Plastics and climate change—Breaking carbon lock-ins through three mitigation pathways

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SUMMARY

The plastic industry is dependent on fossil fuels in various ways that result in strong “carbon lock-in” throughout the value chain and large and growing CO₂ emissions. The industry must decarbonize to reach global net-zero pledges. Although a few initiatives have been launched, they primarily focus on plastic waste. Current research has investigated mitigation potential on different parts of the plastic value chain but remains in silos. Here, we review carbon lock-ins throughout the plastic value chain and identify possible mitigation pathways for each stage of the plastic life cycle. We show how lock-ins are stubbornly entrenched across the domains of production, markets, waste management, industry organization, and governance. Overcoming these carbon lock-ins and achieving zero-carbon targets for the sector by 2050 will require thorough systemic change to how plastics are produced, used, and recycled, including promotion of demand reduction strategies, bio-based feedstocks, and circular economy principles. Strict governance structures, enforceable regulation, and a new proactive and inclusive vision for the low-carbon transition are equally important.

INTRODUCTION

Global awareness of environmental problems associated with plastics has increased rapidly in recent years. There is now wide agreement on the negative consequences that plastic pollution has on marine environments, the diffusion of microplastics into ecosystems around the world, and the failure of contemporary recycling systems to manage the increasing volumes of plastic waste.1–3 Plastics have become almost synonymous with the unsustainability of contemporary life: a linear usage of fossil fuels to produce products with short shelf spans that are commonly discarded and end up polluting natural environments or in landfills or emitting all embodied carbon via incineration. The current situation has been labeled a plastics crisis4 that ne-
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Global GHG emissions from the life cycles of plastics were conservatively estimated to be 1.8 gigatons of carbon dioxide equivalent (Gt CO₂e) in 2015, and under business-as-usual scenarios, they are expected to multiply three to five times over the coming decades.8 The rapid growth of plastic production in coal-dependent regions has led to GHG emissions associated with plastics increased at an accelerating rate.9 It is thus clear that plastics suffer from a strong case of “carbon lock-in,” i.e., a strong path dependency connected to the use of fossil fuels across many domains. To reach net-zero emission targets by 2050, GHG emissions from the value chains and life cycles of plastics must be rapidly reduced with a combination of measures.10 This requires development along new pathways that transform the established structures in the industry.

The research literature has contributed with important insights into how global patterns of plastic production and consumption,11–13 enabled by the creation of demand for plastics in a growing range of sectors,14,15 the growth in international trade in plastics and plastic waste,16–18 the underperformance of contemporary plastic recycling,19–21 and the limited impact of bio-based plastics,22,23 continue to support the development of a linear use of fossil-based virgin plastics. Much of this research is, however, focused on individual aspects and issues connected to the production and consumption of plastics and do not make explicit the connections between materials and technologies, market structures, and governance forms, which all stabilize the current system. There is thus a need to bring together and contextualize the factors that together form the strong carbon lock-in of plastics as well as analyze the potential for breaking this lock-in along the pathways that are highlighted as solutions to the plastics crisis.

Here, we aim to close the gap by identifying sources of carbon lock-in throughout plastic value chains and across the domains of production, end user markets and demand, waste management, industrial organization, and governance as well as review
the potential for the most promising development pathways to break with these carbon lock-ins. This provides a basis for a discussion on the need for a systemic change, which we find is not supported by either industrial investments or policy and governance. This includes promotion of demand reduction strategies, bio-based feedstocks, and circular economy principles, alongside strict governance structures, enforceable regulation, and a new proactive and inclusive vision for transformation. We finally identify remaining key knowledge gaps, outlining a research agenda to support the transition toward a more sustainable system for production and consumption of plastics, which targets zero GHG emissions by 2050.

PLASTICS PRODUCTION, USE, AND GHG EMISSIONS

It is hard to imagine a world without plastics. The petrochemical sector, which produces plastics as well as other chemicals and derivatives, directly contributes more than 1% of global GDP. Although plastics are used for uncountable purposes, some market sectors stand out: packaging (36% of global plastic demand), building and construction (16%), textiles (14%), and consumer and institutional products (10%); together, these sectors cover more than three-quarters of global plastic demand. These highly diverse market sectors have completely different requirements—the term “plastics” thus covers myriad resins, synthetic fibers, and additives, which all have unique properties, although different forms of only a few key polymers make up the majority of all plastics used: polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS). Synthetic fibers are mainly polyester with polyamide, with PP acting as the other main fiber polymer. Plastic production is currently almost entirely based on fossil feedstock, composed primarily of petroleum products and natural gas, but a small share also comes from coal.

Global plastic resin production has increased from about 1.7 megatons (Mt) in 1950 to 368 Mt in 2019, with an average annual growth rate of about 3.5% since 2011. The growth in plastic production during the past 15 years comprises a 3-fold increase in plastic production in China, while it has remained stagnant in Europe and decreased in Japan, as shown in Figure 1. The annual per capita consumption of plastic resin varies greatly between regions, estimated in 2015 to almost 140 kg in the North American Free Trade Agreement (NAFTA) and Western Europe, 108 kg in Japan, 36 kg in the rest of Asia, and 16 kg in the Middle East and Africa. This wide range in consumption underscores the potential future growth in plastic consumption worldwide. As various regions grow both in population and in levels of wealth, plastic consumption is expected to increase, particularly for packaging and construction. Assuming annual growth levels of 2% or 4% (which are also used in the climate impact scenarios discussed below) would lead to global plastic production levels of 680 or 1240 Mt in 2050, as is shown in Figure 1, which would correspond to total production of resin and fiber being 800 and 1460 Mt, respectively. For comparison,
extrapolating the current annual consumption level of 140 kg plastic resin per capita in NAFTA and Western Europe to a projected global population of roughly 10 billion in 2050 results in a global plastic production of 1400 Mt resin (or 1650 Mt resin and fibers), just with the 4% growth scenario, whereas the 2% growth scenario implies a global average annual use of 68 kg per capita, just about half of current NAFTA/EU consumption.

The petrochemical sector is responsible for a large environmental burden: 30% of final industrial energy use, 14% of global oil demand, and 9% of global gas demand and driving 16% of global industrial CO2 emissions, with plastics the largest product category of the industry. There are GHG emissions at all stages of the life cycle of plastics, starting with fugitive methane emissions from upstream oil and gas operations, direct process emissions from chemical reactions and high-temperature heat generation in steam crackers, indirect emissions from energy conversion in the energy sector for polymerization and conversion, to end-of-life (EoL) treatment of products. The carbon footprint of plastics has been estimated to be up to 5 kg CO2 per kilogram of plastic, including on average 2.3 kg CO2 per kilogram of plastic from feedstock production, plastic conversion, and electricity, and 2.7 kg CO2 per kilogram of plastic of carbon being embedded in the material.

