MISSION POSSIBLE

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

ENERGY TRANSITIONS COMMISSION

SECTORAL FOCUS

PLASTICS

The **Energy Transitions Commission (ETC)** brings together a diverse group of leaders from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics from the developed and developing world. Our aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2˚C and as close as possible to 1.5˚C.

In November 2018, the ETC published ***Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century***. This flagship report is available on our website. This report describes in turn:

- Why reaching net-zero CO_2 emissions across heavy industry and heavy-duty transport sectors is technically and economically feasible;
- How to manage the transition to net-zero CO_2 emissions in those harder-to-abate sectors of the economy;
- What the implications of a full decarbonization of the economy are for the energy system as a whole, in particular in terms of demand for electricity, hydrogen, bioenergy/bio-feedstock, and fossil fuels, as well as carbon storage requirements;
- What policymakers, investors, businesses and consumers must do to accelerate change.

This Sectoral Focus presents in more details the underlying analysis on plastics decarbonization that fed into the ETC's integrated report *Mission Possible*. It constitutes an updated version of the consultation paper with the same title published by the ETC in July 2018.

We warmly thank all experts from companies, industry initiatives, international organizations, non-governmental organizations and academia, who have provided feedback on this consultation paper. Their insights were instrumental in shaping the *Mission Possible* report and this updated Sectoral Focus.

The *Mission Possible* report and the related Sectoral Focuses constitute **a collective view of the Energy Transitions Commission**. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report. The list of our Commissioners at the time of publication can be found in the *Mission Possible* report.

In 2019, the Energy Transitions Commission will continue to engage actively and work with key policymakers, investors and business leaders around the world, using our analysis and the unique voice of the ETC to inform decision-making and encourage rapid progress on the decarbonization of the harder-to-abate sectors. We are keen to exchange and partner with those organizations who would like to progress this agenda. Please contact us at info@energy-transitions.org.

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REACHING NET-ZERO CARBON EMISSIONS FROM PLASTICS

Demand for plastics is likely to grow rapidly over the next decades, especially in developing countries as a growing share of the population gains access to higher standards of living and a broader set of consumer goods. Without profound changes in the plastics value chain, **this growth in demand will entail a surge in carbon emissions from plastics**, which could represent 2Gt per annum by mid-century, just accounting for emissions from the production process, and as much as 4.2Gt if accounting for end-of-life emissions[1].

Indeed, plastics entail **two streams of CO_2 emissions**: the production process produces on average 2.5 tonnes of CO_2 per tonne of plastics, while the decomposition of plastics at end-of-life (in particular if it is incinerated) produces about 2.7 tonnes of CO_2 per tonne of plastics[2].

The Energy Transitions Commission has developed a vision of a feasible path to decarbonize plastics throughout their lifecycle based on **4 major routes**: (i) a shift to a circular plastics economy, (ii) the improvement of energy efficiency in the production process, (iii) the decarbonization of the production process, (iv) a partial switch to renewable feedstock.

We believe that it is possible to achieve **a 56% carbon emissions reduction from plastics by mid-century, and even more in developed economies, thanks to greater materials efficiency and circularity** (via mechanical or chemical recycling). Our analysis shows that this can be realized at a low cost if greater coordination throughout the value chain enables the development of new business models in the sector. The fundamental barriers to recycling are indeed not primarily technical, but arise from a combination of adverse policy, market and industry features throughout the plastics value chain that could be overturned.

In parallel, continued growth in virgin plastics production will demand **a decarbonization of the plastics production process**. Energy efficiency improvements could deliver useful, but only moderate emissions reductions. The route to full decarbonization could entail carbon capture, or switch to zero-carbon energy sources for high heat production (biomass, hydrogen or direct electrification). The optimal choice between these different technologies will depend on the price at which renewable electricity is available and on the technical and political feasibility of CCS in particular locations.

Finally, even with a significant increase in plastics recycling (from 9% of end-of-life plastics today to a minimum of 50%[3] by mid-century), **a significant share of plastics will still have to be dealt with at end-of-life, either through incineration** (potentially combined with carbon capture) **or secured landfilling** (while paying particular attention to avoiding plastics leakages in the environment). Using a proportion of **zero-carbon feedstock** (either bio-feedstock or synthetic feedstock) in primary plastics production would help compensate for the carbon emissions from the remaining incineration (or decomposition) of non-recyclable plastics waste.

[1] Estimate from the Energy Transitions Commissions, based on 2.5 tonnes CO_2/tonne of plastic at production stage, 2.7 tonnes CO_2/tonne of plastic at end-of-life stage, and forecasted production volumes of 800 Mt per annum by 2050.
[2] Material Economics (2018), *The circular economy – a powerful force for climate mitigation*
[3] Including both mechanical and chemical recycling

SUPPORTING ANALYSIS AND REPORTS

The Energy Transitions Commission's work on plastics has drawn extensively on the existing literature (cited throughout this document), in particular on:

- Inputs from **two knowledge partners**:
    - A report by **Material Economics** on the potential for greater materials circularity, which particularly focused on Europe – *The circular economy: a powerful force for climate mitigation* (2018) and a follow-up analysis replicating this work at a global scale (commissioned by the ETC);
    - A report by **McKinsey & Company** on supply-side decarbonization options across several industrial sectors – *Decarbonisation of the industrial sectors: the next frontier* (2018);
- Two reference publications:
    - A paper published by Levi & Cullen – *Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products* (2018);
    - A recent IEA report – *The Future of Petrochemicals* (2018).

HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM PLASTICS

ENERGY TRANSITIONS COMMISSION

5% OF TOTAL GLOBAL EMISSIONS

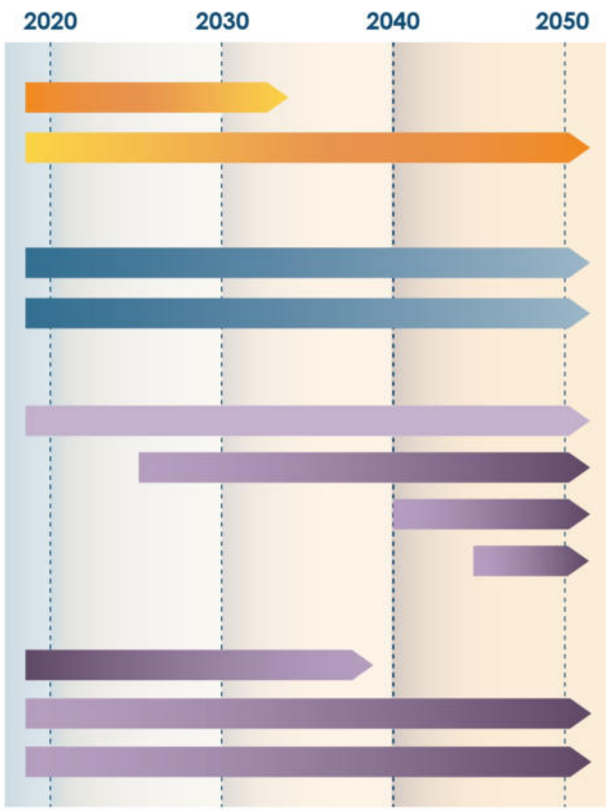
TODAY	2050 BAU
1.5 $GtCO_2$	4.2 $GtCO_2$

PRODUCTION + END-OF-LIFE

REACHING NET-ZERO CO_2 EMISSIONS FROM PLASTICS IS POSSIBLE BY COMBINING 4 MAJOR DECARBONIZATION ROUTES:

Route	Technology	MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Banning of key single-use items Chemical and mechanical recycling	-56% OF LIFECYCLE EMISSIONS
2 ENERGY EFFICIENCY	Energy efficiency improvements in monomer production	-15/20% OF PRODUCTION EMISSIONS
	Naphtha catalytic craking	
3 PRODUCTION DECARBONIZATION	Biomass/waste for heat generation (localized)	-100%
	Carbon capture	-90%
	Furnace electrification	-100%
	New electrochemical processes	-100% OF PRODUCTION EMISSIONS
4 FEEDSTOCK DECARBONIZATION	Switch from coal to gas	-50%
	Use of recycled plastics	-50%
	Use of bio or synthetic feedstock	-100% OF END-OF-LIFE EMISSIONS

TECHNOLOGY APPLICABILITY / AVAILIBILITY OVER TIME



MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO_2	B2B COST	COST TO END CONSUMER
CO_2: +$265/295	+$500 PER TONNE OF ETHYLENE (+50%)	+$0.01 ON A BOTTLE OF SODA (<1%)

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR...

INNOVATION

- Develop higher-quality and higher-volume mechanical and chemical recycling
- Develop low-carbon high heat options for pyrolysis furnaces
- Develop sustainable bio or synthetic feedstock

POLICY

- Impose and gradually tighten embedded carbon intensity standards on packaging, appliances and other manufactured products
- Enforce new regulations on product recyclability and/or on extended producer responsibility
- Create carbon taxes on plastics incineration at least as high as landfilling taxes

INDUSTRY/BUSINESSES

- Plastics producers and users: increase collaboration across the value chain from product design to end-of-life mangement to increase circularity
- Manufacturers: take commitments on recyclability and recycled content in plastics products
- Plastics industry: anticipate policy changes and seize opportunities of growing recycling market

INTRODUCTION – SCOPE OF THE ANALYSIS

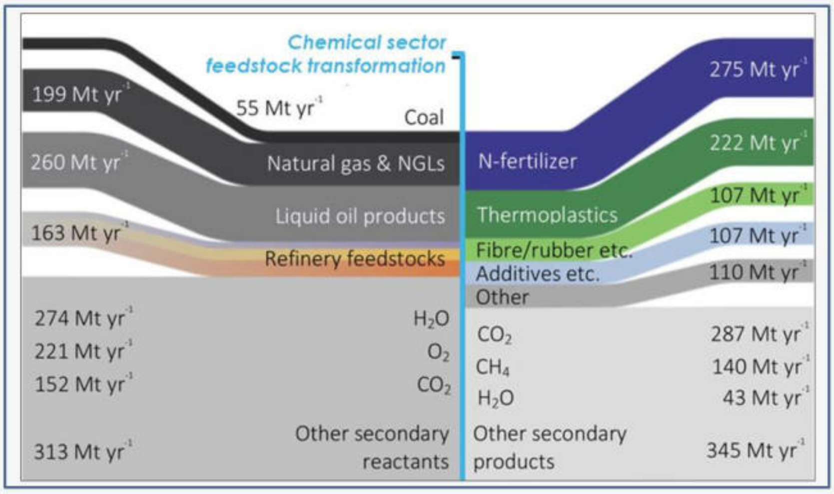
This paper focuses on the potential to reduce CO_2 emissions from the production, use and end-of-life of plastics. Given the complexity of the chemicals and plastics sectors, it is important first to define how plastics fit within the wider chemicals sector, and what is the scope of activities covered in this analysis.

A. PLASTICS WITHIN THE CHEMICALS SECTOR

Exhibit 1 describes the key inputs and outputs of the chemicals sector, within which primarily fossil fuel-based feedstocks are transformed into end-use products. The single largest product category illustrated in the analysis is **N-fertilizers**, with a global output of 275Mt per year, followed by **thermoplastics** at 222Mt per year, fiber and rubber products at 107Mt, and numerous other products accounting for the remaining 217Mt[4]. The industry also produces a significant amount of by-products, some of which are reused as feedstock.

Plastics is one of the two major outputs of chemical industry

Global fossil fuel feedstocks to chemical products



Source: Levi & Cullen (2018), *'Mapping global flows of chemicals: from fossil fuel feedstocks to chemical products', environmental science and technology*

Exhibit 1

The IEA estimates that the production of these different outputs accounts for **1.5Gt of direct CO_2 emissions per year,** of which 1.3Gt are energy related (fuel combustion to generate heat) and 0.2Gt are process emissions[5] (emissions from chemical reactions, corresponding to the difference in CO_2 content between the feedstock and the product). Fossil fuels demand from the chemicals industry – for both chemical feedstock and energy – represents 11% of total final global energy consumption today (14% of oil consumption and 8% of natural gas consumption)[6].

[4] Levi & Cullen (2018), *Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products*

[5] IEA (2018), *The future of petrochemicals*

[6] IEA (2018), *The future of petrochemicals*

60% of total direct CO_2 emissions from the chemicals sector come from a small number of primary chemicals. N-fertilizer ammonia is the single largest source of emissions amongst these with 30% of direct CO_2 emissions from the chemicals sector (~440 Mt CO_2). High value chemicals (including ethylene) and methanol follow with 16% (200 Mt CO_2) and 14% respectively (180 Mt CO_2)[7]. Ethanol and methanol are used as feedstock in the production of complex chemicals like plastic polymers (e.g. polyethylene or polypropylene), which production represent 450-750 Mt CO_2 per year today.

