about interests, conflicts, strategies, and power dynamics when analyzing the transition/transformation from one system to another. In the transformation process, some actors may lose (e.g., power, influence, or money), some may win, and some might not be affected at all. Analyzing these aspects can contribute to the understanding of the dynamics of change and help identify potential drivers as well as barriers (e.g., the overt or covert resistance of some actors or groups).

Although consumers react primarily to affordability and cost structures, their attitudes toward the transformation and its technologies might become more important in the context of decarbonization. Today's consumers have already acquired a certain level of knowledge regarding climate change, its drivers, and the need for mitigation. By consuming, they act as citizens who deliberately participate in new practices or prefer a certain product because of its better environmental performance, although it might come with higher costs.

The concept of LCA has evolved significantly since the nineties (see e.g., Mulaj, 2015 for an overview). It can therefore be assumed that a relevant proportion of todays' consumers have a basic understanding of LCA and are able to evaluate new developments critically (e.g., scarce materials required for batteries for electric cars).

The CE approach to the acceptance of new solutions and alternative products should also consider research on the specific heuristics that individuals rely on to make their decisions. Studies in consumer behavior in the CE have so far focused on the acceptance of specific circular solutions (see Camacho-Otero et al., 2018), on "new" or alternative products, and on their evaluation in terms of environmental performance. However, little is known about what heuristics consumers use to evaluate the environmental impact of products from a carbon-neutral carbon-based chemical industry, which will probably be based primarily on carbon-neutral feedstock (e.g., on biomass or CO_2 from DAC). People who are more interested in climate protection and who might therefore be more motivated to choose a carbon-neutral product may also think about land use and the indirect effects of the use of biomass on biodiversity or the food system. Thus, in addition to reflecting on individuals' parts in a circular carbon value chain, it is necessary to understand behavioral plasticity for the acceptance of future fossil-free solutions. Such an understanding must take into account ***the broader societal discussion*** on land use and carbon management, which may affect individuals' and market acceptance of alternatives.

3.4 Overall aim of the present paper

Due to the large number of actors, loops of use and production paths, the transformation of the chemical industry requires a better understanding of the political framework conditions, the overarching political and local regulation, as well as the possible restrictions on the part of supply chains, consumer work, and end users. So far, the potential of the social sciences has not been sufficiently used.

1) Although there is some social sciences research on local transformation processes and individual behavior in the area of a plastic's circular economy, there is no systematic evaluation of the potential for change and the side effects of certain measures. This is where the plasticity approach from social sciences research regarding energy use behavior would be useful, supplemented by an assessment of possible rebound effects.

2) Although regulations from the field of climate protection and resource conservation are often taken as starting points for the development of transformation pathways (see Kaiser & Bringezu, 2020; Stegman et al. 2022), there is no political science research on an integrated consideration of the various policy fields that are relevant here (e.g. climate protection, bioeconomy, CE).

3) Although individuals are increasingly considered in CE research, especially in their role as consumers, and in some cases also as co-designers of new services and products, there is a lack of analyses of the assumptions and possible misconceptions that individuals might have about the defossilization of plastics production and about the carbon cycle in connection with CE principles.

4. Illustrating the potentials of the social sciences to support the transformation of a carbon-based chemical industry

4.1 Investigating behavioral plasticity – the example of waste separation

One social sciences perspective refers to the assessment of behavioral plasticity. Beyond CE contexts, researchers have already examined the behavioral plasticity of people's mitigation initiatives (see below for examples). Some of the behaviors are also highly relevant in the CE context, such as people's waste separation behavior (see Section 2 for details).

Most existing research in this domain has focused on the mitigation potential, the actual mitigation through diverse mitigation initiatives, and opportunities (i.e., despite the ways in which mitigation initiatives are designed and implemented, opportunities are determined primarily by responders and by their contexts; see examples below) with regard to responders' waste separation behavior. Thereby, previous research implies that mitigation potential has yet to be completely realized in most industrialized countries. As an example, Oluwadipe et al. (2021) point out that, in the UK, current recycling rates (i.e., actual mitigation) are approximately at only 46% instead of the 65% target set by the government.