One of the most comprehensive analyses estimated the life cycle emissions of the global production of plastic resin and fibers in 2015 to be 1.8 Gt CO2e, which correspond to an average of 4.2 kg CO2e per kilogram of plastic. This estimate is based on the use of fossil feedstock and the current energy mix and EoL management, the latter of which consists of 58% landfills, 24% incineration, and 18% recycling. In future development scenarios, the authors found that by 2050, global life cycle emissions of plastics could be as high as 8 Gt CO2e (about 5 kg CO2e per kilogram of plastic), assuming a 4% growth rate and incineration of all plastic waste. The global life cycle emissions of plastic could be considerably lower, about 1 Gt CO2e (1.2 kg CO2e per kilogram of plastic), for a scenario that assumes 2% production growth, 100% renewable energy, bio-based feedstock (sugarcane), and an EoL waste management mix of 44% recycling, 30% incineration, 18% industrial composting, and 2% anaerobic digestion. These scenarios are shown in Figure 2, highlighting the necessity of simultaneously considering the implications of demand growth, feedstocks, EoL, and energy use.

**CARBON LOCK-INS IN PLASTIC VALUE CHAINS**

The production of plastics, as well as many other industries and value chains, are all connected to various sources of carbon lock-in, which create barriers to the mitigation of their climate impact. Carbon lock-in is the “self-perpetuating inertia that is created by large fossil-fuel-based energy systems and that inhibits the emergence of alternative energy technologies” and can be seen as a special case of path dependency in the economy, relying on increasing economies of scope, scale, and networks related to fossil fuel resources. Complex technological systems, therefore, cannot be understood as “a set of discrete technological artifacts but have to be seen as complex systems of technologies embedded in a powerful conditioning social context of public and private institutions comprising a “techno-institutional complex.” This complex has developed over decades, focused on maximizing returns using fossil resources and globalizing markets for fossil commodities. Across energy systems and industrial sectors, GHG emissions are already locked-in for many years to come, driven not least by expectations of continued returns and market growth. Figure 3 is a schematic figure of the five identified carbon lock-ins in the plastic value chains.

**Lock-in in production**

Upstream production units, such as steam crackers and processing plants, are capital intensive; a large steam cracker can cost several billion US dollars. Much of the infrastructure for producing plastics and other petrochemicals is relatively young, with a global average age of 10–15 years—and often even longer in Europe and the United States. A large degree of the lock-in can be attributed to the underlying physical nature of the chemicals and processes routes: individual processes are typically fed by a single-resource input, have a high degree of material and energy integration, and produce an optimized mix of products; production consists of a large network of interconnected processes. Further, these production processes have significant economies of scale, leading to ever-larger production facilities to retain competitiveness in global markets.

Polymer production processes benefit from synergetic advantages because they are fed by a single energy resource (mostly fossil fuel), which provides both the feedstock material and the process energy. Chemical feedstocks account for more than half, and in some studies as high as three-quarters, of total...
energy inputs to the global chemical sector.\textsuperscript{28,41} Upstream petrochemical processes, such as refining and steam cracking, are built around access to fossil fuel supplies, i.e., crude oil for refineries or naphtha for steam crackers, with large integrated sites often located close to where petroleum oil or gas is extracted or brought onshore.\textsuperscript{42} Petrochemical industries are thus typically organized in clusters where several different companies exchange flows and depend on each other.

Process units in petrochemical industries, including steam crackers and other large units, are highly integrated continuous processes operating at very high temperatures and pressures, leading to very high energy demand and associated GHG emissions. These characteristics lead to highly integrated plants, where heat is recovered from processes through exchanger networks, electricity is generated onsite, and water systems are integrated to enable recovery.\textsuperscript{33} Material and energy flows are physically locked-in to operations through the integrated design of reaction vessels, process units, heat exchangers, pipelines, valves, sensors, and control systems, making them difficult to retrofit or upgrade once in operation.

Production of monomers in steam crackers and other upstream petrochemical processes are designed to produce a tailored recipe of co-products as outputs. This provides a synergistic advantage, making best use of the feedstock and minimizing waste, but leads to physical lock-in for the process, because each product is co-dependent on the continued production of the others. Petroleum refining has traditionally been a prominent source of naphtha and olefins for polymer production. However, recent advancements in drilling and hydraulic fracturing of tight oil and shale formations have increased the availability of wet natural gas, particularly in the United States,\textsuperscript{44} leading to the use of natural-gas-based feedstocks in place of more traditional liquids from petroleum processing.\textsuperscript{45,46} Anticipation of a more general shift for transport, from fossil fuels to electric vehicles, has prompted the development of new plants which convert directly from crude oil to plastics and other chemicals (see Box 1 for more details on this development). These trends, toward lighter feedstocks and crude-oil-to-chemical plants, go some ways toward decoupling transport fuel production from petrochemicals; however, the vast majority of production capacity still remains locked-in to traditional product mixes.

The petrochemical sector, in contrast to other heavy industries, is not one or two defined processes but instead the agglomeration of many processes and material flows and hundreds of thousands of plastics and other chemical products.\textsuperscript{29,42} Production processes operate across a vast and complex network of facilities and processes, where a high level of physical integration drives efficiency gains and lower production costs but also locks in the current production paradigm.\textsuperscript{39,53} The high levels of integration within and between petrochemical processes create a physical lock-in, making it difficult to change one aspect without impacting other parts of the process or production system. Potential low-carbon interventions, such as capturing carbon or electrification of process heat, are often
Box 1. Crude oil to plastics: The next big thing?