But it is also important to consider **emissions which result from the use and end-of-life disposal of chemical industry products**. In the case of N-fertilizers, CO_2 emissions result when urea-based fertilizers are applied to the soil, doubling emissions from N-fertilizer (i.e. ~700Mt CO_2, out of which 300Mt are energy-related emissions from ammonia production, and 270Mt process emissions from ammonia production, which can be either directly released (140Mt) or used as a feedstock for urea production and released when applied to the soil (130Mt))[8]. In the case of plastics, as a significant portion of the hydrocarbon feedstock is converted and embedded in the output product, emissions will result if plastics are disintegrated, and more rapidly so if they are incinerated. As Section 1.C will describe, these emissions will increase in importance in future.

This paper focuses on plastics and does not cover N-fertilizer products. It considers both emissions resulting from plastics production and emissions resulting from end-of-life disposal.

[7] IEA (2018), *The future of petrochemicals*
[8] IPCC (2014), *5AR synthesis report*

B. CATEGORIES OF PLASTICS AND RELATED PRODUCTS

Exhibit 2 sets out the range of products covered in various definitions of plastics and related products. Within a total global production of approximately 370Mt in 2013[9], **fibers** accounted for 59.2Mt and **rubber goods** (including tires) for 11.1Mt[10]. In Section 2.E, we briefly consider opportunities to recycle and reuse these products, but **our primary focus in this paper is on the 300Mt more tightly described as "plastics"**.

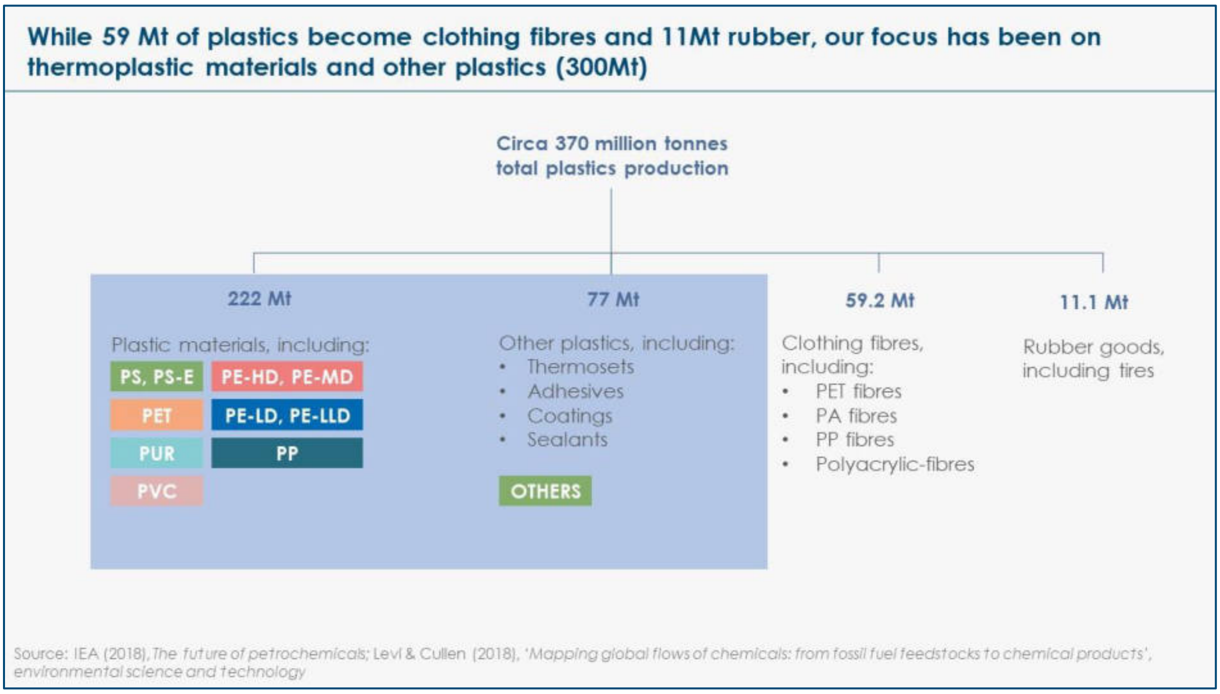


Exhibit 2

Within the "plastics" segment, in turn, **our analysis of the opportunity for greater materials circularity, in Section 2, 3 and 4, focuses particularly on the thermoplastics**, which account for circa 222 Mt of the total[11]. This focus reflects the fact that the opportunities for recycling and reuse are greater here than in respect to thermosets, adhesives, coatings and solvents, which account for the other 77 Mt.

C. PRODUCTION DECARBONIZATION – A FOCUS ON ETHYLENE

The production processes for chemicals and plastics entail an extremely complex set of possible pathways and interconnections with multiple intermediate products. But most of the carbon emissions entailed in the production of thermoplastics arise from the production of the building block monomers – ethylene, propylene plus the BTX aromatics (benzene, toluene and xylene). The production processes for each of these are sufficiently similar that feasible

[9] IEA (2018), *The future of petrochemicals*
[10] IEA (2018), *The future of petrochemicals* and Levi & Cullen (2018), *Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products*
[11] Levi & Cullen (2018), *Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products*

routes to production decarbonization will be similar and entail comparable costs. Within the production processes, **this paper therefore focuses primarily on ethylene** as the single largest high-value chemical produced globally, but the conclusions are likely to be relevant for other categories of monomer production.

D. BROADER ENVIRONMENTAL IMPACT OF PLASTICS

Apart from CO_2 emissions, the end-of-life disposal of plastics can produce numerous other forms of environmental harm, including dangerous **pollution of soils and oceans**, with potentially serious **implications for biodiversity and human health**. Much attention is currently given to these issues, in the public debate as well as in the research, policy and innovation spheres. The broader environmental impact of plastics is relevant to the demand-side analysis in Section 2, since avoiding incineration by placing plastics in landfill could trade one environmental damage (CO_2 emissions) for another. This reinforces the desirability of greater recycling and reuse within a more circular economy. Apart from noting this crucial trade-off, however, this paper does not focus on the other environmental impact of plastics.

1. OVERVIEW OF THE CHALLENGE

Demand for plastics is likely to grow rapidly over the next decades, but net CO_2 emissions will grow even more rapidly if plastics are incinerated at end-of-life rather than recycled, reused or placed in landfills.

A. PLASTICS DEMAND TRENDS

Global plastics production has grown from trivial levels in the 1950s to reach over 320Mt today[12], of which 222Mt are thermoplastics[13]. Thermoplastics production is forecasted to increase significantly to 800Mt per annum by 2050, and **global demand could potentially grow to reach 1,350Mt per annum by the end of the century**[14] [Exhibit 3].

This growth reflects the major consumer benefits which plastics deliver, enabling more efficient and safer food distribution, more comfortable and efficient autos, and better building construction. In some crucial ways, indeed, plastics can help deliver environmental benefits – for instance, through reduced food waste, or lighter weight vehicles.

Given these benefits, plastics use is highly correlated with income. Europeans use about 100kg of plastics per person per annum[15], Americans 139kg, but consumption per capita is only 16kg in the Middle East and Africa and 36kg in Asia, excluding Japan[16]. As a result, while demand in the developed economies may well now flatten out, **demand will grow greatly in emerging economies**, as Exhibit 3 suggests, with big increases likely in Asia and China over the next 30 years, and in Africa and the Middle East throughout the century[17].

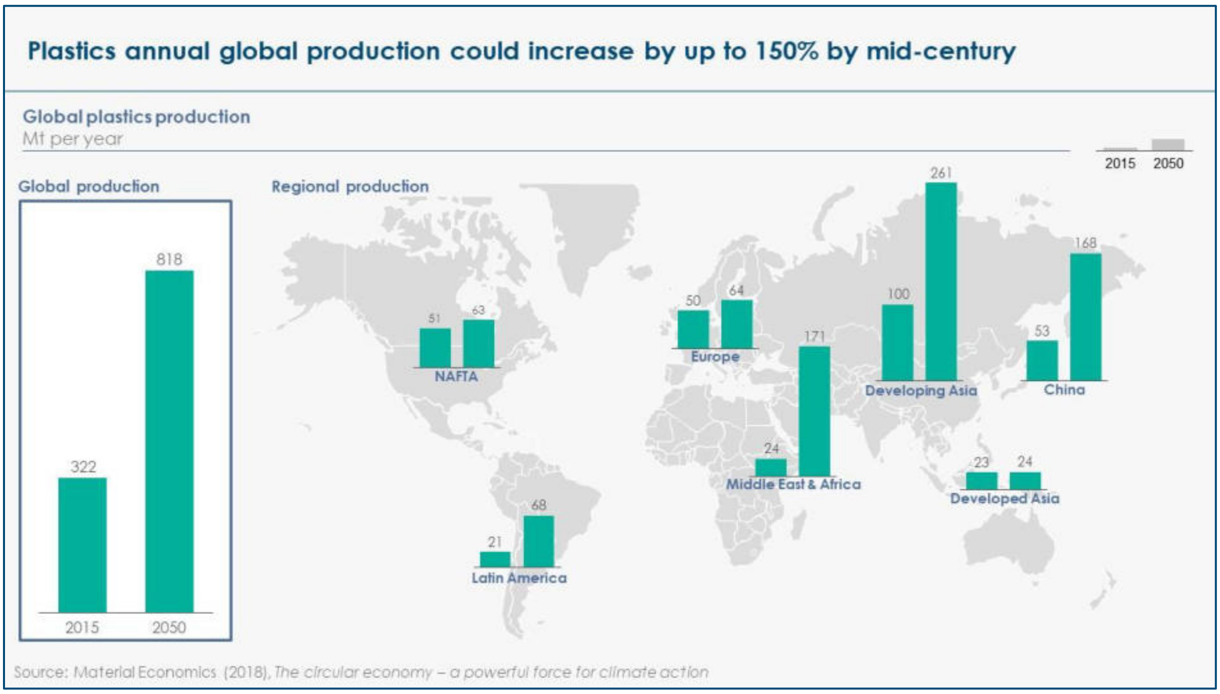


Exhibit 3

[12] IEA (2018), *The future of petrochemicals*
[13] Levi & Cullen (2018), *Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products*
[14] Material Economics (2018), *The circular economy – a powerful force for climate mitigation*
[15] Material Economic (2018), *The circular economy – a powerful force for climate mitigation*
[16] STATISTA (2016), *Per capita consumption of plastic materials worldwide in 2015 by region*
[17] Material Economics (2018), *The circular economy – a powerful force for climate mitigation*

B. MONOMER AND FEEDSTOCK DEMAND TRENDS

This growth in plastics demand will translate in a dramatic growth in demand for monomers, and in turn for the feedstock inputs to monomer production, unless recycled materials replace a large share of primary production. McKinsey estimates suggest that **global ethylene demand will triple over the next 35 years,** primarily driven by demand growth in developing geographies (x5 in Africa, x4 in the Middle-East and India), as well as a tripling of demand in China[18].

As transport decarbonization reduces other forms of demand for oil, oil demand from the chemicals sector could account for **nearly 50% of all oil production by 2050**, up from 14% today[19].

C. CARBON EMISSIONS IN PRODUCTION AND AT END-OF-LIFE

Although estimates vary widely on the level of CO_2 emissions per tonne of plastics in production and at end-of-life [Exhibit 4], calculations from Material Economics point out that CO_2 emissions from primary plastics production and use could amount on average to **5.1 tonnes of CO_2 per tonne of plastic produced** (including the embedded carbon in the material which could be released at end-of-life)[20].

- On the production side, emissions are generated in the upstream production of feedstocks (naphtha, ethane, or LPGs), in the production of monomers via steam cracking and aromatic synthesis, and in the polymerization to produce end products. Estimates for emissions from the monomer production only vary from 1.15 to 1.6 tonnes of CO_2 per tonne of plastics produced. Adding emissions from feedstock production and from polymerization, **emissions from the production process reach roughly 2.5 tonnes of CO_2 per tonne of plastic produced**[21].
- In addition, however, **incineration of plastics can result in about 2.7 tonnes of CO_2 per tonne of plastic burnt**[22] – and, even if plastics are not being burnt, they would still eventually (over a very long-term) produce emissions as the plastic slowly disintegrates. At present, most assessments of greenhouse gas emissions from plastics ignore the emissions from incineration on the grounds that plastics incineration reduces fossil fuel use, which would otherwise occur. But, as other sectors of the economy decarbonize, this approach will no longer apply; and if the world is eventually to reach net-zero carbon emissions, it will have to treat plastics incineration emissions as a net contribution to the global total (unless plastics incineration is combined with carbon capture).

