PLASTICS

Achieving net-zero greenhouse gas emission plastics by a circular carbon economy

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Mitigating life-cycle greenhouse gas emissions of plastics is perceived as energy intensive and costly. We developed a bottom-up model that represents the life cycle of 90% of global plastics to examine pathways to net-zero emission plastics. Our results show that net-zero emission plastics can be achieved by combining biomass and carbon dioxide (CO_2) utilization with an effective recycling rate of 70% while saving 34 to 53% of energy. Operational costs for net-zero emission plastics are in the same range as those for linear fossil-based production with carbon capture and storage and could even be substantially reduced. Realizing the full cost-saving potential of 288 billion US dollars requires low-cost supply of biomass and CO_2, high-cost supply of oil, and incentivizing large-scale recycling and lowering investment barriers for all technologies that use renewable carbon feedstock.

Between 1950 and 2015, plastic production increased from 2 to 380 million metric tons (Mt) year^{-1} (*1*), leading to the ever-increasing plastic pollution of natural environments (*2*–*5*). The production of plastics is expected to increase its share of global oil consumption from 6% today to 20% by 2050 (*6*). Additionally, by 2050, plastics are expected to reach more than 1100 Mt per year and claim 15% of the yearly greenhouse gas (GHG) emissions allotment to keep global warming below 1.5°C (*6*). However, meeting global climate targets will require net-zero GHG emissions by the second half of the century (*7*), so the life-cycle GHG emissions of plastics must be reduced. Strategies to mitigate GHG emission include decarbonization of the energy supply of the plastics supply chain from oil extraction to plastic production, and the implementation of circular technologies (*8*–*12*)—such as (i) chemical and mechanical recycling, (ii) biomass utilization, and (iii) carbon capture and utilization (CCU)—to exchange the fossil carbon feedstock.

Recent literature on individual or partly combined circular technologies shows large-scale projected reductions in GHG emissions (*13*–*18*). However, no study identifies how circular technologies can be combined to achieve net-zero emission plastics. Furthermore, utilization of circular technologies is constrained because circular technologies are generally associated with higher energy demands and costs (*15*).

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Our study shows that by combining recycling, biomass utilization, and CCU, net-zero GHG emission plastics could be achieved with lower energy demands and lower operational costs than those associated with current fossil-based production technologies combined with carbon capture and storage (CCS). For this purpose, we built and used a global bottom-up model for plastics production and waste treatment based on >400, mostly industrially validated, life-cycle assessment compliant and harmonized technology datasets representing the life cycle of >90% of global plastics.

Using this model, we project five pathways for life-cycle GHG emissions of plastic from "cradle-to-grave" in the year 2050. The recycling pathway allows maximal recycling of all plastic wastes, on the basis of a 6% minimal landfilling rate projected by Geyer *et al*. (*1*). By contrast, the biomass and CCU pathways assume that plastic waste is primarily incinerated. The resulting CO_2 emissions are circulated via biomass uptake or CCU. The circular carbon pathway optimally combines recycling, biomass utilization, and CCU. The GHG emissions of all circular pathways are benchmarked to state-of-the-art plastic production and waste incineration, framed as the linear carbon pathway. The current fossil-based industry already includes recycling. Because landfill of plastics will increasingly fade (*1*), the remaining options for plastic waste treatment are energy recovery (represented by the linear carbon pathway) and the recycling pathway. Thus, these two scenarios depict the complete range of potential fossil-based futures for plastic waste treatment.