Several studies have attempted to directly quantify the behavioral plasticity of people's waste separation behavior. Varotto and Spagnolliet (2017) conducted a comprehensive meta-analytical study examining the effect sizes of 47 validated field intervention studies (psychological interventions) on household waste separation behavior. The meta-analysis revealed an overall Hedge's g of 0.29 (95% CI [0.24, 0.33], $p < .001$), indicating statistically significant, small-to-medium sized effects (Cohen, 1988), that is, small to medium amounts of behavioral plasticity in responders' waste separation behavior.

In a recent literature review, Jacobsen et al. (2022) examined the attributes of responders that determine the behavioral plasticity of their waste separation behavior. Results indicate that insufficient knowledge (typically with regard to the characteristics, functions, and consequences of different packaging materials or regarding the correct sorting of plastic packaging waste) is an important attribute for determining individual waste separation behavior (see also, e.g., Knickmeyer, 2020). Furthermore, diverse empirical studies have implied that perceived social norms and responders' motivation to adapt their behavior to these norms also greatly affect behavioral plasticity in waste separation behavior (see again Knickmeyer, 2020 for an overview). In line with these findings, Varotto and Spagnolliet (2017) suggest that social modeling interventions are among the most effective measures in changing responders' waste separation behaviors, although these interventions might not result in the complete realization of mitigation potential either.

In addition to responders' attributes, (behavioral) contexts are also of equal, if not higher, relevance for the behavioral plasticity of waste separation behavior (see, e.g., Timlett & Williams, 2011, for an overview). A large body of evidence suggests that any condition that makes waste separation behavior more difficult for responders strongly restricts behavioral plasticity (see e.g., Goh et al., 2022 for a recent example) —also referring to responders who are characterized by beneficial attributes (see, e.g., Galán-Martín et al., 2021 for an overview). Accordingly, studies have shown that inconvenient features of waste sorting and collection systems strongly restrict responders' daily waste separation behaviors (Aprile & Fiorillo, 2019; Bell et al., 2017; Best & Kneip, 2019; Kushwah et al., 2023; Sörme et al., 2019). Furthermore, Best and Kneip (2019) found that introducing a curbside waste collection system (making source separation of household waste more convenient for responders) was especially effective for the waste separation behaviors of responders characterized by problematic attributes (i.e., low motivation). Consistently, Bell et al. (2017) found that introducing a single-stream waste-sorting system, instead of a dual-stream (requiring more effort for waste separation behavior), increased waste separation behavior (especially for plastic packaging waste). Klaiman et al. (2017) found that requiring responders to clean the packaging after use had a negative effect on willingness to separate waste. Against this background, it is not surprising that Varotto and Spagnolli (2017) also found that mitigation initiatives consisting of techniques that make recycling more convenient and easier to perform by modifying the physical environment (e.g., by increasing the proximity or number of bins or by providing home equipment for sorting waste) are also highly effective in promoting responders' waste separation behavior.

4.2 Investigating potential side effects – the example of rebound and negative spillover effects

As already mentioned above, considering behavioral plasticity in the CE context also implies adding a systemic and integrated assessment of the potential of circular processes. The consideration of possible – negative – side effects of mitigation initiatives and opportunities has so far received only little attention in previous research on CE contexts, and represents another very important contribution social sciences can make for the transformation toward a sustainable carbon-based chemical industry. In order to illustrate its relevance, we will summarize previous empirical findings on such side effects beyond the CE context, but focus on CE-relevant responder contributions (e.g., avoiding and reducing the use of certain products and services applied to the energy-consumption domain).

The actual mitigation achieved by initiatives designed to reduce responders' (e.g., households') energy consumption levels often falls below the expected mitigation potential due to possible side effects of these mitigation initiatives. In this context, (direct and indirect) *rebound* as well as *negative spillover effects* have emerged as relevant negative side effects which lower the mitigation potential of such mitigation initiatives.