[18] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*
[19] IEA (2018), *The future of petrochemicals*
[20] Material Economics (2018), *The circular economy – a powerful force for climate action*
[21] Material Economics (2018), *The circular economy – a powerful force for climate action*
[22] Material Economics (2018, *The circular economy – a powerful force for climate action*

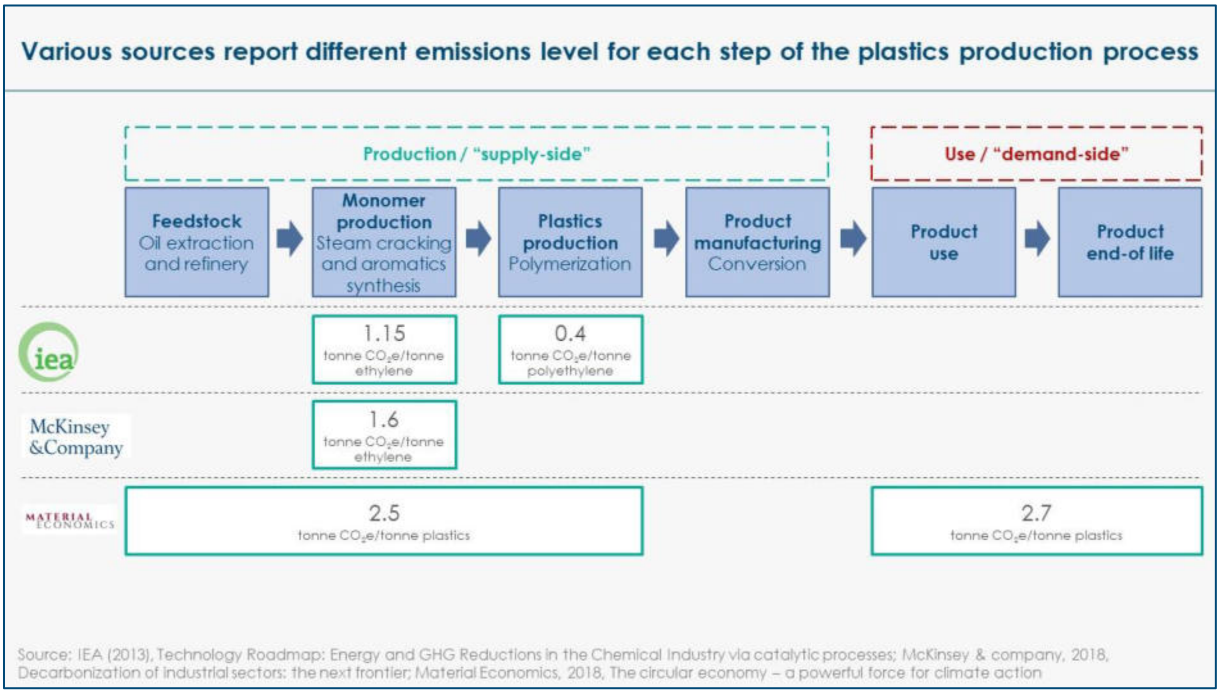


Exhibit 4

Given the expected growth in plastics production over the next decades, this translates into a potential surge of CO_2 emissions from plastics production and end-of-life by mid-century:

- Considering production levels of 300Mt of plastics in 2013 (plastics materials and other forms of plastics, excluding fibers and rubber), **production emissions from plastics production only amount to roughly 450-750Mt CO_2, today**, which is a maximum of 2.5% of total global energy system emissions[23]. If production levels were to reach 800Mt of plastics by mid-century, as forecasted, **emissions from production only could reach 2Gt per annum.**

- If all of the plastics produced every year by mid-century was then disintegrated or burnt at end-of-life, total CO_2 emissions per annum could even reach a theoretical maximum of 4.2Gt by mid-century. In practice, **emissions from the end-of-life of plastics in stock by mid-century will depend on the lifetime of the plastics produced, recycling rates and whether landfilling is preferred to incineration.** Taking into account these drivers, Material Economics estimate that global net emissions from plastics could increase by 188% (up to 2.1Gt CO_2 p.a.) between now and 2050 due to the combination of demand growth, plus higher net emissions from incineration[24] [Exhibit 5]. This progression would be lower in Europe (76%) due mostly to higher recycling rates. Globally, if forceful policies are not implemented, plastics could be **responsible for 16% of the total 2050 emissions which are compatible with the Paris climate objective of well below 2°C**[25].

[23] Based on a range of 1.5 to 2.5 tonnes of CO_2 per tonne of plastics (see previous exhibit)
[24] Material Economics (2018), *The circular economy – a powerful force for climate action*
[25] Material Economics (2018), *The circular economy – a powerful force for climate action* & additional analysis from SYSTEMIQ for the Energy Transitions Commission (2018)

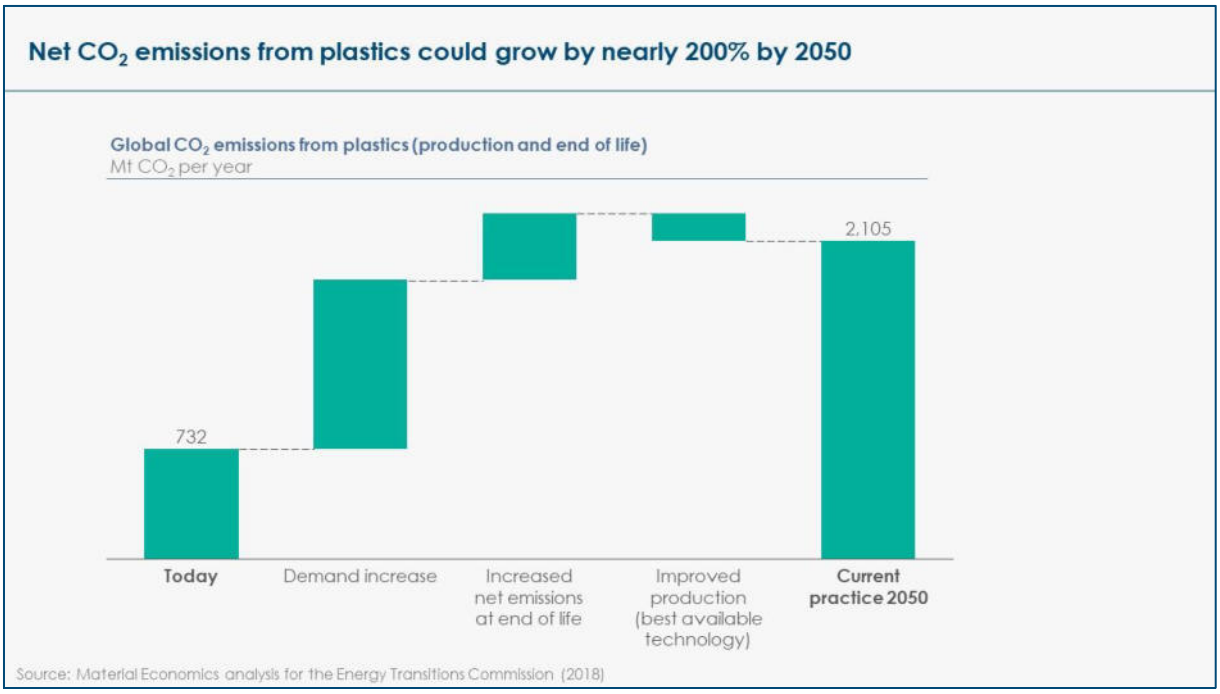


Exhibit 5

It is therefore essential to develop plastic emissions reduction strategies which leverage both demand reduction for primary plastics (in particular through greater recycling and reuse) and the decarbonization of production processes.

2. REDUCING CARBON EMISSIONS THROUGH DEMAND MANAGEMENT AND CIRCULARITY

Demand-side levers are particularly important in the plastics sector, since reduced demand for primary plastics could reduce both the emissions generated in production and those which result from end-of-life disposal. **Primary plastics production could be reduced in two main ways: (i) via reduced end-use of plastics and (ii) via mechanical or chemical recycling.** The scope for reduced end-use of plastics is likely to be modest, given the major consumer benefits of plastics use. Meanwhile, the Material Economics report estimates that **increased materials efficiency, reuse and recycling could reduce 2050 emissions from plastics by 56%**[26]. But to achieve this reduction will require fundamental changes to the economics of the plastics value chain, and other supply-side decarbonization strategies will also be required to address the remaining ~45% of emissions.

A. REDUCING DEMAND FOR PLASTIC PRODUCTS

There are three major ways to reduce demand for plastics:

(i) Net reduction in the use of plastics-based consumer products (in particular through bans of single-use plastics),

(ii) Greater materials efficiency, and

(iii) Materials substitution.

Across the world, many countries are seeking to **reduce demand for particular categories of single-use plastic products**. The targeted products include plastic bags, straws, wet wipes, coffee cups, plastic bottles, and micro-plastic beads. Policies deployed include outright bans, taxes, deposit schemes, and strong public discouragement. In practice, such policies may play an important role in reducing the non-CO_2-related adverse impacts of plastic pollution – from litter and switch system blockage to ocean and food chain pollution. However, the scenario presented on Exhibit 6 suggests that **even dramatic reductions in some of the more discretionary single-use items could only reduce total carbon emissions from plastic by about 10%**, with the biggest potential contribution coming from bottles and food containers[27]. The introduction of the plastic bag £5p levy in the UK saw volumes reductions of -85% between 2015 and 2017; however only equating to an annual reduction of 75,000 tonnes of plastics[28]. While bans could trigger a useful marginal reduction in plastics use, other routes must be found to deliver major reductions in plastics related emissions.

[26] Material Economics (2018), *The circular economy – a powerful force for climate action*
[27] SYSTEMIQ analysis for the Energy Transitions Commission (2018)
[28] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

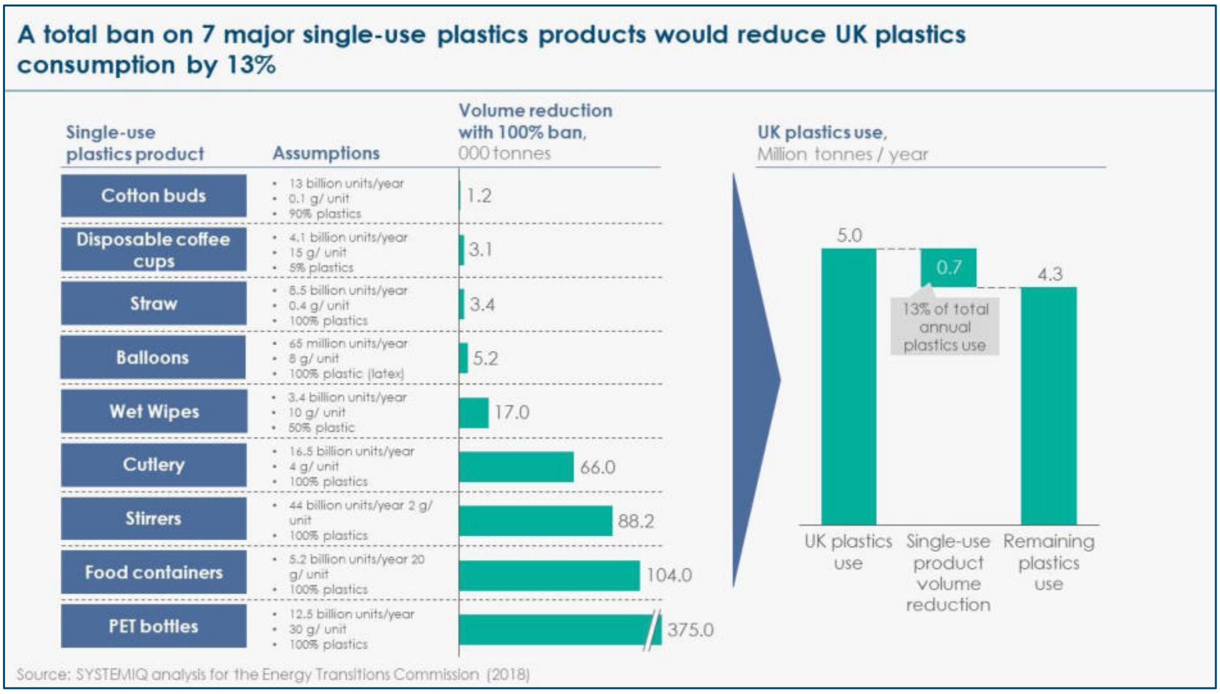


Exhibit 6

It is, however, possible to more significantly reduce demand for plastics through greater materials efficiency, in particular a reduction in the plastic content of plastic-based products and a more intensive use of plastics-based products.

- Technical advances in design (e.g. limiting overuse of packaging) and in the production process (e.g. 3D printing) can be a key driver **lower material intensity of plastics-based products**. For instance, Material Economics estimates that overuse of plastics packaging could be reduced by 20% globally by 2050 and 5% volume reductions could be achieved from more material-efficient electronics[29].
- In parallel, increased lifetime of products, sharing practices (e.g. car sharing) and efforts towards reducing the need for spare capacity (e.g. shared fleets of smaller cars, with a more limited number of larger cars available) can underpin **a more intensive use of plastics-based products**. For instance, Material Economics estimates that plastics demand could be reduced by 35% from more circular automotive and buildings value chains and 10% from other values chains[30].

Finally, **some materials substitution might be possible**, although the scale of the opportunity is very difficult to assess as alternative materials are not yet deployed on a commercial scale. For instance, cellulose-based fibers could potentially replace 15% of plastics used for packaging and 5% for remainder product groups (e.g. textiles and manufacturing)[31]. These new materials would likely require less biomass input than if using bio-based plastics, given efficiency losses in the biochemistry process.