Achieving net-zero emission plastics

Our results show that the recycling pathway, via mechanical and chemical recycling, reduces GHG emissions by 3.0 billion tons (Gt) of CO_2 equivalent (CO_2-equiv) or 64% compared with the linear carbon pathway (Fig. 1A). Up to 4.5 Gt of CO_2-equiv (95%) are reduced by a biomass pathway, where biomass uptake recycles CO_2, compensating for the emissions primarily due to plastic waste incineration and the production of fossil-based feedstocks such as naphtha. Whereas plastic waste and biomass provide carbon and sufficient energy for conversion, CCU technologies require electricity with a low carbon footprint to reduce GHG emissions, mainly to produce hydrogen by water electrolysis (*19*). For the current global average carbon footprint of electricity (*20*), CCU would increase plastics' GHG emissions. However, by using electricity with the current footprint of wind power, commercialized CCU technologies can reduce up to 4.4 Gt of CO_2-equiv (94%). Overall, plastics solely based on recycling, biomass utilization, or CCU fail to reach net-zero GHG emissions, even for wind-based electricity production. Assuming wind-based electricity supply, between 0.2 Gt and 1.7 Gt of CO_2-equiv would have to be abated by negative-emission technologies, such as direct air capture (DAC) with CO_2 storage (*21*), to achieve net-zero plastics.

In the single-technology pathways, waste incineration, biomass, and renewable electricity supply are the residual GHG sources that prevent fully net-zero emission plastics: Even though recycling rates are maximized, all recycling processes produce residual wastes. These residual wastes are incinerated, leading to unavoidable GHG emissions even for maximal recycling rates. Additionally, waste incineration emits small amounts of non-CO_2 emissions, such as carbon monoxide or methane, increasing residual GHG emissions for biomass utilization and CCU. Biomass cultivation emits noncarbon GHGs, such as nitrous oxide, that the CO_2 uptake cannot counterbalance. Even in the most ambitious scenarios of the International Energy Agency (IEA) (*19*), renewable electricity production is not entirely net zero by 2050, with ~13.5 g of CO_2-equiv per kWh (*22*), leading to residual GHG emissions from electricity supply in the CCU pathway. Even wind-based electricity (i.e., electricity production with the lowest current GHG emissions) is not fully net zero (*23*).

By contrast, the circular carbon pathway that optimally combines recycling, biomass utilization, and CCU reduces GHG emission of plastics by as much as 4.73 Gt of CO_2-equiv, assuming wind-based electricity (Fig. 1A). Thus, the plastics' life cycle would even be slightly net-negative. The shift is achieved because the combination of all circular technologies minimizes residual GHG emissions (see materials and methods, as well as fig. S5 for a detailed Sankey diagram).

Biomass takes up CO_2 and thereby offsets CO_2 emitted from waste incineration and production processes. The respective biomass is then gasified to generate synthesis gas, a mixture of hydrogen and carbon monoxide, for methanol production. CO_2 produced during