While the North American expansion of shale gas production has led to a focus on expanding ethylene and polyethylene production based on ethane, increasing the supply of other key monomers and polymers has relied on other feedstocks. Because plastics and other petrochemicals are expected to grow quicker than demand for petroleum, an increasing share of the processed oil is expected to be used for these products. Conventional oil refining produces only a limited volume of naphtha to be used for plastics and other petrochemicals, leading to growing interest in maximizing the production of monomers and platform molecules in “refineries of the future” that fully integrate with the production of plastics and other petrochemicals. This can be implemented through different technology strategies, ranging from modifying both thermal and catalytic cracking of different fractions down-stream of the crude distillation at a refinery to bypassing distillation and running the crude oil directly to a steam cracker. The latter was implemented already in 2014 by the integrated conglomerate ExxonMobil in their Singapore refinery, and they remain one of the stakeholders pushing the crude-to-chemicals agenda. However, other actors in the industry, from fully integrated oil and gas conglomerates to focused plastics and chemicals producers and specialized engineering firms, are also following this route and developing similar processes. For example, the planned Saudi Aramco/SABIC complex at Yanbu was designed to make 9 Mt of petrochemicals directly from 400,000 barrels per day of light crude oil. This plant will convert 45% of the oil to monomers and other petrochemicals, which is much higher than the 5%–20% for traditional refineries. A wave of investments in crude-based technologies has been seen in China recently. This has been expected because China has the highest level of refining and petrochemical integration globally and, therefore, the largest potential for deployment of crude-based production technologies as well as the largest demand for plastics. It is, however, also expected in other regions, such as the Middle East and India. These fully integrated facilities thus represent a new generation of ties between the fossil fuel and plastics industries and generate another layer of carbon lock-in for plastics production that is likely to last for decades.

Technically incompatible with existing plants, requiring extensive plant redesign when modified. For this reason, petrochemical plants are rarely modified to any large extent, and new capacity is expected to be produced via traditional steam cracking routes. Despite global warming targets, most plants still operate according to their original design strategy, restricting the introduction of new low-carbon solutions to new greenfield sites. One study, using detailed datasets of existing fossil fuel energy infrastructure in 2018, obtained an estimate of global committed emissions equal to 162 Gt CO2.

Significant investment in new plants has recently taken place in regions with access to low-cost petrochemical feedstocks (North America, Middle East, and China). Thus, in the absence of costly plant retirement or modification, emissions are locked-in for many years into the future, underlining that “little or no new CO2-emitting infrastructure can be commissioned, and that existing infrastructure may need to be retired early (or be retrofitted with carbon capture and storage technology) in order to meet the Paris Agreement climate goals.”

Lock-in in end use markets and demand

The use of plastics has transitioned from a material used as a (cheap) substitute or imitation of other materials to the creation of new consumer habits and cultures, which over the past decades have become institutionalized. The relative low cost and abundance of (fossil fuel) feedstock coupled with the diverse functionality of plastics have helped create an omnipresent and ever-growing demand for plastics. Cheap and abundant fossil fuel feedstock has helped enable plastics to create a throwaway culture, which has come to epitomize unsustainable consumption across the globe. Plastics have also enabled the growing demand for online shopping and takeaway services, which have changed consumer behavior. Innovations in plastics packaging have, for example, led to a huge array of new food products and eating practices—from single-packaged cheese sticks to fast food. In the same way that steel enabled new frontiers in buildings and infrastructure, plastics made possible both a huge variety of products and services that are essential for modern society and also the cheap and disposable consumer culture that we have come to take for granted.

Plastics have also increasingly displaced other materials. In areas such as textiles, plastics have overtaken traditional materials, such as cotton and wool, with polyester alone accounting for more than half of the global fiber production. With cotton and wool nearing peak production capacity, plastics is projected to account for most of future growth in textiles. Although plastic fibers reduce the water and land use impacts of textile production, polyester has 50% higher GHG emissions than cotton and thus a growing shift from cotton to polyester will significantly increase the climate footprint of textiles. The coronavirus disease 2019 (COVID-19) pandemic illustrates the double-edged sword of plastic consumption. In the short term, it has helped contain the pandemic though the use of personal protective equipment, public hygiene, and food safety. However, in the long term, the rapid increase in consumption of disposable applications is likely to exaggerate the inadequacies and inefficiencies of our current waste management system when dealing with plastic waste and could well trigger an environmental crisis directly related to the COVID-19 pandemic. It could also leave lasting effects on consumer perception and habits concerning single-use plastics, disrupting global momentum on reducing single-use plastics.

The multifunctionality of plastics means that plastics will continue to be ubiquitous in society. This necessitates that its climate (and environmental) impact be mitigated and that the unsustainable consumer habits we have created be addressed. Consumer perception of plastics has changed in recent years, with the threat of plastic pollution and toxicity compelling people to think more carefully about their use of plastics. However, it is not just individual consumption and behavioral patterns that need to be addressed but also the underlying norms and power relationships that support and maintain unsustainable levels of...
plastic consumption. Cheap and abundant fossil fuel feedstocks have helped drive our plastic consumption patterns. To break the carbon lock-in of plastics, one important consideration is for plastic to become more valuable both in people’s minds and throughout the value chain.

**Lock-in in waste management**

The increasing consumption of plastics is reflected in the growth of plastic waste. Plastic waste can be recycled, incinerated with or without energy recovery, or landfilled, if not leaked into the environment. Landfilling remains the dominant waste treatment option for plastic waste. A recent model-based assessment estimates that 220 Mt of plastic waste was generated globally in 2016, of which 31% (69 Mt) was landfilled, 13% incinerated, and 14% recycled. An estimated 19% (42 Mt) was leaked into the environment, and 22% (49 Mt) openly burnt either as fuel or as a means of disposal in absence of waste management infrastructure. It has been estimated that 8,300 Mt of primary and secondary (recycled) plastic waste was generated from 1950 to 2015, of which almost 80% was landfilled or released into the environment. Controlled waste management of plastic waste relies on waste collection infrastructure, which remains underdeveloped in many parts of the world. However, despite significant regional differences, it is estimated that informal collection of plastic waste, such as by waste pickers in developing economies, collects more plastic waste for recycling than the formal recycling sector worldwide.

Although many countries have restricted or banned landfilling of certain waste types, it remains the most common way of treating plastic waste worldwide. If not efficiently managed, landfills may serve as a source of plastic leakage into the environment, just like open dumpsites. Because plastics are commonly regarded as almost completely inert, landfilling of plastic waste may be also regarded as a carbon sink and preferable over incineration from a GHG emission perspective. However, knowledge about plastics degradation under different environmental conditions, such as in landfills, is limited, with significant uncertainty about its long-term fate. Environmental factors, such as humidity, temperature, and UV radiation, highly influence degradation rates and also the type of polymer. Several microorganisms that degrade common polymers have been identified in landfills indicating that increasing, slow releases of GHG emissions from landfills could become a problem, especially because most plastics ever produced have ended up in landfills. Plastics in long-lived products, such as in buildings, can be seen as a temporary carbon sink. However, if incinerated or landfilled at their EoL, these plastics also will eventually emit GHGs. Incineration of plastics, with or without energy recovery, immediately releases the carbon in the plastics into the atmosphere in the form of CO₂. The carbon content typically represents 50%–80% of the weight of plastics, depending on the plastic type.