According to Sorrel et al. (2020), these negative side effects are usually the result of financial or moral benefits responders experience as a consequence of their response to the mitigation initiative. Rebound effects can occur since responders who reduce their energy consumption (e.g., by replacing old energy-demanding devices with new energy-efficient ones) also reduce their energy costs (if energy prices remain constant). These financial benefits increase responders' real income, which will later be re-spent by the responder on other products or services that require energy. Applied on a microeconomic level, this means that due to re-spending, actual mitigation (i.e., greenhouse-gas-emission savings) of the mitigation initiative that caused the behavioral response (i.e., reduced energy consumption) falls below its expected mitigation potential. Depending on the pattern of response, empirical research has shown these rebound effects to range from modest (i.e., 5% to 15% for responses in the energy consumption domain) to very large (i.e., 50% to 100% for responses in the food consumption domain). In addition to such microeconomic effects, there are also relevant rebound-related side effects on a macroeconomic level (e.g., referring to changes in energy prices on regional, national, or even global levels) that could shape relevant contexts for further mitigation initiatives (see Sorrel et al., 2020, for an overview).

Despite rebound effects, negative spillover effects “occur when the adoption of an energy […] action in one domain of decision-making (e.g., travel choices) makes the subsequent adoption of an energy […] action in another domain (e.g., food choices) […] less likely” (Sorrell et al., 2020, p. 9). In contrast to rebound, negative spillover effects are assumed to be caused by changes in responders’ attributes. In the case of mitigation initiatives promoting reduced energy consumption, the adoption of the recommended behavioral changes typically requires responders to invest a lot of resources (e.g., time, money, and convenience, e.g., the need to replace old energy-demanding devices with new energy-efficient ones) but are typically seen as morally right by the responders. Consequently, responders feel less guilty about subsequently behaving in a “bad” way (i.e., morally licensing), for example by using the more energy-efficient devices for longer or more often. Empirical research suggests that the likelihood of negative spillover effects depends on responders’ attributes (e.g., their environmental values, see, e.g., Truelove et al., 2016; or their need for consistency in their responses (see, e.g., Van der Werff et al., 2014) and contexts (e.g., financial or other types of costs related to responders’ initial response to a mitigation initiative; see Sorrel et al., 2020 or Dreijerink et al., 2023 for an overview).

4.3 Investigating the politics of renewable carbon – the case of the EU

The EU has already established policies regarding the three different renewable carbon streams (carbon from the atmosphere, biosphere, and technosphere; Carus et al., 2020) and the sustainable circular (renewable-carbon-based) chemical industry. In the Communication on Sustainable Carbon Cycles, the European Commission set the goal of creating sustainable and climate-resilient carbon cycles (2021). In 2021, the EU incorporated the target of climate neutrality into the European Climate Law. With this step, climate neutrality has been stated as a binding goal for the EU.

The regulation of renewable carbon from the technosphere, which is extracted from recycled (fossil or renewable-carbon-based) materials, has a rather long history in the European waste policy. A central policy is the waste framework directive, which aims to prevent and reduce waste and refers to the CE. However, although these policies exist, public policy research has shown that the political regulation of the economic use of biomass for the production of energy and as a raw material for the production of material goods (e.g., bioplastics) has basically just begun. One important result from political science is that there is some fragmentation regarding the political regulation of renewable carbon from the biosphere (Böcher et al., 2020; Vogelpohl et al., 2022). In the 2000s and 2010s, several policies regulating the energetic use and sustainable production of biomass were introduced (RED; ILUC Directive; RED II; LULUCF Regulation). The political regulation of bioplastics (biobased plastics and biodegradable plastics) has just begun to develop (Vogelpohl et al., 2022). Policies that explicitly address (bio)plastics have been published in recent years (EU Plastics Strategy; Single-Use Plastics Directive) or are currently under development (Policy Framework for biobased, biodegradable, and compostable plastics; Packaging & Packaging Waste Directive). Policy research has shown that mass production, collection, and recyclability of bioplastics are a complex undertaking and that the production of conventional plastics is significantly cheaper. Although public awareness of the need to replace conventional plastics is growing, the EU plastics strategy has placed greater emphasis on recycling and reducing plastic waste. On a stakeholder level, the bioplastics industry, unlike the chemical industry, is not well integrated into European political processes and is therefore less able to assert its political interests, while environmental NGOs tend to reject bioplastics and demand avoidance or recycling (Vogelpohl et al., 2022).

The DAC of renewable carbon from the atmosphere – also known as negative CO_2 emissions or carbon dioxide removal (CDR) – using innovative technologies (e.g., building carbon capture plants) is the latest renewable carbon resource stream. Hence, the respective political regulations that address the use of renewable carbon, carbon sinks, and carbon cycles are just being developed and discussed (Lehtveer & Emanuelsson, 2021; Rickels et al., 2021; Tamme & Beck, 2021).