[29] Material Economics analysis for the Energy Transitions Commission (2018)
[30] Material Economics analysis for the Energy Transitions Commission (2018)
[31] Material Economics analysis for the Energy Transitions Commission (2018)

B. MECHANICAL RECYCLING VS. CHEMICAL RECYCLING

Robust data on how much plastics is currently recycled is generally lacking. At European level, some official statistics suggest that 30% of all plastics are recycled[32]. This figure reflects the fact that in Europe about 9Mt of plastics are collected each year for recycling out of 30Mt reaching end-of-life treatment. However, **the true scale of recycling is much less:** a large share of the plastics stock currently escapes any end-of-life treatment, which means that only about 15% of total end-of-life plastics is really collected for recycling, and solely 10% is actually recycled[33] [Exhibit 7]. In parallel, analysis of the European plastics value chain shows that, of 49Mt of plastics produced for use within Europe every year, only 5Mt are produced by recycling of existing plastic products[34]. **These percentages are likely to be even lower in other regions of the world.** Major barriers must be overcome to achieve a higher percentage of recycling.

Low levels of plastics recycling in part reflect the fact that **most of the recycling volumes are currently treated via mechanical recycling**, which entails cleaning, re-melting and repurposing plastic products which have reached end-of-life, with each polymer type retaining its polymer structure through the recycling process. Mechanical recycling can therefore only be applied to thermoplastics and not to thermosets[35]. Moreover, deficiencies in the current plastics production, use and recycling system limit both the total quantity of plastics collected and recycled, and the quality of recycled products. Mixed waste flows of several different plastic types, the use of multiple additives such as colorants, stabilizers and fire retardants, and the contamination of plastic packaging by the substances enclosed, make it often difficult to achieve "closed-loop" recycling in which plastic materials can be re-used in their original form (e.g. old PET bottles becoming new high-quality PET bottles). Much recycling instead entails "open-loop" down-cycling, with for instance PET bottles turned into polyester fibers for clothes or carpets, or multiple clear plastics ending life as black flowerpots, which cannot be recycled further.

By contrast, **in chemical recycling**, end-of-life plastics can be broken down into smaller constituent molecules (monomers or lighter hydrocarbons) from which it is possible to produce either fuel or any of the different plastic monomers and then polymers. This can be achieved by several different thermal, catalytic or other routes, with different routes being suitable to produce either fuel or new polymers [Exhibit 8]. These processes typically involve the loss of some embedded CO_2, but **they can be applied to all types of plastic** (thermosets as well as thermoplastics) and to composite or contaminated plastic wastes in which multiple polymer types, labels, or other contaminants are mixed together. **At present, the chemical recycling industry is very small.** The crucial issues which will determine its long-term potential are (i) whether costs can be significantly reduced and (ii) whether it will become possible to achieve large-scale and cost-effective chemical recycling of waste plastics to make new plastics ("plastics-to-monomer" recycling), rather than simply transform it into fuel. Indeed, while today it may be reasonable to treat "plastic-to-fuel" recycling as carbon reducing since it reduces the alternative use of fossil fuels, it cannot be a long-term route to a fully decarbonized plastics industry. It is also worth noting that chemical recycling is a more energy-intensive process than mechanical recycling, and that the decarbonization of the high-heat input to the recycling process will be essential to reach a fully decarbonized recycling loop.

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[32] Gabbatiss, 2018, *All plastic packaging to be recyclable by 2030 as part of new EU strategy*
[33] Material Economics, 2018, *The circular economy – a powerful force for climate action*
[34] Material Economics, 2018, *The circular economy – a powerful force for climate action*
[35] Thermoplastics are materials which melt when heated by contrast to thermosets, which set when heated. The former is thus melt-processable and hence easier to recycle.

Both mechanical and chemical recycling would produce dramatic **reductions in total emissions per tonne of plastics produced** [Exhibit 9].

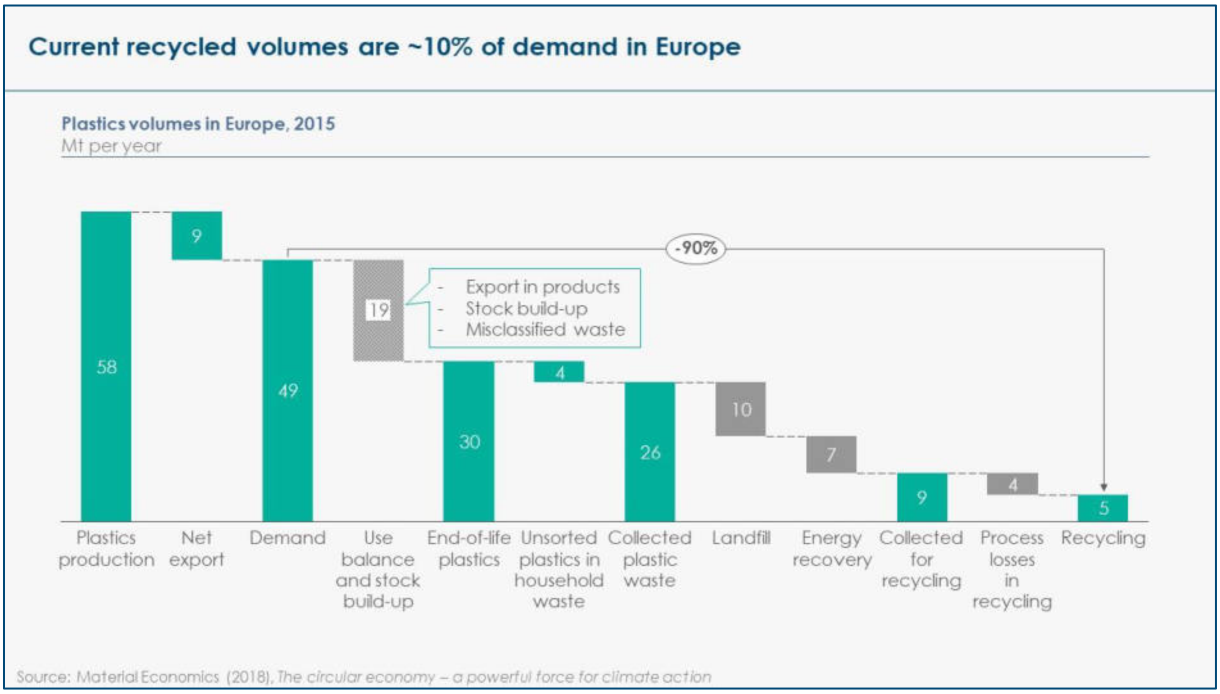


Exhibit 7

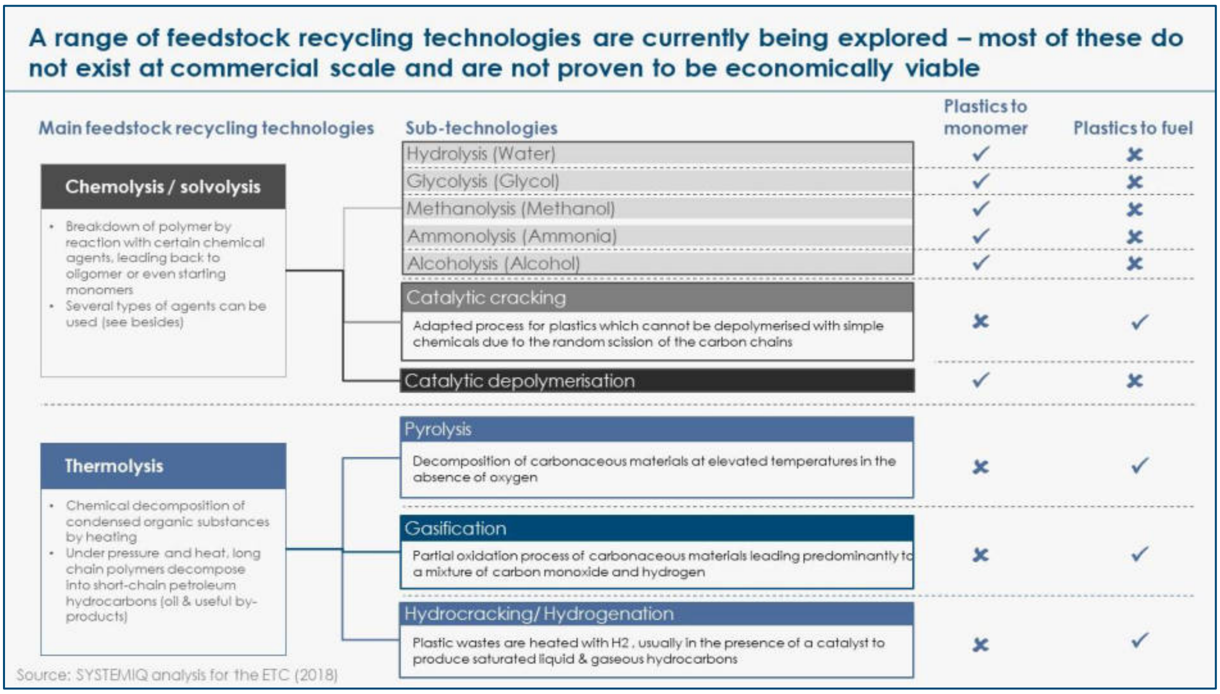


Exhibit 8

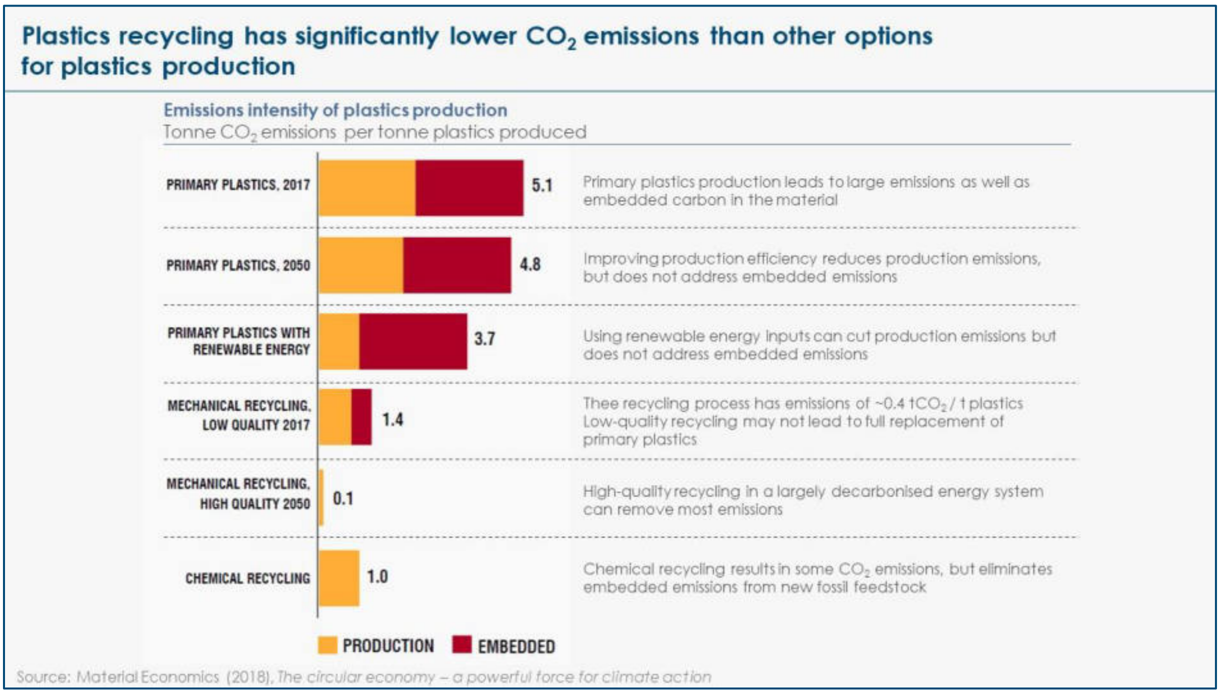


Exhibit 9

C. AN AMBITIOUS MATERIALS EFFICIENCY AND CIRCULARITY SCENARIO

The analysis conducted by Material Economics[36] suggests that **it should be possible, by 2050, to reduce emissions from plastics production and end-of-life treatment globally by 56%** compared to a business-as-usual scenario, through a combination of demand reduction, materials substitution, mechanical and chemical recycling [Exhibit 10]. The analysis has focused on five major plastic types (polyethylene, polypropylene, polystyrene, polyvinyl chloride and polyethylene terephthalate) and four major value chains (packaging, buildings/construction, automotive and electronics) which together account for 60% of total plastics demand.

[36] Section 2.C is entirely based on Material Economics (2018), *The circular economy – a powerful force for climate action*.