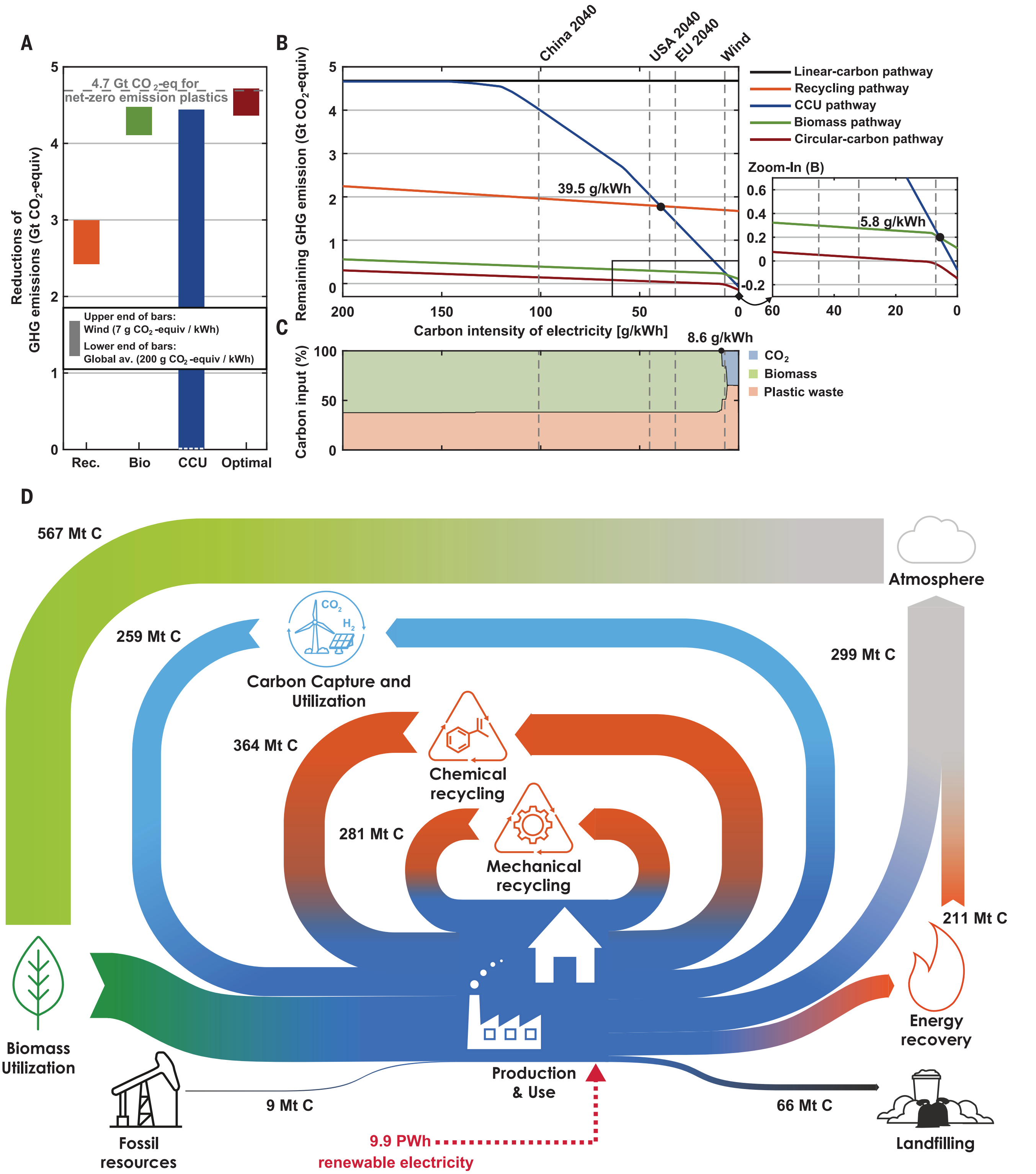

Fig. 1. Potential reductions of global GHG emissions of plastics by four circular pathways in 2050. (**A**) Reductions of life-cycle GHG emissions from "cradle-to-grave" of the four pathways—recycling (Rec.), biomass (Bio), carbon capture and utilization (CCU), and the circular carbon pathway (Optimal)—depending on the electricity carbon footprint. av., average. (**B**) Remaining GHG emissions of the linear carbon pathways and the four circular pathways, depending on the carbon intensity of electricity. The GHG emissions of the linear carbon pathway are not altered as a result of decreased electricity climate impacts, because all electricity is supplied from the energy recovery via plastic waste incineration. (**C**) Optimal carbon input in percentage of the circular carbon pathway, depending on the carbon intensity of electricity. The IEA report (*28*) provides only regionalized electricity impacts until 2040. (**D**) Feedstock supply and waste treatment of the circular carbon pathway for wind-based electricity production with 7 g of CO_2-equiv per kWh. Line width and corresponding values represent the carbon content (million tons of C) of the flows.

biomass gasification is captured by means of established technologies (e.g., the Rectisol process; see materials and methods). No DAC is employed. The captured CO_2 from biomass gasification is directly converted to methanol by thermal hydrogenation. Subsequently, methanol can be used to produce ethylene and propylene, as well as benzene, toluene, and xylene, which are the primary raw materials for the 14 largest-volume plastic materials. The related process technologies for conversion of methanol to olefins and aromatics are already industrialized. In 2017, 28% of the global methanol production was used for ethylene and propylene production (*24*). Thus, producing renewable methanol from biomass and captured CO_2 offsets the primary source of residual GHG emissions in the recycling pathway: the incineration of residual wastes.

