MATERIAL ECONOMICS

EUROPE'S MISSING PLASTICS

Taking Stock of EU Plastics Circularity

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Commissioned by:

Agora Industry

PREFACE

Plastic waste has emerged as a major policy issue in recent years. The EU launched a Plastics Strategy in 2018 and is now considering several policy initiatives to boost recycling and reduce greenhouse gas emissions from waste. Globally, the UN just adopted a global treaty on plastics. At the same time, plastic waste that is currently landfilled or burned is increasingly seen as a potential resource, providing feedstock for a more circular future chemicals industry.

For all the attention to plastic waste, however, there is very little information on the amount of end-of-life plastics in Europe. This study seeks to fill that gap, presenting new estimates of total plastic waste volumes and recycling rates. It reaches a surprising conclusion: that there is 50% more plastic waste in Europe than suggested in current discussions of the issue – some 15 million tonnes per year of “missing plastics”.

This has major ramifications for how Europe proceeds towards a more circular economy and reaches its climate target of net zero greenhouse gas emissions. This report does not advocate for specific policies but identifies several areas to pursue to reach existing targets for recycling and lower carbon dioxide emissions.

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SUMMARY OF FINDINGS

Plastic waste has emerged as a major environmental, industrial and policy concern in recent years. Yet for all the debate of the topic, there are few studies of how much plastic waste there actually is.

This study presents new estimates of European (EU 27+3) plastic waste volumes. It finds that Europe generates about 45 million tonnes of plastics waste per year – 50% more than the 25–30 million tonnes assumed by policymakers and industry.

A key implication is that plastics are not nearly as circular as typically thought: only 15% of end-of-life plastics generated each year are recycled into new materials. The rest are landfilled or burnt to produce heat and power.

This, in turn, has major implications for greenhouse gas (GHG) emissions. It is likely that 24 million tonnes of European plastics are burnt as fuel each year, giving rise to almost 70 million tonnes of CO_2 emissions. Some of this is offset by the fact that plastics replace other fossil fuels, but the net impact on emissions is still 38 million tonnes of CO_2 – about the same amount of CO_2 as is released by 15 million passenger cars in a year.

Emissions from plastic waste are also set to rise substantially, as waste volumes grow, plastics are diverted away from landfills to meet waste policy targets, and power and heat systems are decarbonised, so plastics burnt for energy increasingly displace clean energy sources, not fossil fuels. Improving recycling is thus imperative if the EU is to reach its climate targets. Otherwise, this study finds, annual emissions from plastics will exceed 125 million tonnes by 2050 – more than is emitted by all EU cement plants today.

It is clear that deep, systemic changes – including a major policy shift – will be needed to fit plastics into a circular and net-zero GHG economy. This report ends with an overview of several interventions that have been proposed in Europe and globally. There are eight policy areas that warrant further attention:

1. Recognise the large amounts of untreated plastics and adjust policy goals accordingly;
2. Include CO_2 emissions from end-of-life plastics in the climate policy regime;
3. Reform waste collection to more effectively separate plastics from other waste;
4. Increase plastics productivity to get more out of the plastics;
5. Introduce new policies to achieve higher rates of mechanical recycling;
6. Enable new technologies to enable 70% carbon circularity;
7. Support the use of non-fossil feedstock for chemicals and plastics production;
8. Capture otherwise unavoidable CO_2 emissions.

1. TAKING STOCK OF EU PLASTICS CIRCULARITY

Plastic waste has emerged as a major environmental, industrial and policy concern in recent years. Yet for all the debate of the topic, few studies have quantified plastic waste volumes. This study aims to fill that gap for Europe (EU 27+3). It estimates plastic waste at 45 million tonnes per year – 50% higher than the 25–30 million tonnes assumed by policy-makers and industry. A key implication is that plastics are much less circular than commonly thought: only 15% of the end-of-life plastics generated each year are recycled into new materials.

THE EUROPEAN ECONOMY CREATES 45 MT OF END-OF-LIFE PLASTICS PER YEAR

Today's plastic waste results from past plastics use. Across Europe (the EU 27 plus the UK, Switzerland, and Norway), consumption of plastics stood at 54 million tonnes per year in 2020.[1] Demand has been relatively flat since the early 2000s, fluctuating around 50 million tonnes in the period 2000–2015, with modest growth since.[1]

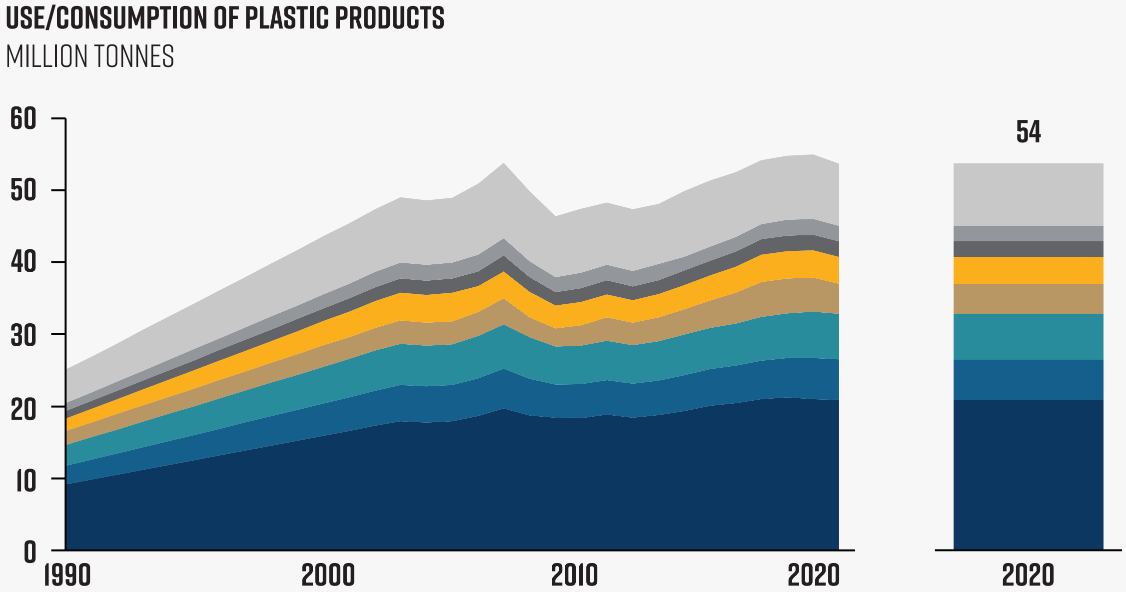
Most plastics are used in products that circulate only briefly through the economy before being discarded: 40% of plastic is used for packaging with a typical lifetime of a year or less, and another 35–40% in products such as electrical and electronic equipment or household goods with lifetimes of 3–18 years. This means that some 90% of plastics become waste within 20 years of their first use. The main exception is the 20% of plastics used in construction.[2] (The estimates presented here exclude textiles and tyres.) The average lifetime of plastics in the economy is 12 years,[3] compared with around 40 years for steel.[4]

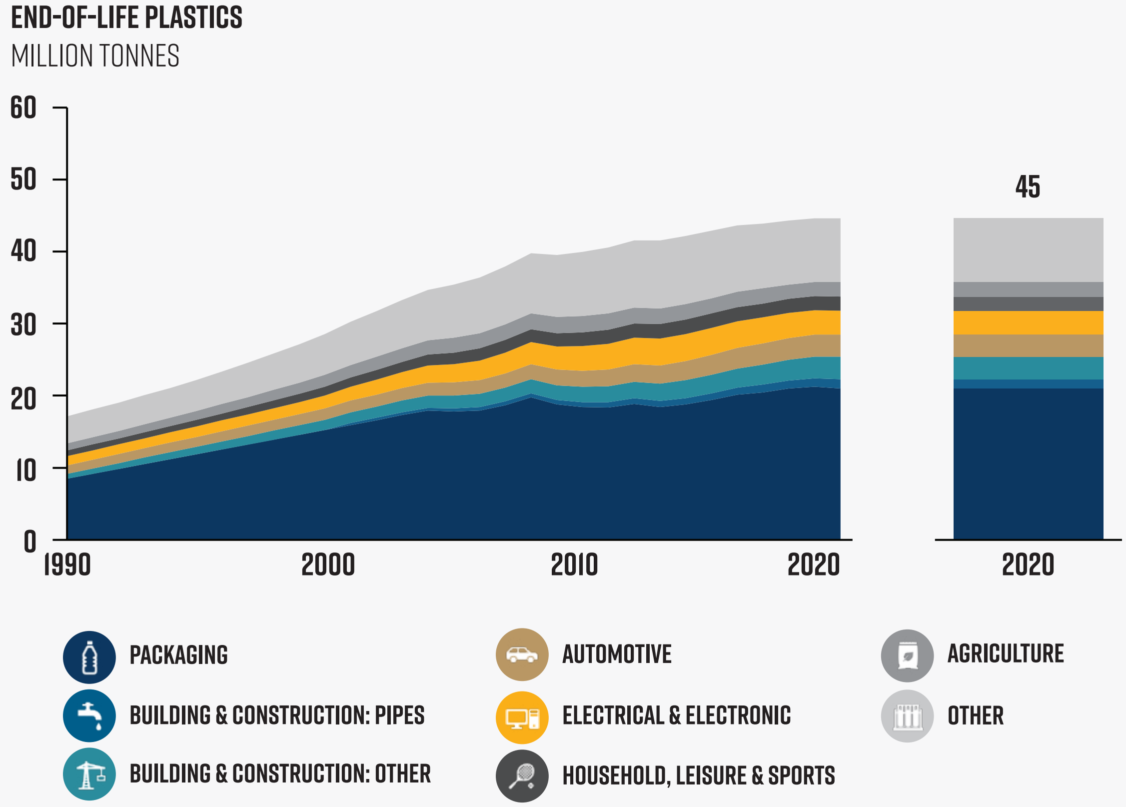
Using a model to track past use and product lifetimes in detail, it is possible to estimate how plastics products gradually turn into end-of-life plastics. We estimate that European volumes of plastics waste reached 45 million tonnes per year in 2020 (Exhibit 1), or 85 kg per person. Of this, nearly half came from packaging.