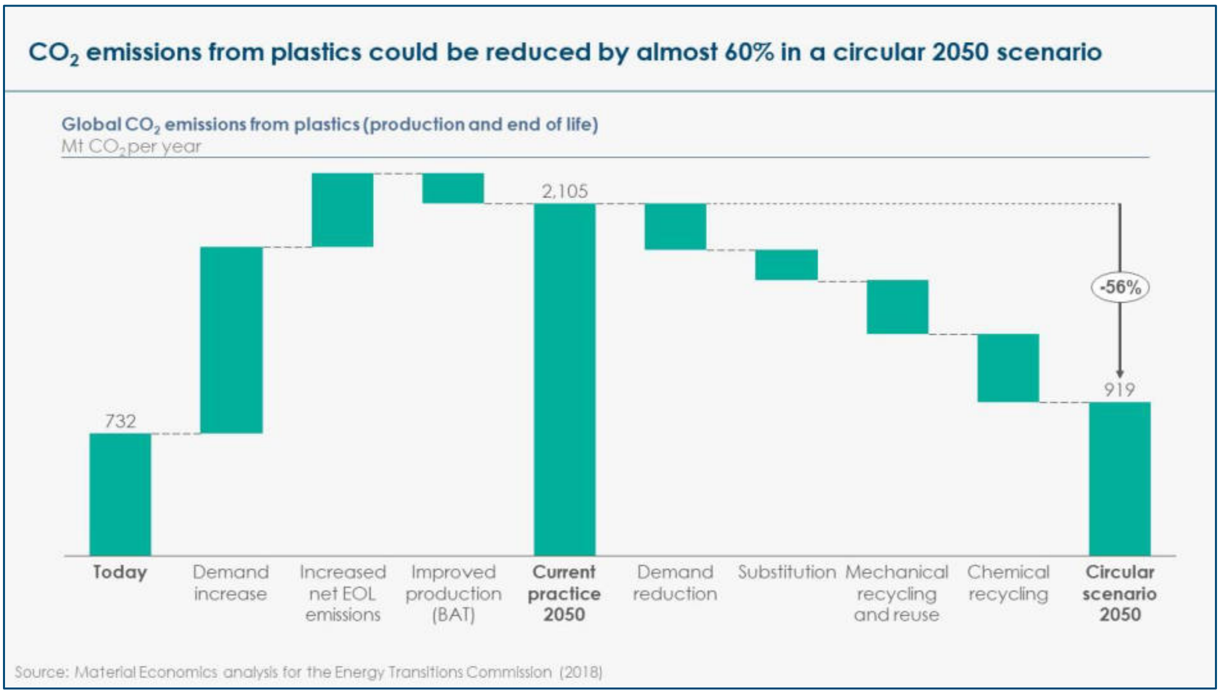
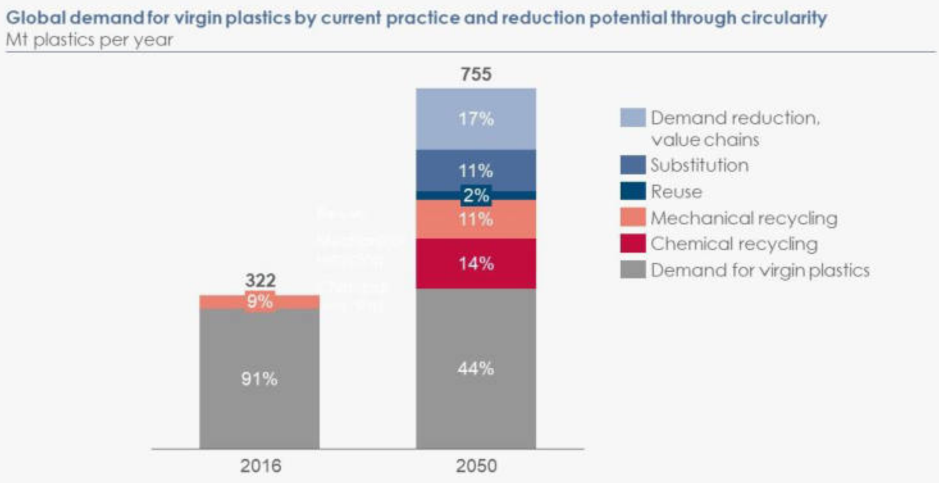


Exhibit 10

Achieving such a reduction of emissions from both plastics production and end-of-life treatment would require [Exhibit 11]:

- **Reducing demand for plastics through greater material efficiency** (as described in Section 2.A), leading to a 17% reduction in total plastics consumption;
- **Substituting fiber-based alternatives for plastics**, which could remove 15% of plastics used for packaging and 5% for remainder product groups (i.e. 11% of total plastics consumption);
- **Increasing plastic reuse** (e.g. reuse of industrial packaging, pipes, PVC carpets, large automotive parts) from 0 to 3.4% of total plastics waste (i.e. 2% of total plastics consumption);
- **Increasing mechanical recycling**, with the aim of meeting 11% of total plastics consumption with mechanically recycled plastics;
- **Increasing chemical recycling** to 55% of all plastics collected for incineration, so as to meet 14% of total plastics consumption with chemically recycled plastics.

Virgin plastics demand can be reduced by 56% by 2050, of which 25% displaced by recycled plastics



Source: Material Economics analysis for the Energy Transitions Commission (2018), based on Plastics Europe, Plastics Recyclers Europe, Eurostat, Material Economics modelling

Exhibit 11

Material Economics recently developed an even more aggressive scenario for the European Union, which shows the **complementarity of mechanical recycling**, which is the most resource-efficient type of recycling, **and chemical recycling**, which allows to recirculate plastics that are not suitable for mechanical recycling (e.g. mixed polymer flows, contaminated plastics, thermosets). Together, the two approaches could bring the **recirculation of plastics to as much as 62% of production in Europe**[37].

The cost analysis suggests that **the average abatement cost of these demand-side measures might be limited:**

- Many of the "high-quality recycling" routes (in which mechanical recycling turns end-of-life products into equally high-quality new products) could in principle result in a negative abatement cost per tonne of CO_2 saved, thanks to revenues arising from high-quality recycled plastics sales which would more than pay off recycling costs, as shown in Exhibit 12.
- Chemical recycling, which is more expensive than mechanical recycling, may impose an abatement cost of around US$50-US$60 per tonne[38], and thus will only occur if carbon taxes or regulation impose such costs on primary plastics production from fossil fuels with which it would compete.
- Substitution of plastics by fiber-based alternatives and greater materials efficiency both come at a cost that Material Economics estimates to be around US$50 per tonne CO_2.

In the first instance, **mechanical plastics recycling could emerge as a large-scale profitable industry**: average costs per tonne of treated plastics could be reduced by 16% compared to

[37] Material Economics (2019), *Industrial Transformation 2050, Pathways to Net-Zero Emissions from EU Heavy Industry*
[38] Assuming that the very process of chemical recycling is decarbonized.

today, while average revenues could increase by 71% as mechanical recycling produces plastics equal in quality to primary production [Exhibit 12].

Altogether, **an ambitious materials efficiency and circularity pathway could result in a 56% cut in global carbon emissions from plastics by 2050** versus base case [Exhibit 13]. With the solution mix presented in Exhibit 10, achieving this significant reduction global carbon emissions from plastics would come at **an average cost of US$36/tonne CO_2**.

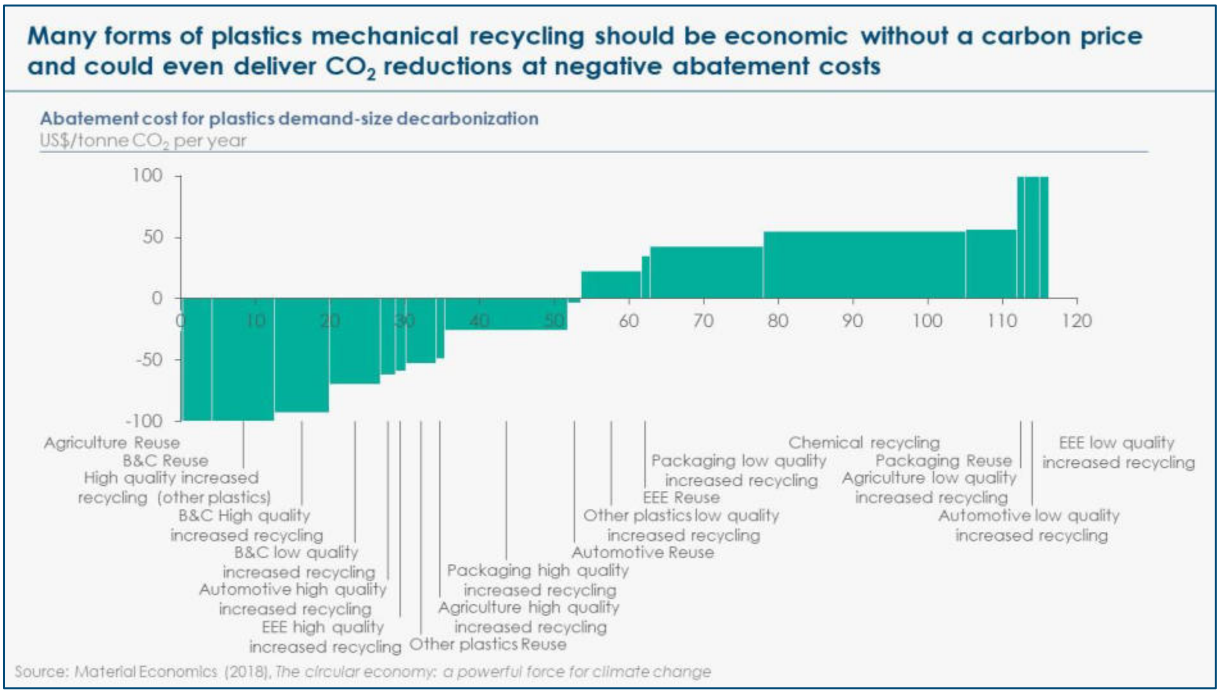


Exhibit 12

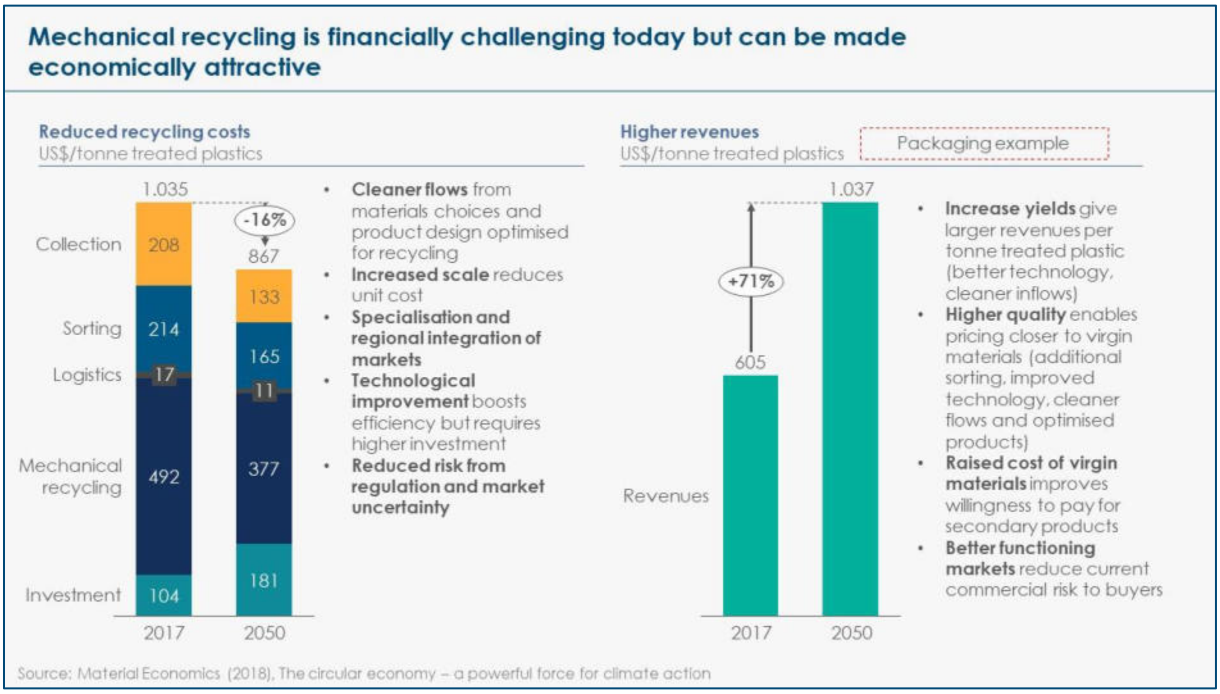


Exhibit 13

D. IMPLEMENTATION CHALLENGES

The good news is that, in principle, we could significantly reduce emissions from plastic production and use, by cutting primary plastics demand by up to 56% globally. The challenge, described in detail in the Material Economics report, is that the fundamental barriers to recycling are not primarily technical, but arise from **a combination of adverse policy, market and industry features** throughout the value chain of plastics production and use [Exhibit 14]:

1. **Price of raw materials:** Primary plastics production from fossil fuel feedstock has historically not faced the taxes required to reflect either its climate impact or the other adverse environmental consequences of plastics use.
2. **Product design:** Many plastic items are designed in ways which make recycling difficult or impossible, and producers do not face incentives to improve design, with insufficient coordination between the recycling industry and upstream producers of plastics products.
3. **Collection:** Public policies and targets often focus on maximizing collection rates, with a more limited focus on maximizing the quality of the collected materials, which would facilitate the secondary production of high-quality plastics.
4. **End-of-life treatment:** Product dismantling techniques often take little account of the implications for high-quality recycling e.g. shredding of cars results in mixed and contaminated plastic wastes which are difficult or impossible to recycle.
5. **Secondary material production:** The recycling industry today is much too small to achieve economies of scale, with recycling processes and policies often locally managed and inconsistent between locations.
6. **Market for recycled material:** Partly as a result, secondary plastics are perceived to be (and in many cases are) of low quality, trading at a significant price discount to primary production.