4.4 Investigating policy instruments for the governance of carbon cycles

In the EU governance for renewable carbon, there are various regulatory options that have an indirect or direct effect on the establishment of innovative technologies and processes for the transformation of the chemical industry. Carbon price mechanisms are an important instrumental approach to regulating CO_2 emissions. They aim at making the emission of CO_2 and other greenhouse gases more expensive as an incentive to emit less CO_2. The most commonly used instruments for this purpose are eco-taxes and emissions trading schemes.

The EU Emissions Trading Scheme (EU ETS) was introduced in 2005 and defined trading periods. We are currently in the 2021-2030 trading period. EU ETS operates according to the "cap and trade" principle: The state sets the maximum emission volume ("cap") for the amount of GHG that can be emitted, which is successively tightened. The state issues emission certificates, which can be traded among companies ("trade"). Caps have been set by the EU since 2013. Initially, emissions trading covered only CO_2 emissions and certain emissions-intensive industries and sectors, that, taken together, were responsible for about 40% of these emissions, including the chemical industry (Reichenbach & Requate, 2008). The EU ETS has later been extended. As an economic policy instrument, the EU ETS has an indirect effect on the transformation of the chemical industry since a gradual shortage of emission rights and the associated increase in the cost of emissions create greater incentives to develop alternative technologies and processes. The effect of the EU ETS exerts economic incentives to save CO_2 or to develop new renewable carbon technologies. Contrary to the original plans, there are currently discussions within the EU about auctioning more certificates in the short term so that the CO_2 price will fall, in order to allow for the additional use of coal-fired power plants that are necessary in the wake of the war in Ukraine. The EU wants to use the expected additional revenue to promote technologies that will make the EU less dependent on gas imports and fossil fuels (Sauga, 2022).

The governance of carbon sinks in the land use sector is addressed in the EU LULUCF Regulation, which covers the period from 2021 to 2030 and builds on the EU LULUCF Decision, which was introduced in 2013 and is applicable until 2020. With this policy, a concrete target has been defined for the land use sector in the EU for the first time. Member states are required to contribute to the enhancement of carbon sinks and to the prevention of net carbon emissions from forests and soils. The central mechanism is the accounting of carbon emissions and removal, which is defined in the LULUCF Regulations using rules and principles that were partly introduced before in the frame of the Kyoto Protocol and the EU LULUCF Decision. The LULUCF Regulation, the EU Emission Trading System (EU ETS), and the EU Effort Sharing Regulation (ESR), which addresses sectors that are not covered by the ETS and that are not connected to land use, make up the three pillars of the EU climate policy (and hence the renewable carbon or carbon cycle policy). After the introduction of the European Green Deal, in which the EU defined the goal of net-zero greenhouse gas emissions by 2050, the European Commission published a proposal for a revised LULUCF Regulation in July 2021, which was adopted by the European Parliament in June 2022 and contains more ambitious goals for emission reduction and negative emissions in the land use sector (Böttcher et al., 2019; Böttcher et al., 2022).

Another instrument for promoting the transformation toward renewable carbon streams is financial support for research and development, for the creation of new processes and technologies. Within the EU Green Deal, research and technology funding represents an important component. The current EU research framework program HORIZON Europe (2021-2027), which is endowed with approximately 95 billion euros, addresses various thematic clusters, including climate-relevant issues. The Innovation Fund (IEA, 2022) is linked to emissions trading and is intended to promote innovative low-carbon technologies. The revenue from emissions trading is used to support research and development projects on low-carbon technologies (European Commission, 2019b), such as DAC.