In addition to GHG emissions, incineration results in residues, e.g., bottom and fly ash. Because incinerators have a lifetime of about 25 years and require continuous input of fuel, they create another infrastructural lock-in to GHG emissions and may prevent changes in the ways plastic waste is managed and treated. In fact, plastic waste is highly desired as an incinerator feedstock, due to its high calorific value, which is needed to maintain efficient combustion. A large share of informally managed waste is also burnt, constituting a significant share of regional GHG emissions, primarily in Asia and Africa, as well as a large source of particles and other hazardous air pollutants.

While recycling has been promoted as a solution for moving toward a circular economy, the contemporary global political economy around plastic waste forms another form of lock-in. Higher-income countries have exported plastic waste for recycling to lower-income countries, primarily China, for decades. This outlet has been used for plastic waste considered too costly to sort and recycle domestically and as means of avoiding incineration and landfilling. In January 2018, China implemented a policy banning the import of most plastic waste, leading to turmoil in the global plastic waste trade network. While plastic waste, in some cases, has been re-routed to other countries in Southeast Asia, other countries have followed China’s example of implementing stricter rules of plastic waste imports. Although this could potentially incentivize investments in improved recycling capacity in countries that have previously exported large volumes of plastic waste, it has immediately in the short term led to a rapidly growing illegal trade as well as an increased use of virgin plastics and redirection of plastic waste to incineration—leading to increasing GHG emissions.

Following new requirements for trade with plastic waste within the Basel Convention, there is hope for improvement, although the lock-in to problematic practices in plastic waste management and trade is likely stronger than the convention. Furthermore, the United States, which generates the most plastic waste globally, is not a party to the convention.

**Lock-in in industrial structures and organization**

The carbon lock-in of plastics in industrial structures and organization dates back to the post-war era, when petrochemicals became the primary domain of the chemical industry as it shifted its resources and knowledge base from coal toward oil and gas. This shift was quick in the United States, where oil companies had spent the war years developing new refining and processing technologies to make use of the fractions of crude oil remaining after producing vehicle fuels—aided in their aim by the establishment of chemical engineering as a field of education and general purpose technology. The shift was slightly delayed in Europe, where the industry was committed to the use of domestic coal reserves, but soon followed. Despite the dominance of the German firm IG Farben in plastics research and innovation in the inter-war era, US firms came to lead the market as it matured.

During those first decades, plastics was “the engine for growth” for the petrochemical industry and remained a foundation for its development throughout the 20th century, as producers constantly invented new demands for plastics and solidified their central role in modern lifestyles, characterized by smooth, colorful, disposable plastic products. Plastics were thus a key market for non-fuel refinery fractions, e.g., naphtha and LPG (liquefied petroleum gas), and became cornerstones of the emerging vertically integrated conglomerates, which controlled both upstream and downstream processing. The institutionalized “special relationship” between fossil fuels and chemicals that was developed already in the 19th century thus survived and grew even stronger in the era of...
plastics. As the industry grew in regions other than Europe and the United States, e.g., Japan and South Korea, which provided an opportunity to break with the institutionalized connections from Western markets, these same structures were instead replicated, effectively globalizing carbon lock-in along the same path.96

The global homophily in the industry remains evident and a source of lock-in in industrial structures and organization. The largest firms are closely connected to each other through corporate boards, joint ventures, and spatial interlock networks.94 They rely on global markets for technology, licensing technologies to and from their competitors or specialized engineering firms.95,96 The petrochemical industry response to environmental concerns has largely been a coordinated denial of its responsibility from the first DDT (dichlorodiphenyltrichloroethane) scandal in the 1960s to the recent marine plastic pollution debate,97–99 and efforts, institutionalized as global self-regulation initiatives, have been criticized for their limited sanction power, although improved through third-party verification.96,97 The pattern is now repeated as large firms are pressured to act on the climate crisis and form industry alliances to manage the problem without international regulation.97 Confident that the calls for a circular plastic economy, which threaten the locked-in business model, remain “long on intentions, [but] short on solutions,”92 these global networks thus create barriers for initiatives, which aim to push an agenda against the carbon lock-in.93

Expecting continued growth and acceptance for fossil-based plastics, the major producers have in the past decade made massive investments in new and expanded production capacity.94 Over the period from 2010 to 2019, 221 billion euros94 were invested in the United States alone in expanding the production of plastics and other chemicals, largely fueled by booming shale gas production, providing plastic producers with high-quality cheap feedstock.43,96 This figure is, however, dwarfed by Chinese investments into chemical production, which amounted to 748 billion euros in the same period.94

Lock-in in governance domain

Because plastics vary significantly and are used extensively in many different domains, the topic also cuts across various policy arenas, e.g., climate,96 environment,97 automotive,98 construction,99 chemicals,100 trade,16 and waste.101 This has historically resulted in a fragmented and uncoordinated governance structure(s) around plastics.102 However, two trends on policies have emerged: market restrictions for single-use plastics and transitioning toward a circular plastic economy.7 The former is evident through the increasing number of policies that aim to reduce plastic pollution by banning specific items, such as carrier bags or straws.103 Restrictions on the transboundary movement of plastic waste have also emerged, most noticeably the Chinese import ban on nonindustrial plastic waste and the 2019 Basel Convention amendment.15,104 The circular economy is also shaping policies on plastics, in particular in the EU105 and China106 and among non-state actors.87 This circular economy is seen as being able to tackle several plastics challenges, such as resource inefficiency, as well as environmental and climate impacts.107

Research has concluded, that although current governmental commitments to reduce plastic leakage can have immediate, concerted, and vigorous effects, they will still—even in the best of scenarios—result in large quantities of plastics accumulating in the environment.94,111 Many plastic pollution reduction policies have even been suspended, canceled, or postponed in the wake of the COVID-19 pandemic,135 albeit far from all. Similarly, although this circular economy is helping to unlock policy and business model innovations, a vast majority of plastics use is still locked into a linear economic system. Despite this broad range of actors favoring a circular economy, implementing circular economic policies and actions is likely to unravel the underlying conflicts of what exactly a circular plastic economy entails.97,108–110 Neither of the policy trends has been able to break the fossil dependency of the plastic sector.