The recycling rates and economics described in the Material Economics report will only be achieved if the problems mentioned above are tackled and solved, and if plastics recycling emerges as a large-scale secondary materials industry producing products equal in quality to primary production. The implications for public policy and other required actions are considered in Section 7.

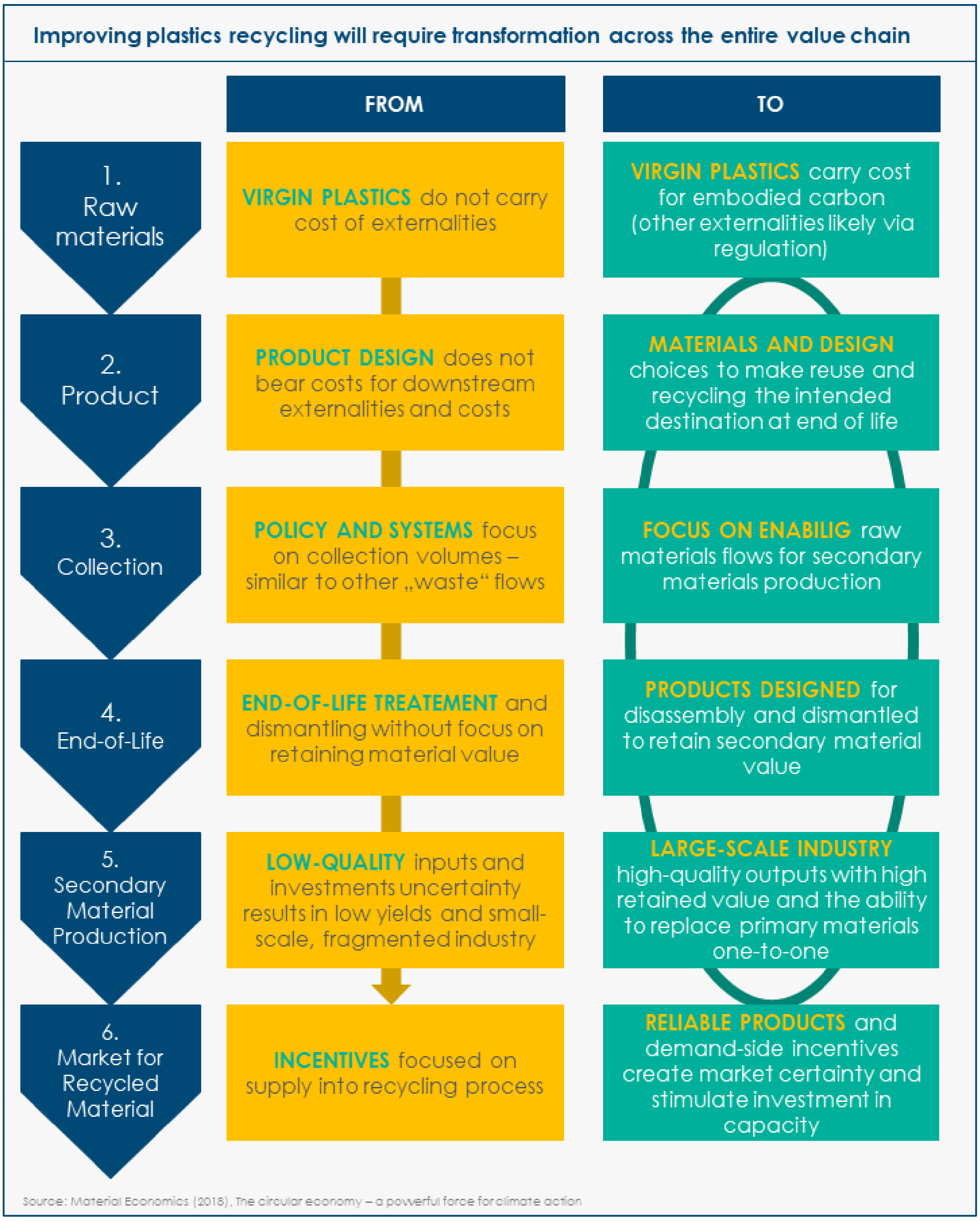


Exhibit 14

E. REMAINING FORMS OF PLASTICS

REMAINING THERMOPLASTICS AND THERMOSETS

While Material Economics describes a credible route to achieve a 56% carbon emissions reduction from plastics versus the 2050 base case, 44% of emissions would still remain. **Thermosets and multiple forms of plastics with small production volumes** will represent by then a large percentage of all non-recycled plastics, and these are much more difficult to mechanically recycle. Further emissions reductions will therefore require:

- **A larger role for chemical recycling** than the treatment of 18% of total end-of-life plastics assumed in the Material Economics 2050 global scenario, which may be possible if the cost of chemical recycling declines over time, but would likely also require higher carbon prices than the levels that would be sufficient to make other recycling opportunities mentioned earlier in this paper economic;
- Public policies which favor **tightly managed landfill operations** over incineration for the small remaining share of plastics which cannot be mechanically or chemically recycled at acceptable cost – indeed creating some form of carbon storage through secured landfilling of plastics;
- **A reduction in the use of specialized plastics**, in order to increase the share of easily recyclable plastics in total plastics production.

FIBRES AND RUBBERS

Most analyses of plastics do not cover either clothing fibers or rubber products (in particular tires), but these products are a significant part of the global chemical industry picture.

- 59.2 Mt of plastic polymer production is used in **clothing fibers** – in particular PET in polyester – and their production accounts for around 142 Mt of CO_2 emissions[39], with roughly 143 Mt of further emissions resulting if, sometime in future, all end-of-life clothing is incinerated[40]. The decarbonization of monomer and polymer production (considered in Section 4) would take much of the carbon emissions out of synthetic fiber production. But increased chemical recycling is required to avoid end-of-life incineration or landfill. There are no technical barriers to such recycling for any of the five major synthetic fibers – PET, PP, Polyamide (PA), Polyurethane (PU) and Polyacrylic (PAN) –, but the economics of recycling are currently unfavorable given today's cheap primary production, located primarily in China.
- Elastomers are combined with other inputs (carbon black, metal, textiles, zinc oxide and additives) to produce **11.1 Mt of tires**. Total emissions from tire production are about 27 Mt, and an additional 57.7 Mt would be emitted if all tires were incinerated at end-of-life[41]. Tires can be recycled into asphalt and some other plastics products, but in practice today only about 3 to 15% are recycled, rather than landfilled or incinerated[42].

Developing recycling strategies for fibers and tires should therefore be a focus for further analysis.

[39] Based on 2.5 tonnes of CO_2 per tonne of plastics in production
[40] Based on 2.7 tonnes of CO_2 per tonne of plastics at end-of-life
[41] Based on 2.5 tonnes of CO_2 per tonne of plastics in production and 2.7 tonnes of CO_2 per tonne of plastics at end-of-life
[42] Smithers Rapra (2017), *Development in recycling and re-use of waste rubber*

3. IMPROVING ENERGY EFFICIENCY

Incremental efficiency improvement in existing steam cracking processes could deliver positive net-present-value returns and reduce energy-related emissions. But with petrochemical plants already tightly managed to minimize energy costs, potential reductions from moving to best available technologies are unlikely to exceed **15 to 20% of monomer production emissions** (and about 7% of total emissions including end-of-life)[43]. Recent IEA analysis[44] identifies naphtha catalytic cracking (NCC) as a production technology capable of delivering 15% process energy savings versus best performing regular naphtha crackers. However, this process entails higher level of investments and its deployment is very limited so far.

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[43] McKinsey & Company (2018), *Decarbonisation of industrial sectors: the next frontier*
[44] IEA (2018), *The future of petrochemicals*

4. PRODUCING ZERO-CARBON-EMISSIONS PLASTICS

This section presents the Energy Transitions Commission's vision of the pathway to produce plastics that would not emit any carbon throughout their lifecycle. It is based on McKinsey's report on *Decarbonisation of industrial sectors: the next frontier* (2018) and on the IEA's report on *The Future of Petrochemicals* (2018). The challenge of producing zero-carbon-emissions plastics is twofold, as both emissions from the production process (Section 4.A) and embodied carbon contained in the feedstock that might be released at end-of-life (Section 4.B) need to be tackled.

A. DECARBONIZATION OPTIONS FOR THE MONOMER PRODUCTION PROCESS

As explained in the introduction, **this sectoral focus concentrates primarily on the decarbonization of ethylene production**, but the conclusions are likely to be relevant for other categories of monomer production, as production processes for each of these are sufficiently similar.

We can distinguish **4 main routes** for the decarbonization of ethylene production, with the optimal choice likely to vary between different locations and over time as a wider range of technological options becomes available:

(i) **Carbon capture could be applied to capture the exhaust gases from pyrolysis furnaces** – and then either stored in underground storage or used in several applications, potentially within the chemical sector itself[45]. In principle, this should be technically straightforward, since there are a limited number of points of emissions in the ethylene production process. Capture cost estimates for first-of-kind applications are between US$56 and US$108 per tonne of CO_2 saved, and could be significantly reduced for n^{th}-of-kind applications. Total cost of CCS will then depend on the cost of transport and storage in specific circumstances (an average of 20US$/t$CO_2$ with regional variations[46]). There are currently no industrial scale CCS installations on pyrolysis furnaces[47]. Furthermore, the carbon capture efficiency is capped with maximal levels estimated around 80-90%.

(ii) **The second potential decarbonization route is a switch to a low-carbon energy source for heat generation.** A switch to sustainable biomass, sustainable biogas or zero-carbon hydrogen would not require major retrofitting of existing installations. However, even if those options are technically feasible today, they would be significantly more expensive than present technology, as shown in Section 4.D below. In the long run, the hydrogen route is likely to be advantaged by the fact that it does not face the same constraints on sustainable supply as bioenergy (see Section 4.C). However, this route will only be zero-carbon if hydrogen is produced from electrolysis of zero-carbon electricity or from steam methane reforming plus CCS.

[45] For further details on the challenges of carbon capture deployment and trade-offs between storage and use, see Chapters 6 and 7 of Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*
[46] IEA (2019), *The Future of Hydrogen – Assumptions Annex*
[47] McKinsey & Company (2018), *Decarbonisation of industrial sectors: the next frontier*

(iii) **The direct electrification route is in theory also feasible**, but, while high-temperature electric furnaces have been built in laboratories and other applications, they are not yet commercially available for ethylene cracking. It is to be noted that this solution would only be zero-carbon if the electricity was derived from renewable sources.

(iv) **In the long run, it is possible that plastics will be produced from entirely new zero-carbon electrochemical processes,** if zero-carbon electricity is abundant and cheap enough. These electrochemical processes are expected to allow greater precision in the design of plastic compounds and might deliver greater yields. These processes are however currently at laboratory stage of development. Most importantly, the large impact on total electricity demand (e.g. 10,000 TWh to decarbonize all primary chemical production) would need to be carefully assessed[48].

B. DECARBONIZATION OPTIONS FOR FEEDSTOCK

The switch to renewable feedstocks, combined with the decarbonization of the production process, could potentially make plastic zero-carbon-emissions across the entire lifecycle of the product, even if plastic were incinerated at end-of-life. Two types of renewable feedstocks could be considered: bio-feedstock (for which CO_2 absorption in the growth of biomass would offset the end-of-life emissions) and synthetic feedstock (which would only be carbon-neutral if the CO_2 input to the synthetic feedstock came from direct air capture).

The biorefinery sector already produces biodiesel and bioethanol for other purposes, in particular for road transport. These biorefined products can be further transformed to feed into the plastics industry. Other bio-based processes have also been developed. **Several options of bio-feedstock are therefore practicable:**

- Biodiesel can be converted into bio-naphtha and used instead of standard fossil fuel-based naphtha in cracking furnaces.
- Bioethanol can be used as feedstock to produce ethylene via dehydration of ethanol.
- Alternative bio-based processes to make monomers are in pilot phase development. Such processes may also make it possible to crack at lower temperatures, reducing the related energy input and emissions from heat production.
- Finally, it is possible to make biodegradable plastics from starchy biomass sources. These can additionally help address the important non-climate-related environmental impacts of plastics (e.g. litter, landfill leakage and harmful disposal in oceans and rivers).