At the same time, recycling reduces the overall demand for biomass and renewable electricity and the corresponding residual GHG emissions. Two classes of recycling technologies achieve the reduction of demand for biomass and renewable electricity. First, mechanical recycling is used to generate recycled resins from plastic packaging waste. Each plastic resin produced via this process does not have to be produced from biomass or CO_2. Second, plastics are treated by pyrolysis to produce naphtha feedstock. This naphtha feedstock is then used in steam crackers and solvent extraction processes to produce ethylene, propylene, benzene, toluene, and xylene. These chemical raw materials can be converted to plastics by conventional, industrialized technologies, reducing the need for biomass utilization or CCU technologies. As a result of recycling, the overall demand for biomass utilization or CCU technologies decreases, as do their residual GHG emissions.

Beyond the reduction of residual GHG emissions, part of the carbon taken up by biomass and CCU technologies is stored in landfilled plastics, given an unavoidable landfilling rate of 6% (*1*). This permanent carbon storage compensates for the residual GHG emissions that still occur in the circular carbon pathway. However, permanent carbon storage in landfills cannot be seen as sustainable (*15*) because landfilling, managed or mismanaged, is the primary cause of plastic pollution (*25*). Nevertheless, a certain amount of plastic leakage seems unavoidable, even in the most ambitious policy scenarios (*26*, *27*). A very conservative assumption that the carbon in landfilled plastics entirely turns into CO_2 would lead to additional emissions of 0.24 Gt of CO_2-equiv. In this case, the circular carbon pathway would lead to net emissions of 0.21 Gt of CO_2-equiv.

The technologies and carbon feedstocks that minimize GHG emissions of plastics depend on the electricity supply's carbon intensity, because different combinations of recycling, biomass, and CCU lead to varying synergies and electricity consumptions (Fig. 1B). As the carbon intensity of electricity decreases, the circular carbon pathway with minimal GHG emissions employs more and more CCU technologies. This trade-off leads to break-even points for the carbon footprint of electricity supply, at which CCU becomes climate beneficial compared with the recycling (39.5 g of CO_2-equiv per kWh) and biomass (5.8 g of CO_2-equiv per kWh) pathways. The electricity supply's carbon intensity also dictates the utilized carbon feedstock in the circular carbon pathway (Fig. 1C): For electricity carbon footprints above 8.6 g of CO_2-equiv per kWh, the optimal pathway is solely based on biomass and plastic waste as carbon feedstock (Fig. 1C). Thus, these carbon inputs would be optimal for 2040 electricity impact predictions for China, the United States, and Europe, which globally produce 57% of all plastics (*24*, *28*).

For electricity with carbon intensities below 8.6 g of CO_2-equiv per kWh, some CCU technologies become beneficial to minimize GHG emissions (Fig. 1C). If wind-based electricity is employed, the optimal circular carbon pathway uses biomass, recycling, and CCU to produce 357 Mt of mechanically recycled plastic and 814 Mt of virgin plastic. The virgin plastic production consumes 429 Mt of chemical feedstock from chemical recycling, 2148 Mt of biomass, and 949 Mt of CO_2. Conversion of the inert molecule CO_2 requires 9.9 PWh of renewable electricity (Fig. 1D).

A complete switch to CO_2-based products requires electricity with a carbon intensity below 6 g of CO_2-equiv per kWh. Today, not even wind power plants can provide such low-emission electricity (*29*). However, the switch from partly bio-based to entirely CO_2-based plastics reduces GHG emissions by only 1.5%. Thus, using either biomass or CO_2 as carbon feedstock results in net-zero emission plastics if combined with large-scale plastic recycling.

Renewable resource demands

Our analysis shows that combining CCU and/or biomass with large-scale recycling can achieve net-zero emission plastics. However, the actual feasibility will strongly depend on renewable resource availability. To this end, two questions arise: Are there sufficient renewable resources to meet the global plastic demand? How does the circular carbon economy perform against other pathways for net-zero emission plastics (e.g., CCS)?

The circular carbon pathway recycles 70% of the plastic waste back to plastics and uses 19.3 EJ of biomass and 9.9 PWh of renewable electricity (Fig. 1D). The effective recycling rate of 70% is the maximum achievable, owing to losses in the recycling processes in the best contemporary technologies and the residual landfilling of 6%. Thus, the effective recycling rate includes only the actually recycled material. For instance, material ultimately incinerated during mechanical and chemical recycling is not counted as recycled.