Several of the largest plastic producers, such as SABIC and Sinopec, are directly or indirectly state-owned, which means the government that should regulate plastic (production) is also heavily vested in and subsidizes their continued expansion.111 Several plastic producers are members of trade associations, which have been active in lobbying efforts to reduce stricter policies on different types of plastic products.112,113 Breaking the carbon lock-in from a governance perspective entails, first of all, more radical governance action—both public and private—on the issue, because the current policies set in motion are not likely to have a significant impact on breaking the global carbon lock-in of plastics. Second, current policies need better alignment to ensure that various strategies on plastics do not lead to conflicting priorities.114 Third, ongoing discussion on a global plastics treaty may serve as a platform for aligning policies and practices on plastics, but it needs a broader focus than plastic pollution, including on climate change, taking the entire life cycle into account.7,115

MITIGATION PATHWAYS FOR PLASTICS

This section presents three major mitigation pathways and their promises and drawbacks, reflecting the heterogeneity of plastics and the implications of this for these pathways and their mitigation potential. The specific mitigation potential of each pathway is difficult to quantify; however, the key aim of this section is to highlight the need to consider several mitigation strategies in order to reach a decarbonized plastic system. The three pathways are as follows: reduce, reuse, and substitute; biobased and alternative feedstock; and recycle and circulate (Figure 4).

Reduce, reuse, and substitute a degrowth economy

Reducing emissions is possible if the use of plastics is decreased through either a reduced need for products or services fulfilled by plastics, reduced use of plastic materials to fulfill specific functions, or reuse of plastic products for the same function. Plastics can also be substituted by other materials with lower emissions. For example, the climate impact from plastic drinking straws, a plastic object that has become a symbol for wasteful use in recent years, can be mitigated via banning the sale of plastic straws, making plastic straws thinner, having washable and reusable straws, or substituting the material of the straw. Breaking the correlation between increasing economic welfare and plastics use is crucial to achieving a significant reduction in the use of plastics. This is likely to start with single-use plastic products and packaging.114 Certain applications of single-use
plastics, such as in the medical sector are, however, indispensable to modern society as long as alternatives are not available. Slowing down the use of resources, and thereby using less material by enhancing product quality, as well as product life extension through design, reuse, repair, and remanufacturing, is important for more complex applications and in applications where reduction is problematic.117 Design strategies to reduce the use of material include designing long-life products, which involves aspects, such as the traceability of materials, durability, reliability, and design for product life extension through reuse of the product itself, maintenance and repair, upgradability, and adaptability as well as disassembly and reassembly.117

Using fewer plastics reduces emissions across the whole value chain, from extraction to EoL, and can also contribute to fewer plastics in landfills and environmental leakage.102 There is no literature that systematically assesses the potential to reduce demand for plastics and resulting emissions through sharing economy, service demand, material efficiency, reuse, or substitution measures. The diversity of polymers, applications, and geographical contexts makes such assessments challenging. Much of the literature on sharing economies is focused on sharing of cars, a product category with a significant demand for plastics. Results are often inconclusive concerning the resulting reduction of the environmental footprint, because it depends on assumptions, context, and second-order effects.118 Literature on reducing the need for products and services fulfilled by plastics is limited and mainly focused on plastic carrier bags.103 One finding is that the effects and their permanence of bans, taxes, and fees to reduce consumption vary widely across geographical contexts.

Material efficiency is an option that has been shown to have significant potential for other materials, such as steel and cement,119 and, when studying sectors, such as buildings, vehicles, and electronics, which together constitute a significant share of plastics demand.120 Assessments that focus on plastics are largely lacking. Light-weighting has been a prominent strategy for plastic packaging, although there are also numerous other strategies for optimization.121 Eliminating packaging or reusable packaging are other options, but these may require further changes of consumer practices, especially for foods. The mitigation potential and possible negative drawbacks of substitution and reduction are poorly understood. For example, improving material efficiency through lightweight laminates of different plastics, instead of heavier homogeneous materials, reduces weight but also reduces recyclability. The choice of polymer in meat trays can significantly decrease the carbon footprint of the packaging, but the emissions are almost negligible compared with those for the meat.122 Priority areas for greener packaging include reduced food waste, energy use, and packaging material, depending on the type of food.123 It may be noted that glass and metal for packaging is often associated with higher emissions due to energy and transport emissions, but this balance may change, as energy and transport are increasingly decarbonized.

There are several options for plastic reuse, ranging from second-hand Lego bricks to plastic crates for transporting vegetables as well as reuse of grocery bags and refill systems. There are few systematic assessments of the mitigation potential of reuse, but a key point for alternatives to single-use products is the number of times they have to be reused, which differs across applications.124 For reuse business models to succeed, end consumers must perceive them as convenient as standard offers on the current market, without large cost increases.108 Substitution of plastic packaging for other materials has been shown to give mixed results, highly dependent on the context, because plastics may be more effective and lighter than alternatives.126 Despite the many policy and industry initiatives, there is thus still little evidence for significant mitigation being achieved through reduction and substitution strategies.

Bio-based and alternative feedstock—A bioeconomy

The second mitigation pathway consists of utilizing renewable plastic feedstock and energy in plastics production, thereby reducing the use of fossil resources and their associated GHG emissions.126 This change in feedstock includes drop-in solutions that would enable the plastic system to remain relatively unchanged and the introduction of new materials that, in turn, would require changes in design, production, and waste management infrastructure.22 There has been a moderate increase in the production of bio-based plastics during the past few years. In 2020, the production capacity of bio-based plastics amounted to 2.1 Mt, which corresponds to about 0.5% of total production.127 The production capacity is forecast to reach 2.9 Mt in 2025. One less developed, but still potential, renewable feedstock for plastic, is captured carbon dioxide,129,130 which could also be synergistically used with bio-based production processes.131 The source and substitution effect of the captured CO₂ are crucial when estimating the climate impact and mitigation potential of such processes.132 Another niche technology with growing expectations is (green) hydrogen, which can be used both as a feedstock and energy source.133 However, both alternatives come with a high energy penalty.