Overall, policies for regulating and establishing DAC techniques and standards are still in the early stages. However, in view of the need to exploit all conceivable technical potential for CO_2 avoidance in climate protection and the potential for captured CO_2 to not only be stored underground but to also be reused, an upswing in regulation can be expected in the upcoming years and decades. The choice of concrete instruments is influenced by several factors and can be contested in the political process (Berker & Böcher, 2022). When it comes to assessing the possibility of introducing or further developing policy instruments, research on policy instrument choice and change is very relevant. Political science research has shown that political instruments are not only selected according to their optimal ability to solve problems. Rather, numerous political influencing factors play a role. For example, the legal conformity of instrument alternatives and the political acceptance of certain instruments, which can encounter varying degrees of resistance from social groups (Berker & Böcher, 2022). It has been shown that economic instruments such as taxes or tradable permits are more difficult to implement than command-and-control-based instruments (see very early Hahn, 1989; Böcher, 2012). In addition, instruments are almost never implemented in the sense of their ideal type – instrument mixes or hybrid instruments are the order of the day, and these are not always coherent and sometimes hinder each other in their effect. In addition, instruments are often used too weakly, so that they often do not reach their full potential (Howlett, 2019; Capano & Howlett, 2020; Howlett, 2021). Particularly in the case of market-based instruments, it has been shown that industry lobbying has led to tax rates or the CO_2 cap in emissions trading not being designed strictly enough, or exemptions being created. What options exist for introducing new policy instruments, reforming existing ones, or abolishing instruments with harmful effects on the climate is therefore a relevant research question with regard to the realization of sustainable carbon cycles. In particular, what Howlett recently referred to as the "dark side" of politics, namely that governments do not only have public interests in mind, is of relevance here: he suggests that one looks much more closely at the power-driven aspects of policy and instrument choice and change (Howlett, 2021).

4.5 Understanding citizens as consumers – do established pro-environmental heuristics work in the context of a CE?

Consumers are becoming increasingly sensitive of the CO_2 emissions of the products they purchase. In a recent systematic international study (including several EU states and the US), two thirds of the consumers were in favor of a CO_2 label (The Carbon Trust, 2020), and companies all over the world have discovered the value of claiming that their products are produced in a climate-neutral way (Überwimmer et al., 2022). Thus, consumers have become relevant stakeholders in the transition toward sustainable carbon-based production.

However, sustainable production in the carbon-based chemical industry faces a particularly great challenge, as the production of polymers, which are central to many further plastic products, is mainly based on carbon feedstock, which has thus far consisted primarily of fossil carbon. As described in Section 1, the newest IPCC report (2022) suggested introducing DAC and the use of biomass feedstock for the transformation of the carbon-based chemical industry. At the moment, both strategies are topics of controverse discussions, particularly led by NGOs (e.g., Wolff, 2020). Increasing the use of biomass implies land use changes and thus indirectly competes with the conservation of ecosystems or land use for food production. The key argument against technologies for capturing CO_2 is that they represent technological solutions and are assumed to indirectly legitimate CO_2 emissions and the continued use of fossil sources (Haikola et al., 2021).

Against this background, it can be assumed that citizens might be less supportive of policies that imply an increase in biomass use or that incentivize carbon capture and CCU. It can furthermore be assumed that in their role of consumer, citizens might be reluctant to buy or pay more for products from a transformed sustainable carbon-based chemical industry.

At the moment, it appears as if most citizens know only a little about the various technologies that can be applied to capture or use CO_2 (for an overview of technologies and a recent questionnaire study, see Kukouzas et al., 2020). The most important finding from Kukouzas et al.'s (2020) study was that the majority of European citizens, regardless of their educational level, have heard about CO_2 and its effects. But only few have a deeper knowledge about the carbon cycle and have heard of capture methods and at the same time consider them to be generally unsafe methods (Kukouzas et al., 2020).

According to Jones et al. (2015), who used a focus group approach, participants with strong environmental worldviews were particularly likely to disapprove of CO_2 utilization. The authors assumed that environmentally concerned people might feel more positive about CCU if it was framed as a strategy to use waste rather than as a strategy for reducing CO_2 emissions.

Regarding the social sciences research on the acceptance of biomass as feedstock, there is a lot of research on the use of biomass energy but none on the acceptance of biomass as feedstock (Gareth et al. 2018). Gareth et al. (2018) investigated attitudes toward biomass use in a deliberative context, in which citizens discussed technologies in a broader context of the transformation toward a fossil-free economy. They concluded that "perceptions of CCS as threatening, uncanny disruptions to natural systems may shift when re-contextualized to include concerns relating to the intermittency of renewable energy, or be ameliorated through perceptions of industrial and bioenergy applications as supporting natural and economic interdependencies" (p. 1).