Of the 2 billion tonnes of plastics used in the European economy since the 1950s, just 28% are still in use. For comparison, 75% of the aluminium ever produced is still in use.[6] The total amount of plastics in the economy (the "stock") stands at 550 million tonnes – 1 tonne per European – and is growing at 8–10 million tonnes per year.

Exhibit 1

EUROPE GENERATES 45 MILLION TONNES PER YEAR OF END-OF-LIFE PLASTICS





NOTE: Plastics consumption is calculated as the sum of 1) demand for plastics sent to converters; 2) recycled plastics produced in the EU; and 3) estimated net trade in plastics in vehicles and electric and electronic equipment.

SOURCES: MATERIAL ECONOMICS MODELLING BASED ON MULTIPLE SOURCES.[5]

METHODOLOGY

We calculate end-of-life plastics volumes using a “dynamic materials flow model” approach. The modelling traces past plastics use from 1950 to 2019. Thanks to data published by Plastics Europe, it is possible to reconstruct both end-use categories (packaging, construction, automotive, etc.) and polymer types in a total of 72 categories. We then add to this an estimate of the total amount of recycled plastics, and the net impact of trade in products that contain plastics, such as cars and electronics.

We then use literature and trade estimates of the typical lifetime of products containing plastics to estimate when plastics used in the past reach their end of life. Summing across past years, product categories and polymer types, the volumes of end-of-life plastics can be calculated.

This approach thus uses mostly data that are directly reported in the normal course of trade, such as the total amount of plastics used by plastics converters in the EU. The key uncertainty is how long products remain in the economy, but sensitivity analysis shows that this does not affect the results significantly. See the Annex for more details on the modelling.

MORE THAN 15 MILLION TONNES OF 'MISSING PLASTICS': PLASTIC WASTE VOLUMES ARE 50% HIGHER THAN TYPICALLY ASSUMED

The numbers presented here will surprise anyone familiar with EU discussions of plastics waste. For example, the EU Plastics Strategy stated: "In 2014, the EU generated about 25 million tonnes of post-consumer plastic waste of which only 30% was recycled."[7] The corresponding estimate for 2020, published by Plastics Europe, is 30 million tonnes. However, the estimates presented here suggests that those calculations fall short by more than 15 million tonnes. So why is there such a large volume of "missing plastics"?

The likeliest answer is that the estimate of 30 million tonnes is incomplete. The underlying study has not been published, but we understand that it is based on a bottom-up inventory of national waste statistics. However, these are tricky data to work with. Waste collection is highly decentralised, and aggregate numbers must be built up from literally tens of thousands of individual estimates from municipal waste systems. Moreover, it is difficult to know the share of plastics in each stream, and to be sure that no important flow has been left out.

Individual country studies show the difficulty of obtaining precise estimates. For example, a 2012 study of plastic waste volumes in Sweden identified 500,000 tonnes of end-of-life plastics per year.[8] In 2019, a more granular effort to quantify the share of plastics in waste resulted in a much higher estimate: more than 1.2 million tonnes per year when additional waste streams were included.[9] This suggests that it may be very hard to know how complete any bottom-up estimate is.

The approach used in this study therefore avoids using waste data. Instead of aggregating millions of individual waste volume estimates, it uses data that are documented in the normal course of trade, such as total plastics production, the amount of plastics sold to converters, and the trade in products. This is combined with estimates of product lifetimes. This method – called a "materials flow analysis"– is not new; it is the standard way to estimate end-of-life volumes for other materials, such as aluminium and steel.[10] The only novelty in this study is applying it to plastics.

Of course, materials flow analyses have their own uncertainties, such as the precise lifetime of products, and how much plastic is contained in products that are imported and exported. This study explores such uncertainties and find that they are unlikely to affect the results by more than 2–3 million tonnes per year (see Annex). Further confidence is provided by comparing the results with other emerging estimates from other materials flow analyses. The results of several studies published in the last few years are almost identical to those of this study.

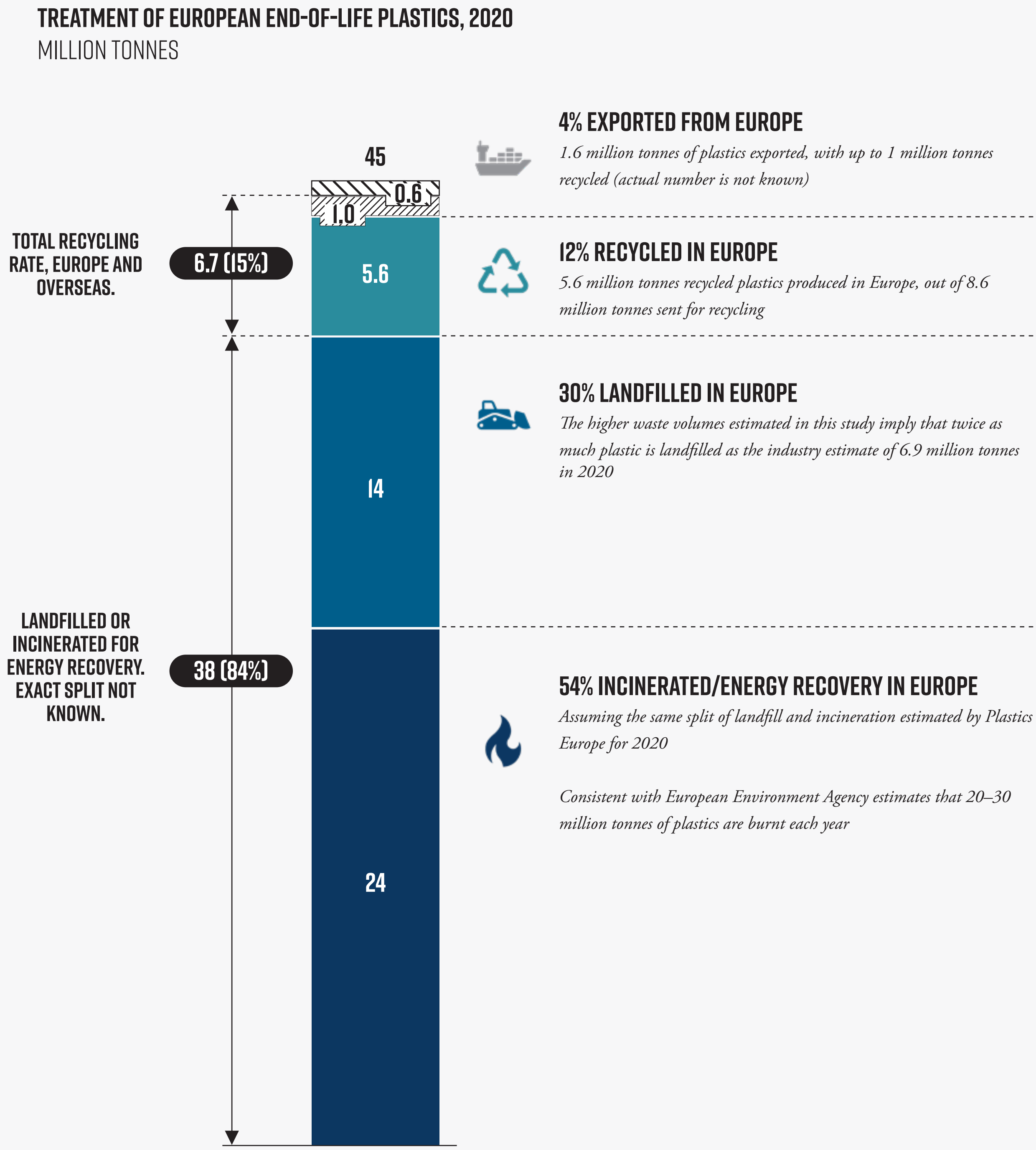
THE EFFECTIVE REYCLING RATE OF EU PLASTICS IS ONLY AROUND 15%

We estimate that, at most, 6.7 million tonnes of recycled materials are produced annually from European plastic waste. This includes 5.6 million tonnes produced by recyclers within Europe (extrapolating from industry data), and 1 million from plastics sent to be recycled overseas (Exhibit 2). The effective recycling rate – measured as the amount of recycled material produced – is therefore about 15% of the total 45 million tonnes of end-of-life plastics.