Bio-based plastics can be derived from different biological feedstocks, such as oil, sugars, starch, and cellulose.134,135 The most common bio-based plastics still use first-generation feedstocks, e.g., corn, sugarcane, and castor bean.136 Drop-in
plastics use a renewable feedstock but are in all other aspects similar to their fossil counterparts, e.g., bio-PE and bio-PET (which is only partly bio-based). However, the biggest market share is currently taken up by plastics which are both bio-based and biodegradable, e.g., polyactic acid (PLA) and starch blends.137 “Bio-based” and “biodegradable” are attributes describing fundamentally different polymer characteristics. Plastics marketed as biodegradable can be fossil based or based on biological feedstock. They are biodegradable only under specific conditions, commonly in standardized industrial composting processes, but not in the open environment.57,138

Large plastics producer firms have taken different approaches to exploring bio-based plastics, with Braskem being able to exploit connections to the large Brazilian bio-ethanol industry to establish bio-PE as the largest drop-in bio-based plastic.139 After concerns were raised relating to land uses (change), alliances were formed to improve the legitimacy on bio-based plastics,140 but historic forecasts of the expected growth rate for bio-based plastics have not been realized,134 and consumers still have a very limited understanding of bio-based plastics.141,142 It is likely that there will be some tension between different stakeholders, with some advocating that bio-based cannot replace (all) fossil-based plastics.141,142 Independent of which decarbonized feedstock alternative is developed, mitigation potential exists in the phase-out of fossil feedstock and energy use within production, but this mitigation potential differs significantly across polymers, contexts, and assessment methods.143,144 Mitigation potential is highly sensitive to emissions from feedstock production, such as land use change emissions.145 Switching to renewable energy within production is a favorable strategy compared with switching feedstocks, not only with regard to the economics and immediate mitigation potential146 but also long-term because the largest mitigation potential resides in adopting these strategies together.9

A key drawback of the suggested mitigation pathway is that it does not include wider sustainability aspects, and the social and economic implications remain largely unexplored.146,147 Bio-based plastics do nothing to address issues, such as excessive consumption, waste management failures, or poor recycling. In fact, some bio-based plastics cause significant problems in existing recycling schemes, e.g., if PLA is mixed with PET, it is degraded in the process, leading to low-quality recycled PET (rPET) and causing problems in operations,148,149 pointing to the need for considering recyclability and functionality already in the design of novel bio-based polymers.23 Furthermore, while there may be opportunities to increase the use of locally sourced plastic feedstock for climate mitigation, employment, and energy security, there are many questions regarding feedstock availability and sustainability that remain unsolved. If petrochemical plastics are to be replaced by bio-based counterparts, this will result in an increased use of land and water,150 with decreased biodiversity outlined as a likely consequence109,151 and uncertainties with regard to the mitigation potential.144 Switching to renewable energy to power energy intense production processes will reduce overall emissions but still allow for a fossil lock-in of feedstocks. Moreover, the energy intensity of mitigation options, such as carbon capture utilization and storage, and especially green hydrogen, would necessitate a colossal investment and energy infrastructure expansion. In one scenario, decarbonizing part of the petrochemical sector through green hydrogen would require the combined current electricity production of the United States and China.152

**Recycle and circulate a circular economy**

Recycling of plastics has recently become the dominant mitigation pathway for decreasing the negative environmental impacts of plastics, including GHG emissions but primarily marine plastic pollution, and an important part of strategies for a circular economy.153 Using recycled plastics for new products avoids the most energy-intensive steps of virgin plastic production, thereby significantly reducing the related climate impact.

Recycling instead of incinerating plastics reduces GHG emissions by 1.1–3.0 kg CO2 per kilogram of plastic compared with virgin plastic production.1 Recycling requires a design for recycling, more efficient collection and sorting of plastic waste, and further development of mechanical and chemical recycling technologies. It requires not only “design for recycling” but also “design from recycling”21: recycled materials must be absorbed by the manufacturing industry and seen as the starting point also for design of high-quality products.21 The recycling rates and the value of recycled plastic could increase and lead to a more economically viable mechanical recycling industry.154

Recycling can be divided into mechanical and chemical recycling processes, of which the mechanical, i.e., re-melting and conversion of plastics to recyclates of different qualities, is the dominant one.20 It requires a series of steps involving collection, sorting, shredding/grounding, washing, and reprocessing before the recycled material is mixed with virgin plastics or mechanically converted to pellets on its own.155 Despite the fact that many plastic types are mechanically recyclable in theory, there are challenges linked to the complexity of collecting, sorting, and pre-treating plastic waste before the actual recycling process; these processes also degrade the polymers.155 Low collection rates of plastic waste remain a key challenge, because the plastic waste is not made available for recycling.155 Plastic products often consist of multiple plastic types or mixes of plastics and other materials, with little harmonization from region to region over what is considered recyclable and the types of products and plastics collected for recycling.2 Collected plastic waste often comes with contaminants and incorrectly sorted material, leading to technical difficulties in achieving recyclates of high quality.156 Furthermore, the plastic waste may contain hazardous substances that are no longer permitted but which are embedded in old plastic products entering waste and recycling streams.157–159 Because mechanical recycling cannot efficiently remove additives, such as plasticizers, fillers, and flame retardants, from plastics, knowledge about the composition of the recycled material is lost, and with that a large portion of the plastics’ value. As a result, a significant share of the plastics collected for recycling is discarded in the sorting and recycling process.160 The recyclates, especially from post-consumer
plastic waste, are often of inferior quality compared with the virgin counterparts, leading to production of low-value products and the need to dilute the recycled plastics with virgin plastics, which significantly affects the GHG emission savings of recycled plastics. In the case of food packaging, which dominates plastic packaging, recyclates have difficulty meeting the legal quality constraints related to food safety. Thus, most recycled plastics still end up in low demand and as lesser-quality non-packaging products, such as garden furniture, fence posts, and pallets.

Chemical recycling has been raised as a promising complement to mechanical recycling, to be used for plastics where mechanical recycling is economically or technically unfavorable. In theory, chemical recycling could enable full recyclability of plastics with outputs of virgin-grade quality. Chemical recycling is often used as an umbrella term for several thermal and chemical process technologies that break down plastic waste into monomers; oligomers; or liquid, solid, and gaseous hydrocarbon mixes. Although there is still some inconsistency in the nomenclature, three main types of chemical recycling can be distinguished: solvent-based purification, depolymerization, and thermal processes (mainly pyrolysis and gasification), with different types more or less suitable for specific polymers. The main advantage with pyrolysis, the most studied chemical recycling technology, and gasification is the possibility to convert more mixed and contaminated material into basic chemicals using the existing petrochemical industry infrastructure. There is, however, no guarantee that the output chemical will be converted into new plastics. Currently, the output from pyrolysis is largely used as fuel, which cannot be considered recycling. Solvent-based purification and depolymerization are not yet commercially available, and their potential as a mitigation pathway on a short timescale (before 2030–2040) is therefore limited. These types of processes are also more attuned to specific polymers, which may also need further optimization for chemical recycling. Today, a handful of industrial-scale pyrolysis plants with plastic waste as feedstock are in operation, but most efforts within chemical recycling remain in different stages of research and development.