However, the costs of bio-based plastics are currently well above conventional fuel-based production (~100% cost premium for bio-based plastics estimated in 2015[49]). Moreover, sustainability constraints on biomass availability are likely to prevent a complete switch of the chemicals industry to bio-feedstocks (see Section 4.C).

By contrast, synthetic feedstock could in principle be produced in large quantities without hitting sustainability barriers, provided cheap, low-carbon electricity is available. Indeed, the production of synthetic feedstock requires the synthesis of hydrogen (produced from

[48] IEA (2018), *The future of petrochemicals*
[49] Horvat and Wydra (2018), *Modelling and Simulating the Dynamics of the European Demand for Bio-Based Plastics*

electrolysis of water[50]) and carbon dioxide (obtained via direct air capture, which is an electricity-intensive process). It would be technically possible to use synthetic feedstock in plastics production today and its use would become inevitable if new electrochemical processes are deployed (see previous section). Cost reduction of synthetic feedstock production would likely result from an accelerated deployment of hydrogen use across multiple sectors of the economy[51].

In the short term, the IEA's recent analysis[52] also highlights the vital importance of addressing very high emissions resulting from Chinese use of coal as a feedstock and fuel source for the chemical industry, including for monomer production. Indeed, **achieving a shift from coal to gas in the Chinese chemical industry** could trigger significant short-term emissions reductions (while not providing a route to full decarbonization), as China represents 16% of global plastics production in 2015 (which could go up to 20% in 2050 in a business-as-usual scenario[53]), out of which ~20% is coal-based[54]. Coal-based plastics production produces more carbon emissions than gas-based production. Current trends are concerning as China is rapidly increasing its coal-to-olefins production capacity.

C.SUSTAINABLE LIMITS ON BIOENERGY AND BIO-FEEDSTOK FOR PLASTICS

Biomass could in theory play a variety of roles in the decarbonization of plastics production, in some cases also offsetting end-of-life emissions:

- In terms of energy input, biomass could be used, potentially in a biogas form, to provide the **heat supply** for cracking furnaces. This would reduce net production emissions (since the CO_2 released in combustion would be offset by the CO_2 absorbed during biomass growth) but would leave end-of-life emissions unchanged.
- Multiple forms for bio-feedstocks could be used to substitute the fossil-fuel feedstock for plastics production (see Section 4.B). These would reduce – and potentially bring to zero – net feedstock-to-end-of-life emissions since, even if plastics are incinerated at end-of-life, the resulting emissions would be offset by the CO_2 absorbed in the original biomass growth.

At present, these bio-based energy or feedstock sources would cost significantly more than fossil fuels[55]. In principle, these costs may decline significantly over time as the biorefinery sector scales up and the biorefinery process gets more efficient. However, cost trends are also likely to be impacted by the potential scarcity of biomass supply, in particular in regions with low levels of biomass per capita.

Indeed, any use of bio-based inputs in plastics production – whether as fuel or as feedstock – needs to be assessed in the context of **broader sustainability issues with regards to the use of biomass**. These are further explored in the ETC's *Mission Possible* report (chapter 6 and 7). The major conclusions are that:

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[50] The use of SMR+CCS to produce synthetic feedstocks is unlikely to make economic sense given that gas could be used directly in the chemicals industry, combined with CCS, without the need for an intermediary step.
[51] For further details on the role of hydrogen in the deep decarbonization of the economy, see Chapter 6 of Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*
[52] IEA (2018), *The future of petrochemicals*
[53] Material Economics (2018), *The circular economy – a powerful force for climate action*
[54] For ethylene production. Servomex (2017), *Coal to olefins*
[55] McKinsey & Company (2018), *Decarbonisation of industrial sectors: the next frontier*

- **Bioenergy or bio-feedstock should be primarily sourced from clearly sustainable waste and lignocellulosic sources**, minimizing use of oil plants which use arable land otherwise available for food production.
- Estimates of the total potential supply of sustainable biomass are inherently uncertain and vary greatly, but the ETC believes that **biomass with energy value of about 70EJ could be sustainably sourced each year** based on different forms of waste only (municipal waste, agricultural residues, wood residues…).
- The IEA estimates that 68EJ of bioethanol and other assorted biomass (representing an even greater amount of biomass input) would be needed to decarbonize all primary chemicals production. Approximately 60% would be used as feedstock (either via gasification or dehydration) and the remainder as process energy[56]. **The potential demand for biomass from the plastics industry could therefore already reach the limits of sustainable supply of biomass globally**, without accounting for other potential uses.
- **Multiple sectors beyond plastics, including electricity generation and transport, will have a claim on these limited biomass resources**, which could drive prices up, or lead to environmentally destructive expansion of biomass-for-energy/feedstock production.
- The ETC reached the conclusion that, given sustainability constraints, biomass use should be prioritized for sectors which have little-to-no alternative to using a form of renewable hydrocarbon to reduce their lifecycle carbon emissions. We consider that **bio-feedstock for plastics production is the second highest priority sector for biomass use, after aviation**, as the only alternative for both these sectors are synthetic fuels which may dominate in the long run but are unlikely to be available at scale in the short term.
- By contrast, **biomass use for high heat generation for cracking would not be considered as a high-priority use**, as there are multiple alternative decarbonization options, including use of CCS, use of hydrogen and direct electrification.
- However, even then, bio-feedstock could not entirely substitute for fossil fuels: ~40EJ of biomass would be required to cover the feedstock needs of the primary chemicals[57]. **The strategy for plastics decarbonization must therefore combine a portfolio of approaches to the CO_2 embedded in plastics:** an as complete as possible shift towards a circular model, the development of carbon sequestration (CO_2 capture and storage on the back of incineration plants, or in the form of solid plastics placed in permanent secure and leak-proof storage which is likely to be cheaper), and an as limited as possible use of bio-feedstock – and possibly of offsets from land use – to compensate for inevitable losses in the value chain.

D. DECARBONIZATION OPTIONS: COST TRADE-OFFS

The optimal choice between the different routes to decarbonization described above will depend on the price at which natural resources (renewable electricity and biomass) are available, and on the technical and political feasibility of CCS in particular locations. **It will therefore likely vary by region.**

As a report by the IEA[58] has highlighted, and as discussed in the ETC report *Mission Possible*, **renewable electricity costs are likely to continue to fall dramatically** in locations with the most

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[56] IEA (2018), *The future of petrochemicals*
[57] IEA (2018), *The future of petrochemicals*
[58] IEA (2017), *Renewable energy for industry*

favorable wind and solar resources, **with consequent dramatic falls in the cost of hydrogen production from electrolysis**. This could enhance the cost-competitiveness of direct electrification, indirect electrification through hydrogen use, and, in time, use of synthetic feedstock.

With regards to production processes, McKinsey analysis suggests that abatement costs could be in the range of US$80 per tonne of CO_2 in the most favorable environment to US$300 per tonne of CO_2, depending on the decarbonization route and on local renewable electricity prices.

- Electrification of furnace heat will become cheaper than deploying CCS in locations where renewable power is available at or below US$25/MWh for greenfield industrial plants and US$15/MWh for brownfield industrial plants[59]. These breakeven points might be higher in regions with limited availability of carbon storage infrastructure but are unlikely to be met in the near future in many locations.
- By contrast, in the shorter-term, hydrogen use for high heat temperature in brownfield industrial plants could become cost-competitive with CCS, even with a higher cost of electricity (with electricity cost of US$70/MWh and a carbon price of US$75/t$CO_2$[60]), given that it does not require a major change in process and equipment.
- Use of bioenergy could in some locations represent a cheaper option, although its use is likely to be limited by constraints on sustainable biomass supply (see Section 4.C)

In parallel, in their bio-based feedstock scenario Material Economics estimates the mid-century cost of decarbonizing European plastics production using bio-based feedstock at US$160/t$CO_2$, which includes the cost of end-of-life treatment[61]. This is lower than McKinsey's global estimate of US$200-1000/t$CO_2$ for decarbonization of plastics production using bio-based-feedstocks, not accounting for end-of-life treatment[62]. These ranges reflect high uncertainties on costs, driven by the lack of maturity of relevant technologies as well as uncertainties on the possible price trajectory of different forms of energy and feedstock (including biomass).

[59] McKinsey & Company (2018), *Decarbonisation of industrial sectors: the next frontier*
[60] SYSTEMIQ analysis for the Energy Transitions Commission (2019)
[61] Material Economics (2019), *Industrial Transformation 2050, Pathways to Net-Zero Emissions from EU Heavy Industry*
[62] McKinsey & Company (2018), *Decarbonisation of industrial sectors: the next frontier*

5. COST OF FULL DECARBONIZATION OF PLASTICS

As Section 2 through 4 argued, it is technically possible to achieve quasi full decarbonization of the plastics sector "within itself", i.e. without purchasing offsets from other sectors, but the plastics sector constitutes a very challenging sector, due to the necessity to tackle feedstock emissions and to the high costs of supply-side decarbonization. These features are reflected in our assessment of the total cost of the full decarbonization of the plastics sector.

Therefore, this chapter considers in turn:

- The cost for the economy of plastics decarbonization derived from the abatement cost per tonne of CO_2 saved,
- The implications of the decarbonization cost for the cost of intermediate products purchased by businesses and of end products purchased by consumers.

A. COST TO THE ECONOMY

Actual abatement costs for the plastics sector will depend on future technological developments and cost trends, as well as on the extent to which demand-side mitigation measures are pursued (in particular the extent of recycling).

McKinsey analysis indicates that the maximum total cost to the global economy of completely decarbonizing both plastics production and end-of-life (through a change in feedstock) would amount to **US$62 billion per year on average by 2050**, which represents only 0.02% of expected global GDP[63]. This takes into account a mix of greenfield and brownfield sites as well as a mix of decarbonization options reflecting regional specificities across the globe.

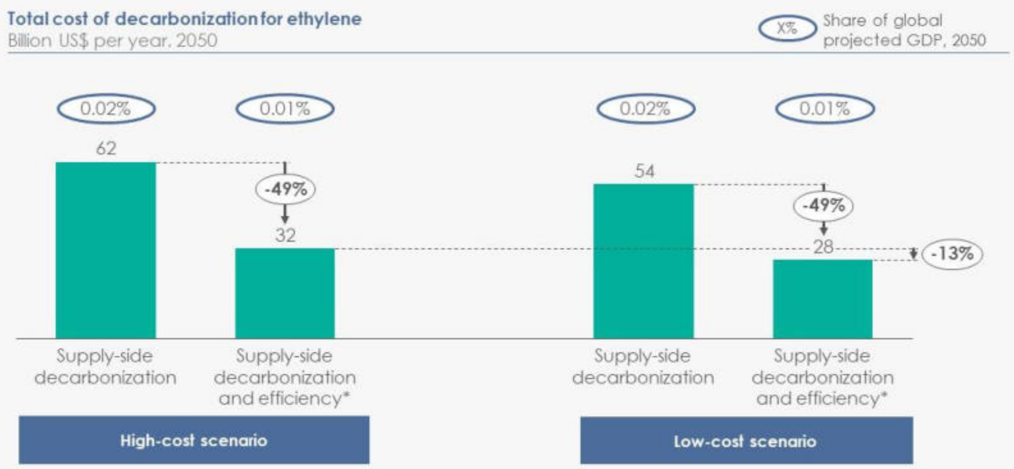
This cost to the global economy of decarbonizing plastics could be further reduced by three factors:

- **Lower renewable energy costs:** The availability of low-cost, zero-carbon electricity would make a slight difference to the cost of ethylene decarbonization: if zero-carbon electricity was available at US$20/MWh across the world, decarbonizing ethylene could cost US$265/t$CO_2$ (instead of US$295/t$CO_2$ if zero-carbon electricity is available at US$40/MWh).
- **Future technological development:** The cost of decarbonization could be dramatically reduced or even eliminated by faster cost reduction of existing technologies, or deployment of unanticipated new technologies. In particular, the cost of addressing embedded carbon could come down drastically if technological improvements make bio-feedstocks from lignocellulosic sources or algae cost-competitive, or if a sharp decrease in both green hydrogen costs and direct air capture of CO_2 costs brought synthetic feedstock to cost-parity.
- **Demand management:** Given the extraordinary potential for primary plastics production reduction described in Section 2, greater recycling and reuse of material could play a major role in reducing total decarbonization costs in the plastics sector. Material Economics estimates the average demand-side abatement cost of plastics at US$36/t$CO_2$[64]. If primary plastics production can be reduced by 56% at US$36/t$CO_2$,

[63] McKinsey & Company (2018), *Decarbonisation of industrial sectors: the next frontier*
[64] Material Economics (2018), analysis for the Energy Transitions Commission

then the higher-cost supply-side decarbonization measures would only have to be applied to the remaining 44% of the production, bringing the total cost to the economy to lower than 0.01% of global GDP.