The remaining 38 million tonnes are either landfilled or incinerated for energy recovery (with some small share mismanaged).[11] The exact proportions are not known. Assuming, for illustration, the same split between energy recovery and landfill suggested by 2020 data from Plastics Europe would suggest that some 14 million tonnes (30%) are landfilled in Europe, and 24 million tonnes (54%) incinerated.[12] The latter is consistent with an estimate by the European Environment Agency that 20–30 million tonnes of plastics are incinerated annually in Europe.[13]

Exhibit 2

TREATMENT OF END-OF-LIFE PLASTICS IN EUROPE, 2020



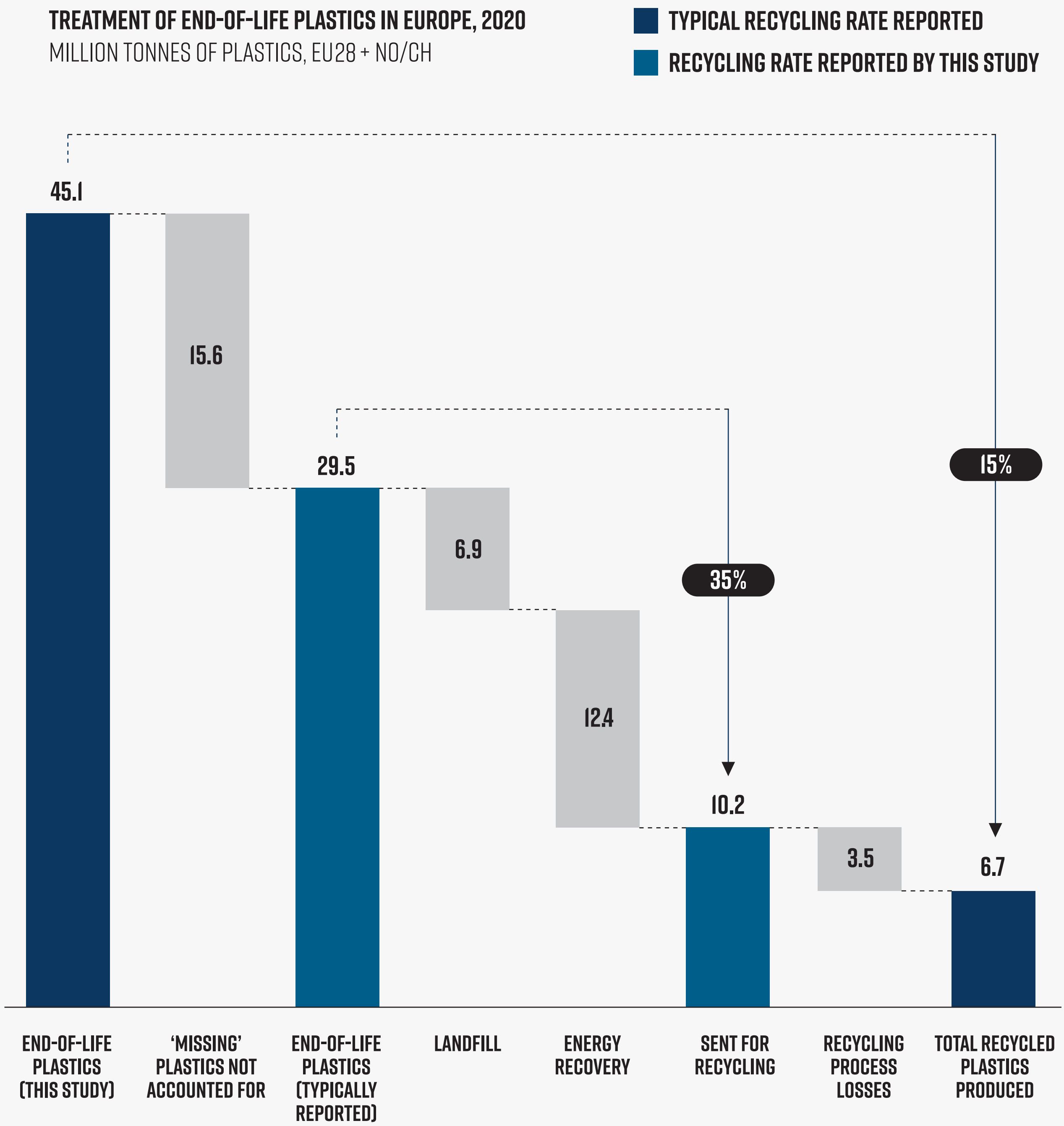
SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES.[14]

The effective recycling rate of European plastics is about 15% of the total 45 million tonnes of end-of-life plastics generated each year

Again, this is a very different number than the 30–35% typically cited for European plastic recycling rates, for two key reasons (Exhibit 3). First, the 35% rate is based on the 29.5 million tonnes of waste that can be identified via bottom-up studies, so it excludes the 15.6 million tonnes of missing plastics. Second, it refers not to recycled materials produced, but to the 10.2 million tonnes of plastics sent for recycling. However, some 35% of plastics are discarded in the recycling process, so the amount actually produced is around 6.7 million tonnes. Excluding plastics sent overseas, the recycling rate would be 12% (based on 5.6 million tonnes of recycled plastics produced in Europe).

Exhibit 3

THE RECYCLING RATE OF EUROPEAN PLASTICS IS JUST 15%



* Includes end-of-life plastics leaked to the environment (including plastic pipes not in use but left in the ground), plastic products illegally exported, illegal waste treatment of waste (e.g., end-of-life vehicles), or plastics part of mixed waste streams that are not reported as collected plastics.

SOURCE: MATERIAL ECONOMICS MODELLING, USING DATA FROM PLASTICS EUROPE, 2021, "PLASTICS – THE FACTS 2021".[15]

2. THE CLIMATE FUTURE OF END-OF-LIFE PLASTICS

The trend towards increased burning of plastics has major implications for CO_2 emissions. If 24 million tonnes of plastics are burnt as fuel each year, this gives rise to almost 70 million tonnes of CO_2 emissions. Some of this is offset by the fact that plastics replaces other fossil fuels, but the net impact is still large, about 38 million tonnes of CO_2 – roughly what is emitted by 15 million passenger cars in a year.

Moreover, these emissions are set to rise substantially, as plastic waste volumes grow, plastics are diverted away from landfills to meet waste policy targets, and power and heat production are decarbonised, so incinerated plastics increasingly replace cleaner energy sources, not fossil fuels. Improving recycling rates is thus imperative if Europe is to meet its climate targets. Without increased recycling, CO_2 emissions from plastics would exceed 125 million tonnes per year by 2050 – more than is emitted by all EU cement plants today.

Plastics incineration for fuel creates net CO_2 emissions of 38 million tonnes per year

THE CLIMATE IMPACT OF PLASTICS

How plastics are used, produced and discarded has major implications for EU climate targets. The use of plastics can help reduce greenhouse gas (GHG) emissions – for example, by reducing food waste, or by helping reduce the weight of vehicles, and thus their fuel use. Plastics are also used in many products that will be needed to reach climate targets, such as electric vehicles and solar panels.

Conversely, however, the production and end-of-life treatment of plastics results in substantial GHG emissions. If the EU is to meet its target of net zero emissions by 2050, those emissions, like all others in the economy, need to be reduced as much as possible. In the next two or three decades, it is thus crucial to solve the thorny question of how we can continue to use and benefit from plastics, while eliminating CO_2 emissions from their production and from plastic waste.

One part of this will be to produce plastics without emitting CO_2. Plastics production "from cradle to gate" leads to on average 2.3 kg CO_2 per kg of plastics (with a lot of variation). Multiple routes exist to avoid these emissions: from carbon capture and utilisation/storage (CCUS) and the use of low-carbon energy in chemicals production, to a shift of feedstock away from oil and gas and towards bio-based and recycled hydrocarbons.[16]

The other part is to handle the substantial amounts of carbon contained in end-of-life plastics. The challenge is to accommodate a material literally built out of carbon in an economy with net zero CO_2 emissions. On average, one kilogram of end-of-life plastics contains carbon equivalent to 2.8 kg of CO_2.[17] The carbon contained in the 45 million tonnes of end-of-life plastics thus corresponds to around 125 million tonnes of CO_2.