The resource demands can be shifted between biomass and renewable electricity because both CCU and biomass can achieve net-zero emission plastics in combination with recycling. By increasing biomass supply and thus reducing the supply of CO_2 and vice versa, the electricity demand can vary between 1.6 and 18.1 PWh (Fig. 2, red line). These electricity demands correspond to 59 to 670% of the

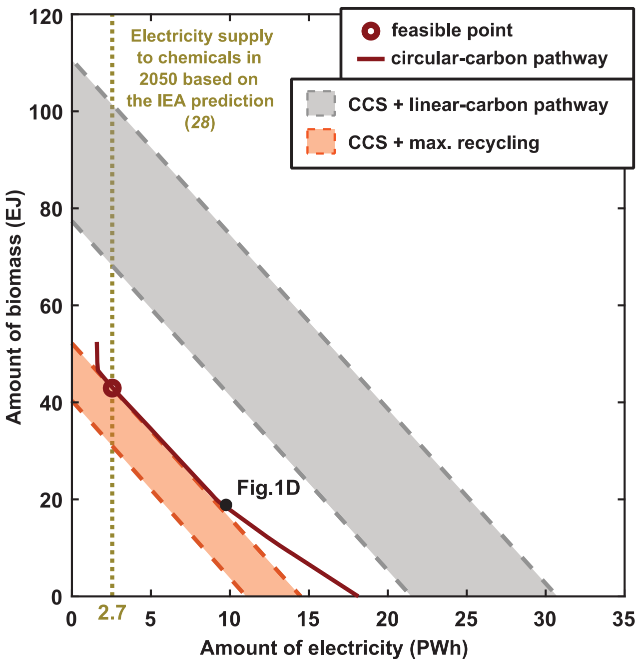

Fig. 2. Demand for biomass and electricity to achieve net-zero emission plastics in 2050. Data for the circular carbon pathway are shown together with those for the linear carbon and recycling pathways with CCS. The range of CCS reflects different sources of CO_2, such as ammonia plants (*34*) or ambient air (*35*). The energy demands for the linear carbon scenarios are based on fossil resources, which are converted to biomass and electricity on an energy basis. The marker annotated with "Fig. 1D" refers to the Sankey diagram in Fig. 1. In both cases, the same amount of electricity and biomass are used.

electricity predicted to be supplied to the chemical industry (2.7 PWh) in the IEA's most ambitious scenario for 2050 (*30*). However, the electricity supply calculated by the IEA follows a cost-optimal demand in the petrochemical industry, to achieve a specific emission-reduction target. Thus, the calculated electricity supply approximates the electricity amount that will be supplied, not the amount that could potentially be supplied to the chemical industry. Furthermore, the plastics industry is not entirely covered by the IEA model, and thus the electricity demands for plastics are not fully represented. However, ~80% of the overall mass of the major bulk chemicals (e.g., ethylene, propylene, benzene, toluene, and xylene) are used for plastics. Thus, we assume the 2.7 PWh of electricity supplied to the chemical industry as a reasonable estimate for a possible amount of electricity that can be supplied to plastics life cycles. As a result, we denote the combination of 2.7 PWh electricity with 42.6 EJ of biomass to achieve net-zero emission plastics as the "feasible point" (Fig. 2).

Estimates of biomass availability vary widely from 30 EJ to >1000 EJ per year (*31*). An expert consortium found that an estimate of 100 EJ is supported by "high agreement" in literature (*32*). The International Renewable Energy Agency (IRENA) estimates that an additional 287 EJ are available (*22*, *33*) from using lignocellulosic biomass and food wastes as well as land made available by technology and farming improvements. Considering the future biomass demand (104 EJ) of all other sectors (*30*), IRENA's estimated untapped biomass supply equals 183 EJ. Thus, the biomass demand of 42.6 EJ at the feasible point would represent 23% of this remaining untapped biomass potential. However, the access to this untapped biomass relies on boosting crop yield, reducing food waste, afforestation, and improving livestock management to free pastureland (*22*, *33*).