Decarbonizing ethylene would cost significantly less if pursuing demand management and energy efficiency improvement opportunities



Note: The term "efficiency" covers energy efficiency, materials efficiency, materials circularity, and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* and Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 15

B. B2B COST AND END-CONSUMER COST

Decarbonizing plastics will have a trivial impact on the cost of end consumer products in which plastics is used, but a material impact on the cost of raw materials.

- As an example, if the cost of decarbonizing plastics was passed throughout the supply chain, the maximal impact on the price of a bottle of soda priced US$2 would be less than 1%, which is an additional US$0.01 (using an assumption of 1.7tCO_2 per tonne of ethylene and the high-range abatement of supply-side decarbonization of US$295/tonne of CO_2). This makes it likely that consumers would be willing to support policies – whether carbon pricing or industry commitments to "green plastics procurement" – which would drive plastics decarbonization. High consumer awareness about other environmental impacts of plastics would probably contribute to the acceptability of this very small increase in prices as well.
- However, at the intermediate product level, the impact on the price of a tonne of ethylene could be as much as +50%, which translates into +45% per tonne of plastics (from US$1000 to US$1450 per tonne). It is interesting to compare this potential price increase with the volatility of ethylene prices today: the plastics value chain already faces spikes in intermediate products prices of similar magnitudes. However, chemical companies could have to fund large upfront investments and plastics buyers sustain durably higher ethylene prices, which could create serious competitive distortions between companies if policy requirements did not apply equally to all relevant domestic and international competitors.

6. CONCLUSIONS AND POLICY IMPLICATIONS

Achieving the decarbonization of plastics as presented in Sections 2 to 4 – at the cost analyzed in Section 5 – will require forceful public policy action on both the demand and supply sides, and major changes to business investment and practices across the plastics value chain.

A. DEVELOPING A CIRCULAR PLASTICS ECONOMY

A circular plastics economy in which ~60% of virgin plastics demand is reduced must play a major role since (i) production decarbonization alone would not eliminate end-of-life emissions and (ii) reduced primary production of plastics will reduce the amount of carbon storage capacity, renewable electricity or biomass otherwise required to decarbonize plastics supply, and thus reduce the total cost of full decarbonization.

A huge expansion in the role of mechanical recycling is possible and essential, combined with a major and growing role for chemical recycling. This requires **the development of a large-scale secondary plastics market,** underpinned by high-quality and high-volume recycling. Two main policy drivers can accelerate progress on the recycling front: tighter regulations on the plastics value chain and carbon pricing.

The full plastics value chain, from product design to waste systems, should be revisited to ensure better coordination between producers and users of plastics, so as to create plastic products and handling processes which enable high-quality recycling. The key challenge will center around the fair allocation of responsibilities as well as costs and benefits across the value chain. This will not be achieved without major changes at multiple points in the value chain, in particular:

- Price of raw materials: adequate carbon pricing of the input to the chemicals/plastics industry, which will increase the competitiveness of recycled material (in particular from chemical recycling);
- Product design: designing products to make collection, sorting and high-quality recycling easier, by creating new incentives for product manufacturers, for instance through extended producer responsibility;
- Collection: a revision of collection processes focusing as much on the quality of collected materials than on quantity, and covering large enough geographical areas to enable a scale-up in recycling facilities;
- End-of-life treatment: redesigning dismantlement practices to prevent the mixing of materials which occurs, for instance, when cars are shredded;
- Secondary materials production: improving the quality of secondary materials, thanks to measures to improve the quality of the flow going into recycling, but also potentially through the standardisation of secondary plastics;
- Market for recycled materials: incentivising the use of recycled materials, which should also be facilitated by higher quality of secondary materials and better pricing of raw materials.

In parallel, explicit or implicit carbon prices would increase the value of secondary materials relative to primary materials. This could further enhance the cost-competitiveness of mechanical recycling, bring chemical recycling to cost-parity, and discourage incineration of end-of-life plastics – whereas landfill taxes as applied today incentivize incineration as much as recycling. Our analysis suggests that **taxes equivalent to US$60 per tonne of CO_2**

(about US$140 per tonne of plastics) could make chemical recycling economic, and greatly increase incentives to mechanical recycling[65]. Given the international nature of plastics production and trade, national taxes on upstream production emissions could produce harmful competitiveness and production relocation effects. But downstream taxes – e.g. taxes on the purchase of consumer goods made out of primary plastics as against secondary plastics – or taxes on landfill and incineration would not create this danger.

However, even an ambitious scenario for recycling and reuse, however, would not achieve a 100% recycling rate. Multiple thermoset and small-volume specialty plastics are either impossible or very costly to mechanically recycle; recycling processes will never achieve 100% yields; and collection and sorting processes will never be perfect. A path to net-zero CO_2 lifecycle emissions from plastics will therefore have to entail some combination of:

- Circular practices as described above;
- The substitution of other products for plastics;
- Some replacement of fossil fuel feedstock with bio or synthetic feedstocks, although this will be constrained by availability and cost of these feedstocks;
- A remaining role for secured plastics landfilling but managed in such a tightly controlled fashion that it can avoid all local environmental harm and eliminate almost all CO2 emissions, with plastic storage thus becoming a variant of carbon capture and storage.

[65] Material Economics (2018), *The circular economy – a powerful force for climate action*

B. DECARBONIZING PLASTICS PRODUCTION

Supply-side decarbonization is also possible and achievable at costs likely to be between US$200-300 per tonne of CO_2 and US$450-500 per tonne of plastics (if applied only to emissions from the production process)[66].

4 main routes could deliver this decarbonization of the production process: (i) carbon capture with storage or use, (ii) a switch to low-carbon energy sources for heat generation (e.g. biomass, biogas or zero-carbon hydrogen), (iii) direct furnace electrification or (iv), in the longer run, electro-chemistry processes. In addition, **decarbonizing the feedstock input to plastics** can happen through (i) a switch from coal to gas feedstock in the short term as a transitional option in China, (ii) the use of recycled plastics as a feedstock or (iii) the use of bio or synthetic feedstock.

It is neither possible nor necessary to predict in advance which of these routes will dominate, since **the optimal solution will likely vary between different locations and over a period of time,** reflecting, for example, differences in carbon storage and transport costs, in renewable electricity costs, and in the supply of sustainable biomass. Innovation is likely to create new opportunities to reduce energy inputs, costs and emissions in ways which are unknowable today.

Given this complexity, public policy should not seek to define one specific decarbonization pathway but should **create the incentives and conditions in which a mix of these routes will certainly be pursued.** The two public policy levers to achieve this are:

- Carbon taxes imposed on the emissions produced from plastics production, ideally coordinated and imposed on an international basis;
- R&D support for technologies which might become cost-effective in future, including for instance electro-chemistry, and the production of biofuels and bio-based feedstocks from sustainable waste, residue, lignocellulosic, or algae resources.

[66] Using a tighter, more conservative range than the widely varying estimates presented in section 4.

7. RECOMMENDATIONS

To drive both the decarbonization of plastics production and the necessary reshuffling of the plastics value chain required to increase circularity, the Energy Transitions Commission recommends the following key innovation, industry and policy actions.

A. RESEARCH & DEVELOPMENT

Three simultaneous agenda should be pursued in terms of R&D.

First, R&D support should be dedicated to **innovations which facilitate higher-quality and higher-volumes recycling**, such as:

- Increasing the efficiency of recycling through automation (e.g. dismantling and sorting plastics) and digitalization (e.g. sensors, rapidly reducing costs of marking different materials and products);
- Reducing the cost, improving the energy efficiency, and enabling high-quality in chemical recycling – in particular for residual thermosets and other non-recyclables;
- Developing other non-polluting end-of-life solutions for non-recyclable plastics (e.g. secured landfilling, reuse…);
- Re-designing plastic products and materials to facilitate sorting, disassembly and recycling after use.

Meanwhile, the **4 main routes to the decarbonization of the production process of primary plastics** are all in the R&D phases of development, with the exception of biomass variants (which carry their own inherent complexity related to resource competition and sustainability challenges). Private and public R&D efforts should therefore focus on:

- Industrial-scale carbon capture installations on pyrolysis furnaces;
- Alternative, low-carbon high heat processes, in particular through the use of hydrogen or direct electrification;
- Electro-chemistry.

Finally, **bringing lifecycle carbon emissions from plastics to zero will require a shift to renewable feedstock,** especially for plastics that are hard to recycle, such as engineering plastics and thermosets. Although some bio-based routes are already technically available, R&D support would be required to:

- Develop the production of bio-feedstocks from sustainable waste, residue, lignocellulosic, or algae resources;
- Improve the efficiency of the biorefinery process;
- Reduce the cost of electrolysis and direct air capture of CO_2 to enhance the cost-competitiveness of synthetic feedstocks.

B. PUBLIC POLICY

In such a complex value chain, governments should create the **incentives and conditions for a mix of demand-side and supply-side routes to be pursued.**

R&D SUPPORT

Governments should support the R&D agenda described above, with a particular focus on early-stage demonstration and first industrial-scale pilots. This entails that public R&D funding programs dedicated to low-carbon energy should recognize that plastics decarbonization, including the development of recycling technologies, fits within the scope of their activities. This is the case, in particular, for individual country's commitments to double R&D spending in clear energy as part of Mission Innovation.

REGULATIONS

A key driver of more circular practices will be tighter regulation. These can include bans on some single-use products, but key focus should be put on driving better coordination across the plastics value chain to make higher recycling rates feasible, with regulations on:

- **Product design**, especially for packaging, appliances and other key consumer goods, by imposing obligations or standards for their recyclability and/or their recycled content;
- **Waste collection and management** (e.g. extended responsibility of producer, end-of-life collection and recycling targets for local authorities that encourage high quality over quantity and incentivize public-private partnerships for the deployment of recycling infrastructure, facilitation of waste trade across borders…), and
- **Product recycling** (e.g. standardization of recycled materials to improve their real and perceived quality).

In addition, increasingly tight **embedded carbon intensity standards** could also be imposed on major manufactured products with high plastics content sold in any given country, in order to simultaneously drive the decarbonization of primary plastics production and higher recycling, while circumventing any international competitiveness issue that would arise from imposing regulations on production.

EXPLICIT OR IMPLICIT CARBON PRICES

The setting of an explicit or implicit carbon price would simultaneously increase the value of secondary material relative to primary, discourage incineration, improve the economics of mechanical recycling, make chemical recycling cost-competitive, and drive a market-led search for the least-cost supply decarbonization pathway.

- Our findings suggest that introducing **a carbon price** of \$50 per tonne of CO_2 would drive the deployment of chemical recycling and that a carbon price of \$100 per tonne of CO_2 would accelerate progress on supply-side decarbonization solutions. This has the potential to significantly impact intermediate product price (+50% for ethylene), but with an observed trivial end-product price increase.
- Such a carbon price could be implemented by individual regions **at downstream level rather than upstream level** (i.e. on the end product rather than on plastics production), although an internationally coordinated upstream carbon price would be ideal due to the fragmented and global nature of plastic production and trade.
- **Specific taxes on plastics incineration**, at least as high as taxes on plastics landfilling, are essential to drive higher recycling rates – and can be imposed without any risks in terms of international competitiveness.
- On the flip side, **rewards (e.g. tax breaks)** could be put in place to facilitate uptake of recycled plastics and favor re-use and recycling over landfill and incineration.

C. ACTION FROM PLASTICS PRODUCERS AND CONSUMERS

The integral component to enabling greater plastics recycling, beyond technology, is **a large scale, regionally integrated secondary plastics market**. Due to the potential financial rewards in successfully closing the loop and capturing today's lost economic value, individual company commitments, as well as industry collaborations, will play powerful roles in driving change.

Individual industry players should anticipate the probable tightening of the regulatory framework in which they operate, which will encourage plastics decarbonization and favor the development of a more circular plastics economy and seize growing business opportunities in the secondary market. While these activities may result in higher initial CAPEX, higher revenues from higher-quality recycled outputs will provide financial returns on investment.

However, **developing a circular plastics economy** will require simultaneous action along value chains, and a concerted industry-wide effort to overcome the various implementation barriers to achieving high-quality recycling rates. Industry initiatives can, starting with regional initiatives, for instance at European level, aim in particular at:

- **Developing joint voluntary commitments** – for instance, the retail and consumer goods sector could commit to ban the use of single-life plastics and packaging by 2025 or to use only truly recyclable materials in packaging;
- **Developing collaborative projects across the value chain** focused on (i) re-designing plastic-based products for optimal function in after-use systems, (ii) extending and increasing producer responsibility, (iii) improving the waste collection, dismantling and sorting systems to enable higher-quality recycling;
- **Developing standardization of plastics products** (e.g. through limiting mixing of materials, limiting use of additivities, advanced adhesives, shift to recyclable polymers, advanced marking and tracking systems…) **and recycling processes** (e.g. dismantling and shredding avoiding mixing of material components).

Finally, industry players should individually or jointly invest in R&D projects that will enable them to develop and drive down the cost of the broader set of supply-side technologies (described above), which will be required to decarbonize the plastics production process as well as mitigate the impact of the CO_2 embedded in plastics.

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