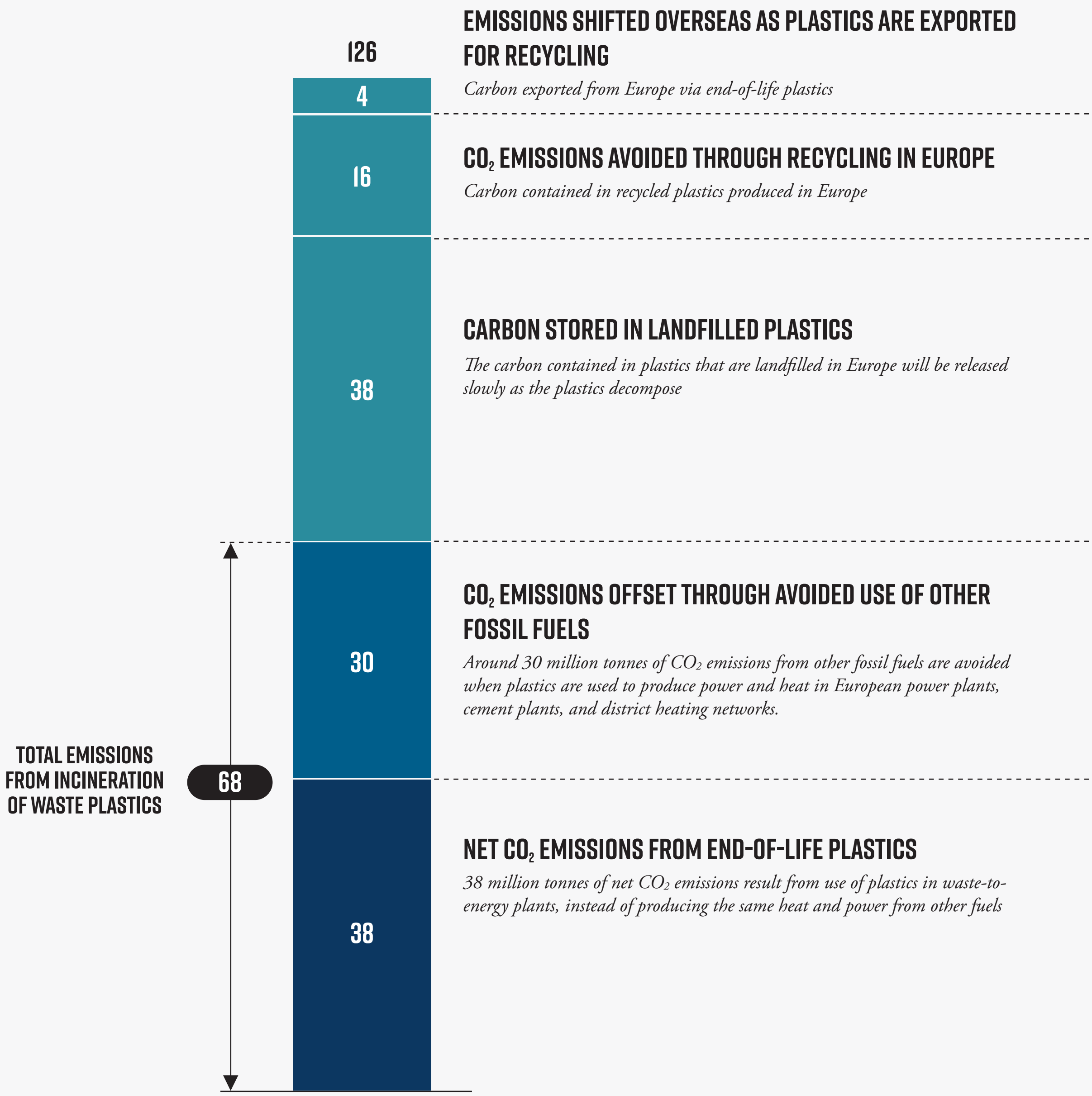
Not all carbon in end-of-life plastics is released as CO_2 to the atmosphere all at once (Exhibit 4). When plastics are recycled or landfilled, the carbon is instead stored. But for the estimated 24 million tonnes burnt each year today, the gross emissions are just under 70 million tonnes of CO_2. This is offset in part by the fact that using plastics as fuel avoids the use of other fossil fuels in European power plants, cement plants and district heating networks. We estimate that this offsets about 30 million tonnes of CO_2 emissions per year.[18] The net emissions from incineration of plastics thus are an estimated 38 million tonnes of CO_2 per year.

Exhibit 4

CURRENT NET EMISSIONS FROM END-OF-LIFE PLASTICS ARE 38 MILLION TONNES OF CO_2 PER YEAR

TREATMENT OF EUROPEAN END-OF-LIFE PLASTICS, 2020

MILLION TONNES CO_2 EQUIVALENTS



SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES.[19]

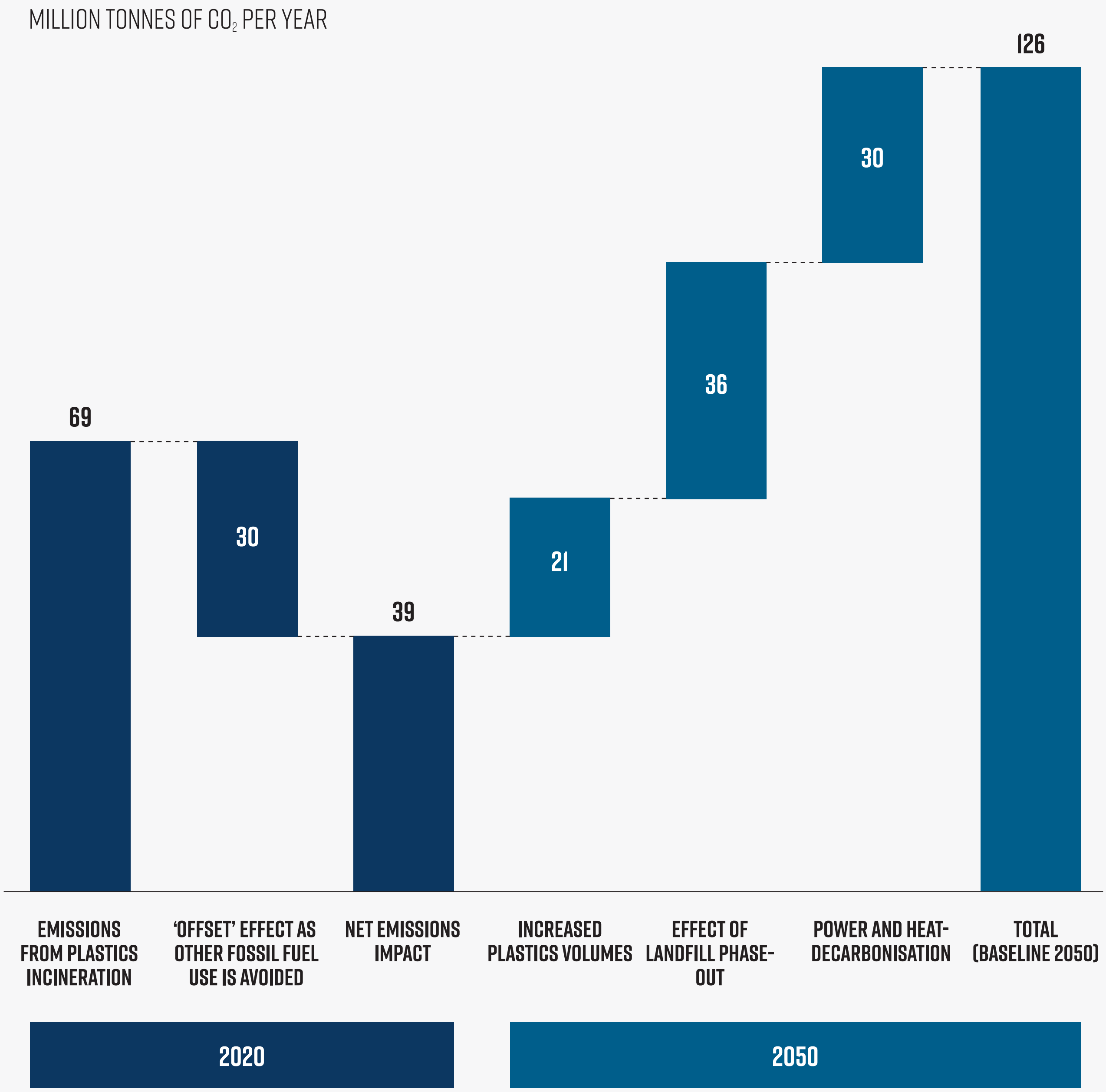
NET CO_2 EMISSIONS FROM END-OF-LIFE PLASTICS COULD MORE THAN TRIPLE BY 2050

Three factors are driving up net CO_2 emissions from plastic waste. First, plastics use is projected to grow, resulting in roughly 30% larger plastics waste volumes by 2050.[20] Second, Europe has set a goal of phasing out landfilling of waste. This has many benefits, but for a given recycling rate, it also means that more plastic is diverted towards energy recovery, creating more CO_2 emissions. Finally, the "offset" benefit is smaller as power and heat are decarbonised: in a net-zero economy of 2050, plastics burnt for fuel would not replace other fossil fuels, but would instead displace low-carbon sources of energy. Adding all these effects, unless recycling rates are increased, annual net emissions from plastic waste could be as high as 126 million tonnes of CO_2 by 2050. For comparison, the CO_2 emissions from cement production were 114 million tonnes in 2020, while EU refineries emitted 113 million tonnes.[21]

To be clear, this is an illustrative "what-if" scenario of what would happen unless recycling is increased. Turning it around highlights the imperative of increasing plastics circularity to meet climate targets.

Exhibit 5

WHY INCREASING CIRCULARITY IS CRITICAL: MULTIPLE TRENDS PUSH TOWARDS LARGE INCREASES IN CO_2 EMISSIONS FROM END-OF-LIFE PLASTICS



Notes: The analysis illustrates the effect of 30% growth in plastics volumes, EU landfill targets fulfilled without an increase in recycling rates, and a reduction in CO_2 intensity of power and heat as per EU scenarios in the EU Long Term Strategy.