To put the renewable energy demand into perspective, we compare it to the linear carbon pathway that would need 4.7 Gt of CO_2 storage (e.g., using CCS) to reach net-zero emission plastics. In this case, 76.9 EJ of fossil-based energy and 1.9 to 33.9 EJ of additional electricity for CCS would be required (Fig. 2, gray area). The range of electricity reflects the nature of the CO_2 source, ranging from a high-concentration stream [e.g., produced during ammonia synthesis (*34*)] to the dilute scenario of DAC (*35*). The industrial-scale separation of CO_2 from the gas streams during ammonia and hydrogen production is well established and frequently performed by the Rectisol process considered here (*36*, *37*). However, currently, the separated CO_2 is not stored and most often is simply released to the atmosphere. For DAC, recently published data for the Climeworks plants in Hellisheiði, Iceland, and Hinwil, Switzerland, are used, assuming wind-based electricity supply (*35*). Overall, the linear carbon pathway plus CCS would consume between 78.8 and 110.8 EJ of energy. Thus, the circular carbon pathway at the feasible point, with a total energy consumption of 42.6 EJ of biomass and 9.7 EJ of electricity, could potentially save between 34 and 53% of the total energy demand.

Energy demands can be further reduced by combining the recycling pathway with CCS to achieve net-zero emission plastics (Fig. 2, orange area). This combination requires 40.6 to 52.2 EJ while achieving net-zero emission plastics, reducing energy by an additional 1 to 12% compared with the circular carbon pathway. Thus, the total life-cycle energy demand differs by up to 12% between CCS, biomass, and CCU. However, in all cases, recycling plastic waste reduces the energy demand relative to the fossil-based benchmark with CCS.

Although the decreased energy demand may appear counterintuitive because of the anticipated lower efficiency of biomass and CO_2 conversion, it can be rationalized by energy conservation over the complete life cycle and recycling: The pathways based on fossil sources, biomass, and CO_2 can recover the energy contained in plastics only during waste incineration. Energy recovery is inefficient because of unavoidable losses from thermal energy to electricity conversion that result from thermodynamic limitations. Therefore, plastic waste incineration will inevitably never suffice to close the energy loop and maintain 100% of the energy content. By contrast, recycling essentially conserves the energy content of plastics by reusing plastic waste and avoiding its incineration, thus lowering energy demands. A major difference is that the linear pathways can exploit fossil energy generated over millennia, whereas the biomass and CCU pathways need to generate their energy now.

To achieve these reduced energy demands, the circular carbon economy can rely on commercialized recycling technologies. All technology datasets used in the main paper are based on already-commercialized technologies using industrially validated data or process simulations. Sorting household plastics and mechanical recycling are already industrial practice in western European countries such as Germany and Austria (*38*). Whereas plastic packaging can be efficiently recycled mechanically, mixed and other plastic wastes lack mechanical recyclability (*39*, *40*). In this case, pyrolysis offers a promising large-scale avenue to increase recycling rates (*41*).

Additionally, early-stage technologies to convert plastic waste to respective monomers are currently under development (*42*, *43*). To highlight the potential benefits of technology development, we include emerging technologies in the supplementary materials (see materials and methods for modeling principles and technology pathways). By leveraging potential chemical recycling, biomass utilization, and CCU technologies with low technology readiness levels (i.e., the technology has been maximally validated in the lab), the circular carbon pathway could reduce the energy demand by 83% relative to the linear carbon pathway with CCS (see materials and methods and figs. S3 and S4).

However, even promising recycling technologies at low technology readiness levels cannot

Table 1. Operational costs of linear and circular carbon pathways at the feasible point. Operational costs are shown for oil, biomass, CO_2, and electricity, as well as for the amount of waste treated by mechanical (Mech.) recycling, chemical (Chem.) recycling, and energy recovery (left to right). Prices are provided in table S12. / indicates zero operating cost.