The main drawback of chemical recycling is the high energy demand required to deliver elevated temperatures and/or pressure for processing. This leads to questions about the future competitiveness of the process at an industrial scale and its environmental impact. Few assessments of the climate impact of chemical recycling have been made so far, leading to large uncertainties regarding their mitigation potential. Comparative analyses show different potential across polymer groups and stress the point that it is not a universal solution. The potential as a mitigation pathway would be strengthened if the processes are powered with renewable energy sources and designed to fully capture and utilize all the carbon in the waste plastics. Yet, because the role of chemical recycling is primarily to support mechanical recycling, rather than replace it, it can be argued that a direct comparison between chemical and mechanical recycling, for example by using life cycle assessment (LCA), is not useful. The main drawbacks of chemical recycling include the high energy demand required to deliver elevated temperatures and/or pressure for processing and questions around potential low yields and scalability of the technology.

**DISCUSSION**

**Connecting lock-ins and mitigation pathways**

The sustainability issues highlighted by the contemporary plastic crisis have become priorities for an increasing number of actors and initiatives; however, the ambitions and targets of these initiatives and strategies fall short of mitigating the negative climate impact of plastics because they tend to be focused on mitigating plastic pollution. Although the potential for each mitigation pathway is not well mapped, we assess that no single mitigation pathway is likely to achieve deep decarbonization alone; instead, multiple pathways are needed in order to break the lock-in between fossil resources, energy, and plastic value chains. The pathways have the potential to induce change in different parts of plastic value chains and life cycles but also encounter different types of challenges. When looking across the lock-in domains identified previously in this paper, we identify a number of challenges that each of the pathways must overcome to fulfill their potential to contribute to significantly reduce the climate impact of plastics. Figure 5 summarizes the key challenges for each of the pathways in overcoming identified lock-ins in different domains of plastic value chains.

Starting off with the first pathway, reduced demand for virgin plastics is perceived as a threat to a large part of the existing industry, because it might result in stranded assets, production over-capacity, and a costly reorientation to survive. Socio-cultural norms and consumption practices may be difficult to change and will require policy development and experimentation. The potential for reduced use differs widely across geographies, and an increased use in developing economies is still likely. Even though this pathway aims at creating less waste, substitution may generate new waste management challenges and have negative side effects, depending on solution and application.

The second pathway, bio-based and alternative feedstock, faces somewhat different challenges. There is relatively weak support for introducing bio-based feedstock by policymakers, possibly as a result of the strong connection with fossil oil and gas industry but also due to uncertainties associated with the sustainability impacts of land and water use. Bio-based feedstock markets behave differently from their fossil counterparts due to seasonal variation and different geographic availability, and their processing requires a new knowledge base in the industry. Furthermore, introducing bio-based or biodegradable plastics creates challenges for production, recycling, and waste management infrastructure. Consumer confusion between bio-based and biodegradable, combined with a higher cost, also creates barriers for the development and implementation of this pathway.

The third pathway, increased recycling and circularity, faces key challenges despite its popularity among public and private actors. There is a need to develop and implement circular and recycling policies and business models in order to change the market logics toward more sustainable value chains. The slow adoption of new standards and strict policies in this domain shows the complexity of the task. New investments must be
made to improve the recyclability of the wide variety of end products. At the same time, the recycling infrastructure needs process development and modifications to improve efficiency throughout the complex process of collecting, sorting, and introducing recycled material back to the market, regardless of its performance and appearance.

While acknowledging the need for pursuing mitigation pathways both in parallel and through complementary efforts, there are also trade-offs that will have to be made to break all aspects of lock-in. Several of these have already been highlighted: pursuing demand reduction by extending product lifetimes yields conflicts if more plastics have to be used to make the product last longer; light-weighting has significantly impaired the recyclability of plastic packaging by introducing laminates that cannot be effectively recycled; the markets for novel bio-based polymers may for several years be too small for effective dedicated recycling; and chemical recycling reinforces lock-in in production technologies and only moderately reduces GHG emissions.

The complexity of navigating these pathways should not lead actors to defer from action. When firms, policymakers, and stakeholders develop road maps, it is, however, imperative to acknowledge these conflicts and identify procedures of managing them.

What becomes evident across the identified pathways is the need for low-carbon energy to run the energy-intensive operations throughout plastic value chains because the fossil energy mix used currently constitutes a large share of the associated emissions. This has been highlighted before when looking at virgin plastics production but is worth emphasizing in light of recent contributions that show also the significant climate impact of plastic conversion due to the energy demand of conversion processes, such as injection molding. Although there may be immediate gains to make in terms of climate impact by optimizing the use of energy in production, it is obvious that low-carbon electricity is a key for this stage of the value chain. Increasing plastic recycling will also lead to increasing energy demand to close the loop, especially for the chemical recycling technologies currently under development. Despite large volumes of decarbonized energy being a cornerstone of low-carbon development for plastics, there is

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**Figure 5. Identified key challenges for each mitigation pathway**

Key challenges for the three mitigation pathways (top) in overcoming the different domains of carbon lock-in (left).

| Production          | Market demand        | Waste management | Industry organisation | Policy and governance |
|---------------------|----------------------|------------------|-----------------------|-----------------------|
| Stranded assets     | Consumption norms    | Negative or unknown side-effects | Perceived as a threat | Growth and development policy |
| Production over-capacity | Unknown potential    | New waste challenges | Reorientation to survive | Lack of knowledge |
| Complex value chain |                      |                  |                       |                      |
| Incompatible with current infrastructure | Consumer confusion    | Modified or new recycling infrastructure | Fossil connections | Weak support |
| Sustainability issues | Higher price         | Waste challenges remain | Feedstock behavior | Unclear climate impact |
| Demand for recyclability | Performance and appearance | Complexity of collection and sorting | New competences |                      |
|                      |                      | Waste management capacity | Restructure of market focus |                      |

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seemingly a lack of strategic action on behalf of the industry to incentivize, support, or take part in supporting such a development.