SOURCE: MATERIAL ECONOMICS MODELLING, AS EXPLAINED IN TEXT.

3. IMPLICATIONS FOR POLICY AND FOR COMPANIES

It is clear that deep, systemic changes will be needed to fit plastics into a circular and net-zero GHG economy. The policies adopted to date have not supported either high rates or circularity or reductions of CO_2 emissions. New measures are needed to reach the policy goals that European countries have set themselves. This section highlights eight policy areas that warrant attention:

1. Recognise the large amounts of untreated plastics and adjust policy goals accordingly;
2. Include CO_2 emissions from end-of-life plastics in the climate policy regime;
3. Reform waste collection to more effectively separate plastics from other waste;
4. Increase plastics productivity to get more out of the plastics;
5. Introduce new policies to achieve higher rates of mechanical recycling;
6. Enable new technologies to enable 70% carbon circularity;
7. Support the use of non-fossil feedstock for chemicals and plastics production;
8. Capture otherwise unavoidable CO_2 emissions.

1. RECOGNISE THE LARGE AMOUNTS OF UNTREATED PLASTICS AND ADJUST POLICY GOALS ACCORDINGLY

Current plastics strategies and policy-making at the EU and Member State levels are based on numbers for plastic waste that miss about a third of the total volume. They also set targets and interventions on the assumption that Europe has already achieved a plastics recycling rate of 30% or more, when this study suggests it is actually 15%.

While this study has presented a first set of new estimates, there is a need for follow-up research and analysis to produce complete data on end-of-life plastics.

2. INCLUDE CO_2 EMISSIONS FROM END-OF-LIFE PLASTICS IN THE CLIMATE POLICY REGIME

As discussed above, CO_2 emissions from end-of-life plastics are already substantial, at 70 million tonnes (gross) and some 38 million tonnes (net) per year. Also as noted, emissions are set to grow substantially unless new policies are introduced.

Most of these emissions are not addressed by the current climate policy regime. Notably, unlike CO_2 emissions from industrial production or electricity generation, the fossil CO_2 emissions from waste incineration are not included in the EU Emissions Trading Scheme (EU ETS), except in a few countries, such as Sweden and Denmark, that have chosen to opt them in.

Various proposals have been made to change this situation. Numerous groups within the European Parliament have recently proposed that emissions from waste incineration should be included in the EU ETS. Individual countries, such as Germany, also aim to introduce separate CO_2 charges for fossil CO_2 emissions from incineration of waste.[22] Other countries, such as Denmark, have set targets to reduce the overall volume of waste that is treated via energy recovery.[23] There also are initiatives to equip some waste incineration with carbon capture and storage, with projects underway in Sweden and Norway.

Choosing the right policy instrument(s) will require a careful weighing of pros and cons. However, the baseline expectation should be that additional policies are needed to reverse the current trend of increasing CO_2 emissions from end-of-life plastics.

3. REFORM WASTE COLLECTION TO MORE EFFECTIVELY SEPARATE PLASTICS FROM OTHER WASTE

Based on the estimates presented in this study, just 23% of end-of-life plastics are even sent for recycling. Most of this is collected through systems paid for via extended producer responsibility (EPR) schemes for packaging, electric and electronic equipment, vehicles, and other products. However, the findings of this study show that the large majority of end-of-life plastic remains untouched by these schemes – mixed in with a variety of municipal, commercial, demolition, and other waste streams. A different collection strategy is therefore needed.

Some countries already are starting to take steps towards greater separation of plastics from other waste. Plants in the Netherlands, Norway and Sweden are now separating plastics from mixed waste streams, recovering 75–80% of the residual plastic in mixed municipal waste. Applying such “post-sorting” technology adds costs, but it provides an immediately available route to towards increased plastics circularity.

4. INCREASE PRODUCTIVITY TO GET MORE OUT OF THE PLASTICS USED

This study assumes a 30% increase in the use of plastics by 2050. However, numerous studies have shown that there is an important agenda of materials efficiency: a range of business models and strategies that enable the use of less material without compromising on function or benefits. This is not specific to plastics, but is as relevant for steel, aluminium, paper and board, and other materials. It is analogous to the much more familiar agenda of improving energy efficiency.

For plastics specifically, a range of previous studies have suggested that it is in fact possible to derive the same benefits while reducing the amount of material used.[24] Examples include new delivery models for plastics packaging, increased reuse of plastics products, use of higher-performing materials, reduced over-specification, longer product lifetimes, and increased use of sharing business models. This is as much a business agenda as a policy one, and many companies are already exploring how to get as much value as possible out of plastics.

5. INTRODUCE NEW POLICIES TO ACHIEVE HIGHER RATES OF MECHANICAL RECYCLING

The new estimates show that Europe largely fails to turn its end-of-life plastics into new materials via mechanical recycling. Despite long-standing extended producer responsibility (EPR) schemes, only 12% of the 45 million tonnes of end-of-life plastics are turned into new materials in Europe, and at most 15% if the material sent for recycling overseas is included. This is far below the technical potential – so a new approach is needed.

To raise recycling rates, change will be needed at every step of the plastics value chain, from materials production to product design, to collection and eventually recycling (Exhibit 6). One way to pursue this could be to reform EPR schemes.[25] For example, an approach called "ecomodulation" would make it more expensive to put hard-to-recycle materials or products on the market. It remains to be seen whether this can overcome the structural problems that have held back collection and recycling rates to date, despite EPR schemes. Producing materials from recycled plastics remains expensive, so companies have strong economic incentives to do the bare minimum to comply with mandates, resulting in low-quality materials that are unsuited to most uses.

Another approach is to complement the supply-side push of EPR schemes with demand-side policy: encouraging or mandating the use (rather than the production) of recycled materials. This was first introduced with the requirement in the Single-Use Plastics (SUP) Directive that plastic PET bottles should contain 25% recycled material by 2025, rising to 30% for all plastic beverage bottles by 2030.[26] More recently, the European plastics industry has supported a revision of the Packaging and Packaging Waste Directive to target up to 30% recycled content in plastics packaging by 2030.[27]

Early signs are that this can give a boost to recycling. The SUP Directive's targets, combined with industry commitments for recycled content in bottles, have triggered a substantial price premium for food-grade recycled PET plastics. That, in turn, is triggering investments in new recycling capacity. If this could be replicated for packaging broadly, the resulting market premium would enable investment in higher-quality but higher-cost recycling.

6. ENABLE NEW TECHNOLOGIES TO ENABLE 70% CARBON CIRCULARITY BY 2050

To make plastics compatible with European targets for climate neutrality, recycling rates of at least 60–70% are likely to be needed – similar to those achieved for aluminium today.[28] Mechanical recycling can provide perhaps half of this level.[29] But for the other half, additional recycling methods are needed.

Chemical (or "molecular") recycling offer a range of technologies with the potential to close this carbon circularity gap. They are less about recycling in the traditional sense, and more a set of technologies to repurpose end-of-life plastics as feedstock for new chemicals production – from which new plastics can be made. Jointly, they can be a second pillar for a strategy of high carbon circularity in the plastics system.

While many of the technologies required for chemical recycling are known and have been tested, deployment is only nascent today. There are some [20] very small-scale projects, dominated by pyrolysis at the scale of a few tens of thousands of tonnes.[30] However, several companies are now planning for larger investments, to the tune of several hundred thousand tonnes each.[31] Policy and value chain orchestration will both be needed to make such investments profitable.

7. SUPPORT THE USE OF NON-FOSSIL FEEDSTOCK FOR CHEMICALS AND PLASTICS PRODUCTION

End-of-life emissions arise because almost all plastic is produced from fossil feedstock. Recycling offers one way out – and the one that in the long term will be the most promising. In addition, it is possible also to use bio-based feedstock, converting waste biomass to the chemicals from which plastics can be made. This is significantly costlier than standard production, but it is starting to enter the market. In the long term, it is likely to be one of the highest-value potential uses for biomass within a net-zero economy.[32]

8. CAPTURE UNAVOIDABLE CO_2 EMISSIONS

Finally, it is likely that some share of plastics will always need to be burnt, alongside other waste. Even if in the long term, this is restricted to a much smaller share than today, it is unlikely that all plastics can be collected and separated for recycling (even aluminium has only about a 70% recycling rate today in Europe.[33]

The use of carbon capture and storage (CCS) then provides a final guardrail against CO_2 emissions. Using CCS on all 500 waste-to-energy plants would not be feasible, but some large plants already are planning to capture CO_2.[34] For fossil-based plastics, this would be a way to store fossil CO_2, but CCS on waste can also be used for net carbon removals by burning biomass waste and storing the resulting CO_2.