Prices, pathway	Oil (billion USD)	Biomass (billion USD)	CO_2 (billion USD)	Electricity (billion USD)	Mech. recycling (billion USD)	Chem. recycling (billion USD)	Energy recovery (billion USD)	Total (billion USD)
Low prices, linear carbon pathway	675	/	/	/	/	/	164	839
High prices, linear carbon pathway	946	/	/	/	/	/	164	1110
Low prices, circular carbon pathway	18	212	1	54	82	413	42	822
High prices, circular carbon pathway	25	639	3	162	82	413	42	1366

leverage their potential unless sufficient plastic waste is collected and made available. A recent study predicted that, in 2040, 88% of the plastic demand will still be lost in managed landfills and waste incinerators (32% combined) and through waste mismanagement (56%) (*27*). To increase collection rates, landfill bans have proven highly effective in European countries such as Germany, the Netherlands, and Sweden. In Europe, landfilling dropped by 34%, whereas recycling increased by 64% between 2006 and 2014 (*44*). Once the collected waste is in a managed system, recycling can be fostered by implementing recycling quotas. However, a proper waste management infrastructure is missing in many low- and middle-income countries that would offer the largest potential to access plastic waste (*26*, *45*). To gain access to these untapped resources, millions of households must be connected to waste management services. Lau *et al.* argue that this monumental task requires linking local service chains [e.g., the informal sector (*4*)] to the value chain (e.g., recycling) by increasing the profitability of material recycling through investments in waste management infrastructure and improved coordination for collection, sorting, and management of plastic wastes (*27*).

Operational cost

Operational costs differ between the linear and circular carbon pathways in two major aspects: (i) the costs for feedstock and energy to produce plastics and (ii) the costs for "end-of-life" treatment of postconsumer plastics (e.g., landfilling, energy recovery, and chemical and mechanical recycling). Taking into account the expected price ranges (see materials and methods and table S11) for biomass, CO_2, electricity, and oil (*30*, *46*) as well as the operational cost for mechanical recycling (*47*) chemical recycling (*36*), and waste incineration (*47*), the operational costs of the circular carbon pathway vary between 822 and 1366 billion USD on a global basis in 2050 (Table 1). Thus, the circular carbon pathway lies in the same cost range as the linear carbon pathway, which has operational costs between 839 and 1110 billion USD. Assuming costs at the low end for all resources would lead to nearly identical cost for the linear carbon pathway (839 billion USD) and the circular pathway (822 billion USD). For high oil prices (~70 USD per barrel) as well as low-cost supply of biomass, CO_2, and renewable electricity (~5 USD per GJ, 30 USD per ton, and 2 USD per kWh, respectively), the circular carbon pathway would save 288 billion USD in operational cost.

Depending on the resource prices, the respective CO_2 abatement of 4.7 Gt of CO_2-equiv would cost –61 to 112 USD per kg of CO_2-equiv abated. This range has considerable uncertainty, owing to the broad price ranges for oil, biomass, CO_2, and electricity. However, even the high-end carbon cost of 112 USD per kg of CO_2-equiv is in the predicted range of prices for CO_2 certificates in Europe or mid-century social costs of carbon (*48*, *49*), indicating that, with regard to operational costs, current carbon price scenarios would suffice to reach net-zero emission plastics.

The abatement costs are based only on the operational costs and do not include capital expenditures. However, an increase in capital expenditures can be expected to provide plastic, biomass, or CO_2 as resources. These investments are needed for the infrastructure to provide the renewable carbon feedstocks to the production facilities of the chemical industry and to convert the renewable feedstock to plastic products. Although a full assessment of capital expenditures is not possible, owing to the lack of data in this publication, the increase can be estimated from a recent calculation by the IEA. To reduce the GHG emissions of the petrochemical sector, which is closely connected to the plastic industry (*50*), the IEA estimated an investment need of 1.5 trillion USD (*51*) to save 0.9 Gt of CO_2-equiv yearly after 2050. Although these investment amounts do not fully represent those required to achieve net-zero emission plastics, they clearly indicate that the additional capital expenditures will increase abatement costs. Assuming the same capital expenditures as those of the IEA, an average production plant lifetime of 30 years, and 0.9 Gt of CO_2-equiv savings for these years, the abatement cost would increase by ~56 USD per ton of CO_2. However, a more in-depth assessment of capital expenditures is desirable to guide future investment decisions and properly define the respective CO_2 abatement costs to achieve net-zero emission plastics.