Such studies make it apparent that in order to develop transformation strategies for sustainable carbon-based chemical production, it will be important to figure out how to embed these technologies within a broader understanding of both consumer needs and the requirements of a future fossil-free carbon-based industry.

In order to achieve full CE literacy, it is relevant for consumers to understand the need to reduce their consumption of material resources, for them to figure out how to reuse and recycle, and to understand carbon cycles and the need for biomass as feedstock. An important way to build trust in CCS technologies and new forms of biomass use lies in the design of biomass strategies and the relationships between these strategies and general sustainability policies, which also embrace the change in the food system, biodiversity loss, and development that remains within planetary boundaries.

5. Discussion

According to the IPCC (2022), a fundamental transformation of the carbon-based chemical industry is needed, including closing the use loops for carbon and CO_2 through increased circularity, the use of biomass feedstock, and potentially direct air capture of CO_2 or otherwise captured CO_2 as a new carbon source. This transformation has many implications for different actors, can only be achieved through well-designed joint efforts of the many actors in the field, and has to be based on a supportive international and national policy framework. The plastics industry is of particular importance here, as plastics represent the most demanded and commercially marketable material with strongly increasing levels of production during the past decades (Zobkov et a., 2018.). Research to support and inform the transformation process has so far focused mainly on the industrial system, although there is also a growing tradition of social sciences research on the relevant actors in a circular plastics economy.

Against this background, the overall aim of the present paper was to identify developing fields in the social sciences which are crucial to inform the transformation process toward a sustainable carbon-based chemical industry. Fields that were explored and should be enlarged are the individual consumer, the dynamics of political framework conditions, and the overall literacy of citizens who are relevant supporters of the transformation (see Section 3).

We see a great need for systemic research in order to assess behavioral plasticity and adverse side effects in CE contexts. As shown in Section 4.1, comprehensive empirical research implies that actual mitigation effects lag behind the potential for theoretical mitigation. These findings reveal the need for systemic research for assessing behavioral plasticity depending on specific contexts. Only then would it be possible to provide an integrated assessment in order to appropriately consider responders'/consumers' roles in the transformation toward a sustainable carbon-based chemical industry. Against this background, it should be clear that in addition to the transformative research that has primarily been conducted locally, there is a great need for comprehensive field research in the CE context. As illustrated in Section 4.2, negative side effects (e.g., rebound or negative spillover effects) can also represent an important restriction for the actual mitigation potential of diverse mitigation initiatives and can thus also be a relevant restriction on the transformation toward a sustainable carbon-based chemical industry.

Furthermore, we would like to draw attention to the need for research regarding the relevant political framework conditions. Although there is a growing body of political science research on the relevant policy fields, what has been missing so far are studies that take a cross-sectoral, integrated perspective independent of individual policy areas in order to examine all politically relevant aspects for a transition of the chemical industry (see Section 4.3 and 4.4).

Finally, there is a need for further research on the heuristics which consumers and actors use to evaluate new technologies and products in the context of changing technologies, particularly the use of biomass or CCS (see Section 4.5 for details). It seems that consumers and citizens evaluate these technologies primarily on the basis of beliefs rooted in conflicts between climate mitigation and other sustainability targets. Thus, more attention should be paid to a social sciences approach that focuses on differentiated knowledge and heuristics about the upcoming transformation in order to provide a reliable estimation of the mitigation potential that lies within the transformation toward a sustainable carbon-based chemical industry.

6. Conclusion

The transformation toward a sustainable carbon-based chemical industry is a challenging and complex process, which cannot only rely on technological innovations. This complex process involves many actors and will be strongly shaped by societal changes (i.e., changes in consumers' use and consumption decisions or practices as well as on changes in political frameworks and their support by citizens).

Social sciences CE research has only just begun to build a deeper understanding of the needs and willingness of involved actors in the transformation of the carbon-based chemical industry, with a particular focus on consumers. This perspective should be broadened and approaches should be advanced that are capable of assessing consumers' potential for change regarding various possible transformation pathways for the chemical industry, conceived as embedded in the transformation toward a climate-neutral future. A comprehensive description of the possibilities for such a transformation could be the basis for society, politicians, entrepreneurs, citizens, and consumers to take part in the informed decisions that will shape a future climate-neutral chemical industry.

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