Exhibit 6

IMPROVING PLASTICS RECYCLING WILL REQUIRE TRANSFORMATION ACROSS THE ENTIRE VALUE CHAIN

MECHANICAL RECYCLING AND REUSE OF END-OF-LIFE PLASTICS
Mt, SHARE OF PLASTICS DEMAND

FROM		TO
VIRGIN PLASTICS *do not carry cost of externalities*	1. RAW MATERIAL	**VIRGIN PLASTICS** *carry cost for embodied carbon (other externalities likely via regulation)*
PRODUCT DESIGN *does not bear costs for downstream externalities and costs*	2. PRODUCT	**MATERIALS AND DESIGN** *choices to make reuse and recycling the intended destination at end of life*
POLICY AND SYSTEMS *focus on collection volumes – similar to other 'waste' flows*	3. COLLECTION	**FOCUS ON ENABLING** *raw materials flows for secondary materials production*
END-OF-LIFE TREATMENT *and dismantling without focus on retaining material value*	4. END OF LIFE	**PRODUCTS DESIGNED** *for disassembly and dismantled to retain secondary material value*
LOW-QUALITY *inputs and investment uncertainty results in low yields and small-scale, fragmented industry*	5. SECONDARY MATERIAL PRODUCTION	**LARGE-SCALE INDUSTRY** *with high-quality outputs with high retained value and the ability to replace primary materials one-to-one*
INCENTIVES *focused on supply into recycling process*	6. MARKET FOR RECYCLED MATERIAL	**RELIABLE PRODUCTS** *and demand-side incentives create market certainty and stimulate investment in capacity*

SOURCE: MATERIAL ECONOMICS ANALYSIS.

ANNEX: TECHNICAL DETAILS

SENSITIVITY ANALYSIS: PRODUCT LIFETIMES AND TRADE

A material flow analysis has the advantage of accounting for all materials: it is well known how much plastic material is produced and traded, and which thus enters the economy. However, it also requires some assumptions on variables that are harder to observe, and especially the distribution of product lifetimes – that is, how long it takes for cars, packaging and other products to reach the end of their life. The assumptions used in this modelling closely follow those in other research studies, using a distribution for each product category. While lifetimes are uncertain, it turns out that for European plastics use this uncertainty does not affect the results greatly. The base case estimate of 2020 end-of-life plastics volumes is 45 million tonnes. Increasing lifetimes by 50% would reduce this only marginally, to 42 million tonnes.

The assumptions used in this modelling closely follow those in other research studies, using a distribution for each product category. While lifetimes are uncertain, it turns out that for European plastics use this uncertainty does not affect the results greatly. The base case estimate of 2020 end-of-life plastics volumes is 45 million tonnes. Increasing lifetimes by 50% would reduce this only marginally, to 42 million tonnes.

A 50% increase already starts to stretch plausible assumptions about product lifetimes. For example, it would imply that packaging takes, on average, 1.0 years to return as waste; cars, 25 years; and electric and electronic equipment, 15 years. These are all longer than the typical turnover of packaged goods, average scrapping age of cars, or time to obsolescence of most electronic equipment. Even if lifetimes were doubled, however, our plastic waste volume estimate for 2020 would only fall by another 1 million tonnes. All in all, we conclude that the main findings of the study therefore do not depend on uncertainty about these lifetimes.

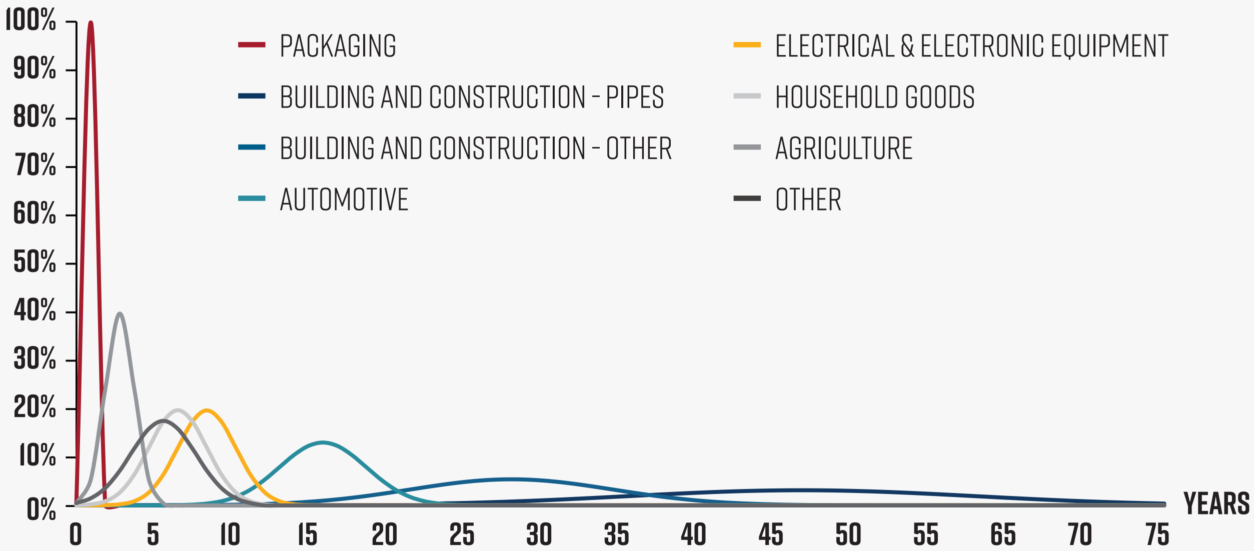
The reason for this relative insensitivity to lifetimes is that European plastics use has been relatively stable since 2000. As noted above, average annual use was 50 million tonnes in the entire 2000–2015 period.

Exhibit 7

SENSITIVITY OF RESULTS TO LIFETIME ASSUMPTIONS

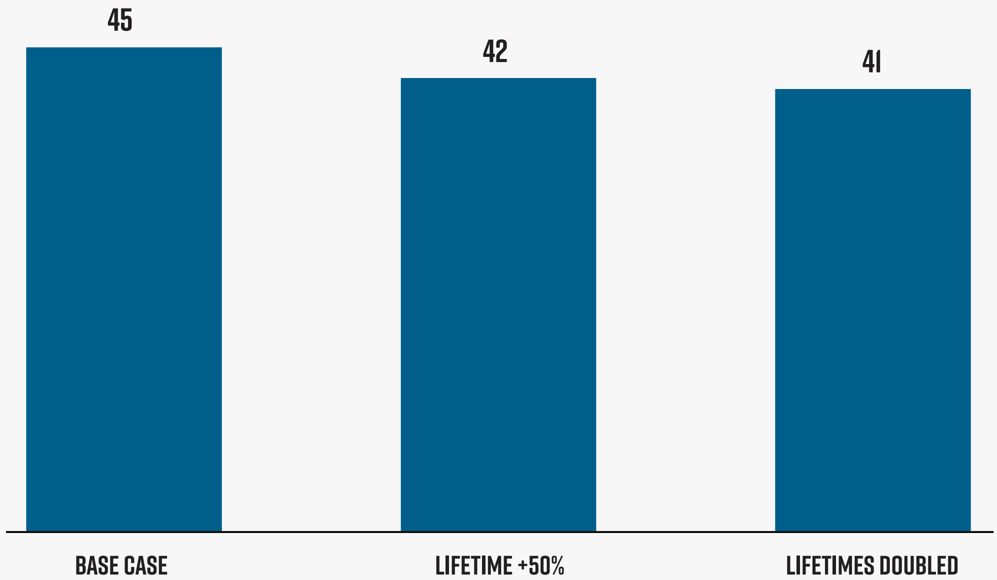
BASE CASE LIFETIME DISTRIBUTIONS

% PLASTIC RETURNED; YEARS



2020 END-OF-LIFE PLASTICS WITH DIFFERENT LIFETIME ASSUMPTIONS

MILLION TONNES OF PLASTICS PER YEAR



SOURCE: MATERIAL ECONOMICS SENSITIVITY ANALYSIS.[35]

SENSITIVITY ANALYSIS: TRADE

Trade is an important part of the materials flow analysis. Some plastic is used in Europe but exported as products – for example, as part of exported vehicles. Likewise, various products that contain plastic are produced elsewhere and then imported into Europe, where they eventually give rise to plastic waste at their end of life. Finally, some products that end their service life in the European economy are exported for use in other parts of the world – for example, used trucks are commonly exported and used for several more years in other countries, reaching ending their service life there.

The modelling accounts for trade in two key categories. For vehicles, it accounts for the plastic contained in vehicles imported to Europe, exported prior to sale, and exported prior to scrapping. For electronic and electric equipment, it accounts for the net trade balance in around 200 categories of goods. The analysis takes into account estimates of the large illicit flows of end-of-life products (i.e., outside the extended producer responsibility schemes set up to handle them).

Both of these factors do affect the modelling. The net trade in vehicles resulted in around 0.6 million tonnes of plastic leaving the European economy each year in 2015, falling to 0.3 million tonnes in 2020. Conversely, the net trade in electrical and electronic equipment results in a net flow of around 0.6 million tonnes. Therefore, neither category has a substantial impact on the modelling results.

Trade in the other main categories have not been modelled in this study. The largest omitted category is likely that of packaging. Europe is a net importer of many categories of packaged goods, and much of that packaging is not accounted for in the modelling. To the extent this affects the modelling, it thus is likely to bias the estimate of end-of-life plastics downward somewhat.