Policies for circular and net-zero emission plastics

Our results indicate that net-zero emission plastics can be achieved by using technologies that are already available and commercialized. To materialize the potential, policies that foster the deployment of circular carbon technologies need to be designed and implemented. We identify two crucial technological changes that will be necessary to achieve net-zero emission plastics: (i) increase plastic recycling rates and supply more plastic waste feedstock, and (ii) deploy CCU or biomass technologies, depending on local availabilities of renewable electricity and biomass. Fostering such changes requires economic incentives.

Economic incentives can play a crucial role in increasing plastics' circularity and achieving net-zero emission plastics. However, under the current structure, pricing carbon emissions would have, at best, limited impact in incentivizing plastic circularity. Current emissions trading schemes (such as the EU ETSs) focus on production processes and exclude end-of-life management processes (*52*) such as incineration from the scope, leading to a problem in shifting from one stage of the life cycle to another. Including plastic waste incineration in emission pricing schemes through, e.g., extended producer responsibility policy would be a step forward to incentivize recycling (*53*). For carbon pricing to effectively reduce GHG emissions throughout the plastics' life cycle and improve the circularity of plastics, the entire life cycle of plastics must be covered within the scope of carbon pricing.

Additionally, local municipalities often conduct waste management as a service, particularly collection and sorting, for residents and/or local companies. Because the residents pay for the service, incentives to generate a usable waste stream are limited. In return, municipalities often receive postconsumer waste of low value and poor quality. These postconsumer wastes are then treated at the lowest potential costs (e.g., waste incineration or, even worse, landfilling) instead of being properly sorted. Thus, collection and sorting are commonly the bottlenecks of recycling industries (*39*). Policymakers should aim to incentivize value addition at the beginning of the waste value chain: the plastic consumer. In this scenario, a deposit system for plastic materials could provide a potential avenue for consumers to provide valuable plastic waste feedstock directly from the start. These deposit systems have been very successful in combination with landfill bans in Europe (*44*).

Although increasing the availability of plastic waste is one important point to be addressed through policy-making. Current policies also subsidize oil exploration and production of fossil products and thereby offer a cheap and abundant alternative to plastic waste, biomass, and CO_2 as renewable carbon feedstocks. In the oil and gas industry, investments in the extensive infrastructure have already amortized. By contrast, plastic waste, biomass, and CO_2 utilization are in their infancy, and investment possibilities currently do not satisfy private investors because of their lower return on investment. As a result, the initial capital investment largely disincentives potential investors, particularly in the recycling area (*54*). However, investment firms such as BlackRock are becoming increasingly interested in including climate impact in their investment decisions (*55*).

Thus, the use of globally agreed policy instruments (*56*) to increase the availability of plastic waste as a resource and provide economic incentives for increased investment in biomass and CO_2 utilization can advance the pathway toward net-zero emission plastics. However, the improvements regarding energy consumption and GHG emissions must be carefully balanced with other environmental impacts known to arise from large-scale usage of biomass or renewable electricity. These environmental impacts include an increase of terrestrial acidification and water eutrophication due to biomass utilization (*57*) and elevated metal depletion and water consumption due to the increase of solar and wind-based power plants (*58*). Looking ahead, the circular carbon economy could hold its promise to redesign plastics production systems such that decoupling from fossil carbon resources achieves net-zero emission plastics with lower energy demands while requiring reduced operational costs and, thus, combining economic and environmental well-being (*6*).

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SUPPLEMENTARY MATERIALS

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Achieving net-zero greenhouse gas emission plastics by a circular carbon economy

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Reducing net emission

The great majority of plastics in current use are sourced from fossil fuels, with additional fossil fuels combusted to power their manufacture. Substantial research is focused on finding more sustainable building blocks for next-generation polymers. Meys *et al*. report a series of life cycle analyses suggesting that even the current varieties of commercial monomers could potentially be manufactured and polymerized with no net greenhouse gas emissions. The cycle relies on combining recycling of plastic waste with chemical reduction of carbon dioxide captured from incineration or derived from biomass. —JSY

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