**Remaining key knowledge gaps**

A number of important remaining knowledge gaps are identified that future research must fill to break ground for the mitigation pathways. It has to be emphasized that the lack of publicly available data about petrochemical processes and flows is a key barrier to understanding the consequences of physical lock-in and assessing the mitigation options for the sector. This has made reliable and transparent assessments of GHG emissions accounts and future mitigation options, across the whole life cycle of chemical products, particularly challenging.

Reducing the use of plastics on a global level seems unlikely when considering the rapid demand growth that can be expected in emerging economies in the coming decades. However, reaching the lower-demand scenario would require a significant reduction of demand compared with the current situation in Western economies. Key questions are thus “To what degree could reduced demand for plastics be reached independently of other resource use?” and “In which domains is a significantly reduced use most likely to be achieved?” Because a portion of demand reduction can be achieved through improved material efficiency measures, it is key to develop measures and instruments for material efficiency. Further, because some of this reduction is likely to occur through substitution, it is imperative to understand the trade-offs when substituting plastics for other materials completely or partially, e.g., through the use of composites, and how such substitutions affect the material life cycle and affect different types of applications and value chains.

Regarding recycling, most analyses are focused on the recycling of plastic packaging waste, because this is both the largest and most widely collected waste stream, although this differs across geographical contexts. This variety should be analyzed further to ensure that the livelihood of vulnerable communities working with informal plastic recycling is not compromised when expanding plastics recycling. To fully reach the mitigation potential of the recycling pathway, more knowledge is needed on the possibilities and boundaries of recycling other plastic waste streams. Because textiles are the second largest sector, in terms of plastic waste generation, it is essential that recycling technologies for synthetic fibers—primarily polyester—are developed, together with more efficient practices and infrastructures for collecting and managing waste textiles that consumers would be likely to be able to sort cleanly. Although plastic waste from the automotive as well as building and construction sectors is more heterogeneous, this type of waste is primarily generated in regulated professional settings. It is thus key to quickly identify the current best practices that can be diffused to improve collection and sorting. Finally, we need policy experimentation and analysis to advance the safe use of recycled plastics in more types of products. In areas with very low levels of recycling, more research should be conducted on local conditions and capacities for upscaling recycling infrastructure, innovative solutions to increase sorting and collection, initiatives (public/private) that can facilitate increased recycling, and support for locally closed loops for plastics.

Finally, the potential for a global governance structure to mitigate plastic pollution is under scholarly study and being developed within international institutions, but there is, to date, little connection between these experiments and a unified climate governance of plastics. It is, therefore, important to identify the opportunities for synergies and potential overlap between climate governance and other initiatives targeting plastics, e.g., plastic waste trade, industrial decarbonization, and a potential global convention on marine pollution. More research is also needed on how the three pathways play out on a local level. Socio-technical and political conditions vary greatly and impact the feasibility and potential of various solutions, e.g., what works in Europe may not work in Asia and so forth. Similarly, the impact of certain pathways on other countries needs to be more thoroughly understood so that the problem is not simply exported to other countries, e.g., restrictions on plastic waste trade. Zooming in on individual sectors of plastics, more research into solutions in areas beyond packaging is needed, including agriculture, construction, and thermoset plastics. Zooming further in on individual polymers, more research is needed on their respective potentials according to the different pathways, e.g., PET and PE work well with recycling, while PVC is often something recyclers want to avoid in their waste streams. Zooming back out, more research is needed on how to navigate this complexity within the emerging global plastic governance architecture.

**OUTLOOK AND CONCLUSIONS**

This paper has presented a review and examination of the plastics carbon lock-in in several dimensions as well as three pathways for mitigating the climate change impacts of plastics. Reducing the use of plastics, recycling materials to close the loops, and switching to bio-based and alternative feedstocks are pathways that together with low-carbon energy can support the shift to near-zero emissions. However, this review shows that the potential, feasibility, and implementation of the pathways are all underexplored topics.

The complexity of plastic value chains is striking in comparison to other energy- and emissions-intensive material industries. This is manifested in the variety of interconnected processes and companies in petrochemical clusters, huge diversity of plastics, and omnipresence of both short- and long-lived products across all domains of modern life. As a result, the fossil lock-in is very strong. The pathways are also complex and certain measures sometimes in conflict. For example, to reduce plastics use through light-weighting may impair recyclability and increase emissions elsewhere. This complexity, including uncertainty concerning the effectiveness of measures and conflicting interests across value chains, hampers the envisioning of zero emission futures and how to get there.

Adding to the complexity, the chemicals industry has a history of self-regulation while policy and governance efforts mainly target chemicals safety. There are emerging efforts to manage littering, improve recycling, and reduce some single-use plastics through various policies. However, these efforts have incentivized only marginal changes to existing value chains and business models. Neither industry itself nor policy is currently aiming for the systemic change needed to break
the fossil carbon lock-in and comply with international climate policy objectives.

The review leads to three important observations. First, aligning with climate policy objectives and breaking the carbon lock-in require visions, strategies, and targets for this sector as well as for individual chemical clusters and corporations. As noted above, this is not an easy task. Second, the pathways suggested are relatively unexplored, and current initiatives are weak in relation to what is needed. The diversity of applications and uncertainty about “what works” is an argument for supporting technology development, innovation, and experimentation across value chains. Third, improved governance capacity is clearly needed to push the development toward zero emissions, including instruments to disincentivize the ongoing expansion of fossil resource use. In addition, government policy is important for reshaping markets, improving waste management, and providing effective and contextually adapted infrastructures aligned with the three pathways.

Looking toward 2030 and beyond, there is a clear need for decisive action by both policymakers and industry to reduce the climate impact of plastics. Following pledges for climate neutrality by 2050 or 2060 made by key economies recently, a window of opportunity for global collaboration has opened. The plastics and chemicals industries will account for an increasing share of remaining emissions, if other large emission sources, such as transport, electricity generation, and the steel industry, implement their already existing visions and strategies to reach zero emissions. As a result, the pressure will only continue to increase on plastics to break the carbon lock-in. This would be in line with the ambitions for a circular economy, which will need to see massive investments in resource management, where developed economies could take a leading and supporting role to aid emerging economies, which now bear a proportional large share of the burden of both climate change and plastic waste pollution.

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AUTHOR CONTRIBUTIONS

Conceptualization, F.B, L.J.N., and T.D.N.; investigation, all authors; writing – original draft, all authors; writing – review and editing, F.B., L.J.N., T.D.N., K.E., A.F., and E.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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