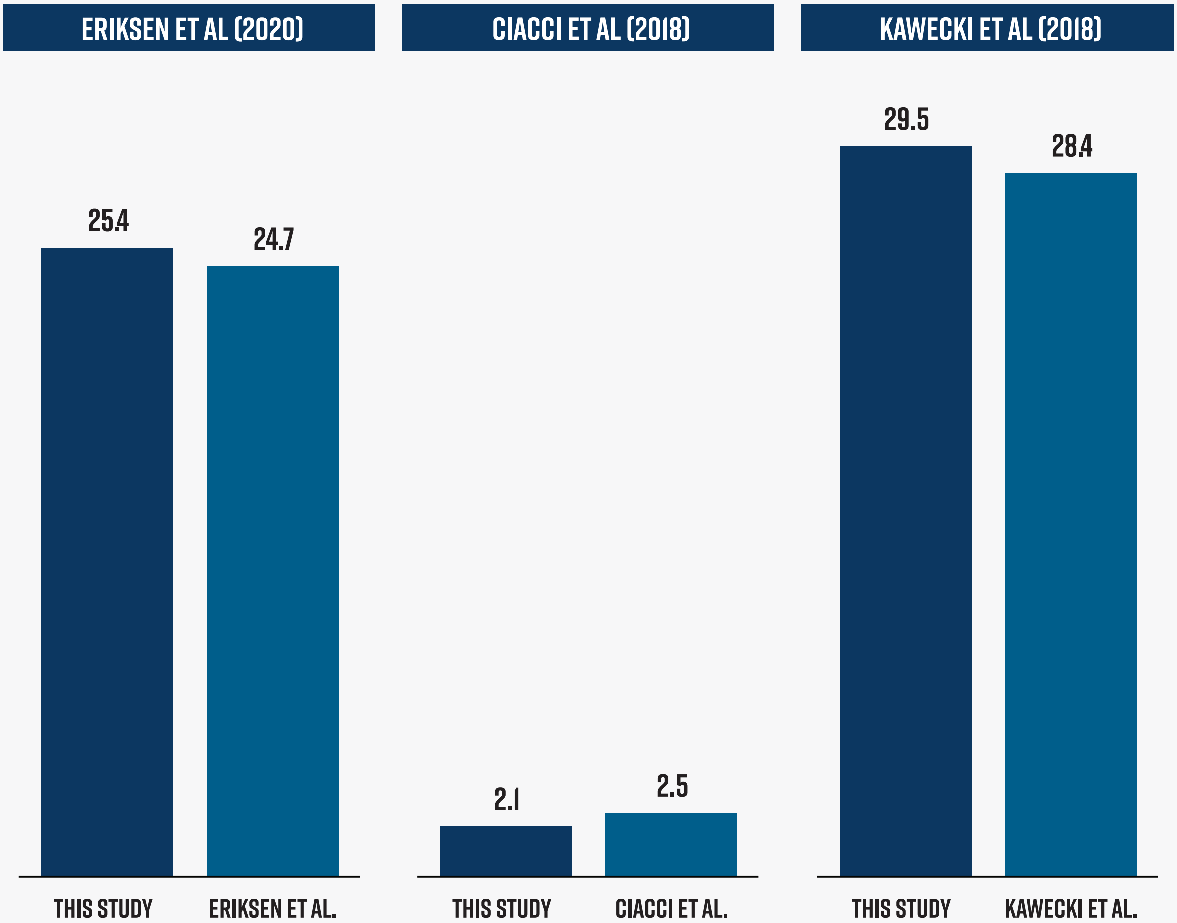
COMPARISON TO OTHER STUDIES

Finally, a comparison with three other studies of end-of-life plastics flows finds strikingly similar results to this study (Exhibit 8). These span somewhat different scopes, so the comparison is shown for the polymers and applications that are modelled both in this study and in the comparison study.

Exhibit 8

COMPARISON OF MODELLING RESULTS TO OTHER STUDIES

COMPARISON OF END-OF-LIFE PLASTICS ESTIMATES FROM DIFFERENT STUDIES
MILLION TONNES OF PLASTICS, YEAR AND SCOPE VARY



SCOPE	**PE, PP, PET**	**PVC**	***7 TYPE OF PLASTICS**
COMMENT	*When adjusting for fibres (not included in this study), the two analyses reach the same conclusion that c. 25.5 Mt of end-of-life plastics is generated in 2016*	*Results of this study are 15% lower than in Ciacci et al because that study identifies a higher usage of PVC plastics over the analysed period (1980-2012)*	*When adjusting for fibres and societal stock build-up, both sources come to a similar estimate of 28-29 Mt of end-of-life plastics for the seven polymers in 2014*

* LOW-DENSITY POLYETHYLENE (LDPE), HIGH-DENSITY POLYETHYLENE (HDPE), POLYPROPYLENE (PP), POLYSTYRENE (PS), EXPANDED POLYSTYRENE (EPS), POLYVINYL CHLORIDE (PVC), AND POLYETHYLENE TEREPHTHALATE (PET)

SOURCE: MATERIAL ECONOMICS SENSITIVITY ANALYSIS.[36]

ENDNOTES

[1] Total consumption/use of plastics in the EU27+3 is made up of underlying converter demand (49 million tonnes, Mt), use of recyclates (4 Mt), and net-trade of plastic products (0.3 Mt). See endnote 5 for detailed information calculations and sources used.

[2] Most plastic products are relatively short-lived, with some notably exceptions such as plastics used in building & construction. The relevant lifetime is the number of years products are in use in the economy (rather than, say, plastic products' technical or theoretical lifetime). Plastic packaging represents 40% of European plastic demand and typically has a lifetime of 1 year or less. Due to varying lifetimes, buildings and constructions have been split into plastic pipes and other plastic uses. Plastic pipes are assumed to have a lifetime of 50 years, while other plastic products in building and construction are assumed a shorter lifetime of ~30 years. Assumed average lifetimes for the remaining plastic segments are the following: 17 years for automotive, nine years for electrical and electronic, seven years for households, leisure, and sports, three years for agriculture, and six years for other plastic products.

Sources used include: Eriksen et al., 2020, "Dynamic Material Flow Analysis of PET, PE, and PP Flows in Europe: Evaluation of the Potential for Circular Economy," *Environmental Science & Technology*; Geyer, Jambeck, and Law, 2017, "Production, Use, and Fate of All Plastics Ever Made," *Science Advances*; Ciacci, Passarini, and Vassura, 2017, "The European PVC Cycle: In-Use Stock and Flows," *Resources, Conservation and Recycling*; Patel et al., 1998, "Plastics Streams in Germany—an Analysis of Production, Consumption and Waste Generation," *Resources, Conservation and Recycling*; Mutha, Patel, and Premnath, 2006, "Plastics Materials Flow Analysis for India," *Resources, Conservation and Recycling*; Wang et al., 2021, "Critical Review of Global Plastics Stock and Flow Data," *Journal of Industrial Ecology*.

[3] Calculated based on assumed lifetimes and plastic converter demand per segment for 2018. See endnote 2 for information about lifetime assumptions. Plastic converter demand per segment is based on data from Plastics Europe, 2021, "Plastics – the Facts 2021. An Analysis of European Plastics Production, Demand and Waste Data."

[4] Material Economics analysis based on lifetime of products in the economy and share of total steel demand in Europe. The analysis can be found in Material Economics, 2020, "Preserving Value in EU Industrial Materials - A Value Perspective on the Use of Steel, Plastics and Aluminium.". Data from Eurofer and Pauliuk was used for the calculations, see EUROFER, 2018, "European Steel in Figures 2018"; Pauliuk et al., 2013, "The Steel Scrap Age," *Environmental Science & Technology.*

[5] At the core of this report is new quantitative modelling of the EU plastics system. We have used a dynamic materials flow modelling framework, the standard approach to estimate recycling rates for materials such as aluminium or steel. The modelling estimates end-of-life flows based on the historical use of 9 polymer categories and 8 end-use segments, economy residence times for each application, and import and export estimates of products (vehicles, electronics, etc.) before end-of-life. The findings are calibrated using a range of sensitivity/uncertainty analyses and comparisons with other published studies.

The material flow analysis uses 8 plastic end-use segments, chosen based on previous segmentation by other studies (e.g., Plastics Europe and Geyer et al.,). Buildings and constructions have been split in two because of varying lifetimes of plastic products in this sector, with pipes assigned a lifetime of 50 years while other products have a shorter lifetime of 30 years. Differences in lifetimes in other sectors are not as significant and have not been further split up. See endnote 2 for detailed information about lifetime assumptions.

End-of-life plastics are calculated based on plastic use and lifetime of plastic products. Use of plastics is in turn the sum of converter demand, use of plastic recyclates, and net-trade. The values are mainly calculated based on data from Plastics Europe for the region EU27+3 (Norway, Switzerland, and the United Kingdom).

Plastic Europe has published detailed production and converter demand data over the past 20 years in their annual report "Plastics – the facts" (previously known as "The Compelling Facts About Plastics"). Plastics Europe, n.d., "Plastics – the Facts. An Analysis of European Plastics Production, Demand and Recovery [Previously Known as 'The Compelling Facts About Plastics'] (2004–2021)." Values have also been compared with data from Eurostat, 2021, "EU Trade since 1988 by HS2,4,6 and CN.". For data prior to 2000, we have linearly interpolated production data based on available data and calculated demand based on the production-to-demand data 2005–2020. There is significantly less precision in data prior to 2000. However, the model indicates that over 90% of end-of-life plastics generated in 2020 were produced after the year 2000, which mean that the uncertainty of demand data before the year 2000 has only limited impact on total end-of-life plastics generated.

For recycled plastics used in the EU, values have been based on plastics sent to converters in the EU, production losses, and exports of EU produced recyclates. End-of-life plastics collected for recycling in Europe is based on data from Plastics Europe and Plastics Recyclers Europe. Plastics Europe has data of end-of-life plastics collected for recycling for the years 2006–2020 (after 2012, the data is only published every other year). The ratio of generated end-of-life plastics and plastic waste collected for recycling in 2006 has been used to calculate collected end-of-life plastics for the years before 2006 where no published data is available. Of all collected plastics, Europe exported around half of this in the years 2006–2013 based on data from Plastics Europe (Plastics – the Facts) and Eurostat/European Environment Agency (European Environment Agency, 2013, "Exports of Waste Plastics and Selected Waste Metals from EU Member States, 1999–2011," 1999–2011.). Finally, only half of the plastics sent to EU recyclers returns to the EU economy – the rest ends up as losses or exports. Around 35% of plastics sent to recyclers end up as process losses or plastics sorted out of the process. This is calculated based on data from Plastics Europe, which shows that 7.5 Mt of plastics were sent to EU recyclers in 2018 and that this produced 5.6 Mt of plastics (the 35% has been assumed for all years). In addition, about 20% of the recyclates produced in the EU are exported. This ratio is assumed for all years and based on 2018 data by Plastics Europe.

Net-trade of products containing plastics has been analyzed for key product groups, but only marginally affects the total net flow of plastics in Europe. For the two groups Automotive and Electrical & Electronics, net-trade is calculated based on net-trade of vehicles/electronics, and the average plastic content per product. For other sectors, net trade has not been calculated. Sources for net trade include ACEA - European Automobile Manufacturers' Association, 2021, "Automobile Industry Pocket Guide 2020-2021," 202; 2021, "EU Passenger Car Production," *ACEA - European Automobile Manufacturers' Association* (blog); Emilsson, Dahllöf, and Söderman, 2019, "Plastics in Passenger Cars - A Comparison over Types and Time"; Kearney, 2012, "Plastics. The Future for Automakers and Chemical Companies"; European Environment Agency, 2014, "Imports and Exports of Electrical and Electronic Goods."

[6] Bertram et al., 2017, "A Regionally-Linked, Dynamic Material Flow Modelling Tool for Rolled, Extruded and Cast Aluminium Products," *Resources, Conservation and Recycling*.

[7] European Commission, 2018, "A European Strategy for Plastics in a Circular Economy."

[8] Fråne et al., 2012, "Kartläggning Av Plastavfallsströmmar i Sverige."

[9] Nordin et al., 2019, "Kartläggning av plastflöden i Sverige.". Notes: The bottom-up method can have large uncertainty ranges. There are two main

reasons why the bottom-up method underestimated end-of-life plastics. (1) Excluded plastics flows - the 2017 analysis included 422 thousand tonnes of end-of-life plastics from commercial mixed waste streams, a category excluded in the 2010 estimate. (2) Under-valued plastics flows - some categories such as construction & demolition, sorted household waste, and EOL vehicles were previously underestimated. Between the two estimates, these categories all increased by more than 100%, whereas other plastic flows grew by just 18%.

[10] Bertram et al., 2017, "A Regionally-Linked, Dynamic Material Flow Modelling Tool for Rolled, Extruded and Cast Aluminium Products," *Resources, Conservation and Recycling*; Müller et al., 2014, "Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods," *Environmental Science & Technology*; Pauliuk et al., 2013, "The Steel Scrap Age," *Environmental Science & Technology.*

[11] Mismanaged plastic waste and losses in the environment, including plastic waste ending up in oceans.

[12] Plastics Europe estimates that 29.5 million tonnes of plastic waste arose in 2020, of which 10.2 million tonnes were sent for recycling within Europe or abroad, 12.4 million tonnes were incinerated, and 6.9 million tonnes were landfilled. That means roughly 64% of the plastic waste that was not recycled was incinerated. See Plastics Europe, 2021, "Plastics – the Facts 2021. An Analysis of European Plastics Production, Demand and Waste Data."

[13] European Environment Agency, 2021, "Plastics, the Circular Economy and Europe's Environment.".

[14] The recycled volumes produced are directly reported from recyclers and stood at 4.9 million tonnes per year in 2018. Total volumes sent for recycling have since grown from 7.5 million tonnes in 2018 to 8.6 million tonnes in 2020, implying recycled plastics production of 5.6 million tonnes. In addition, 1.6 million tonnes of EOL plastics were sent for recycling outside of Europe. A high assumption is that these are recycled with the same yield losses as in Europe, producing 1 million tonnes of recycled plastics. Adding the two gives the estimated 6.7 million tonnes of recycled plastic production from European plastic waste. Sources: Plastics Europe, 2019, "The Circular Economy for Plastics – A European Overview."

[15] Plastics Europe, 2020, "Plastics – the Facts 2020. An Analysis of European Plastics Production, Demand and Waste Data." (2021).

[16] Material Economics, 2019, "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry."

[17] The carbon content of plastics types differ significantly. For example, incineration of one tonne of PVC plastic leads to emissions of 1.4 tonnes of CO2; PET, 2.3 tonnes; olefins (PE, PP), 3.0–3.2 tonnes; and polystyrene, 3.4 tonnes. The weighted average carbon content for the estimated EU composition of polymers if 2.8 tonnes of CO2 equivalent per tonne of plastics. The CO2 released depends on the share of carbon in the total molecular weight of the polymer. The numbers here are derived from standard chemical formulations for the most common polymers.

[18] This estimate is based on current waste-to-energy being used for electricity generation, heat provision in district heating, and direct use as fuel, not least in cement production. Comparing to average CO2 intensity of fuels used in these sectors, we find that using plastics as fuel releases 2.8 kg CO2 per kg burnt, but that each kg of plastic in turn avoids the release of 1.7 kg CO2 from other fossil sources that would be used. The net impact therefore is 1.1–1.2 kg CO2 per kg plastics used as fuel.

[19] Material Economics analysis based on multiple sources. See references in text.

[20] SYSTEMIQ and Plastics Europe, 2022, "ReShaping Plastics - Pathways to a Circular, Climate Neutral Plastic System in Europe (Forthcoming)."

[21] Data are from the EU Emissions Trading System (ETS) data viewer: https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1.

[22] EUWID, 2021, "Müllverbrennung Könnte Sich Durch BEHG Um 50 Prozent Verteuern | EUWID Recycling Und Entsorgung."

[23] The Danish Government will "Reduce incineration capacity by 30 percent from 2020 to 2030" and "By 2030, Denmark will reduce the amount of incinerated plastic waste by 80 percent". Source: Ministry of Environment of Denmark, 2021, "Action Plan for Circular Economy - National Plan for Prevention and Management of Waste 2020-2032," 2020–32.

[24] Pew Charitable Trusts and SYSTEMIQ, 2020, "Breaking the Plastics Wave"; Ellen MacArthur Foundation, 2017, "The New Plastics Economy - Catalysing Action"; Material Economics, 2018, "The Circular Economy - A Powerful Force for Climate Mitigation"; 2019, "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry."

[25] Current EPR schemes are supply-side policies: they mandate that producers finance collection of plastics and processing at a recycling plant. However, it is often significantly more expensive to produce high-quality plastics than it is to do the bare minimum processing that fulfils statutory definitions of recycling. Stakeholders interviewed highlighted that, in many cases, the incentive created by EPR schemes is therefore for basic recycling processes that result in a significant downgrading of plastic materials, putting on the market recyclates that have materially worse properties than new plastics, and which trade at a significant discount See: Material Economics, 2020, "Preserving Value in EU Industrial Materials - A Value Perspective on the Use of Steel, Plastics and Aluminium.". The low recycling rates achieved to date are closely linked to this. Worse, it is possible that a mandated supply of low-quality materials not only fails to replace new plastics in many applications, but even encourages higher materials use by making low-cost materials available. See: Zink and Geyer, 2017, "Circular Economy Rebound," *Journal of Industrial Ecology*.

[26] European Commission, n.d., "Directive (EU) 2019/ of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment," *Official Journal of the European Union.*

[27] Plastics Europe, 2021, "Press Release - European Plastics Producers Call for a Mandatory EU Recycled Content Target for Plastics Packaging of 30% by 2030."

[28] Material Economics, 2019, "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry"; 2020, "Preserving Value in EU Industrial Materials - A Value Perspective on the Use of Steel, Plastics and Aluminium."

[29] Not all plastics are mechanically recyclable, and for those that are there are limits imposed by co-mingling, accumulation of additives, downgrading, and wear and tear on polymers. A three-fold increase in mechanical recycling would be huge increase, requiring systemic change to product design and throughout the value chain.. See: Material Economics, 2019, "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry."

[30] Material Economics, 2022, "Scaling up Europe - Bringing Low-CO2 Materials from Demo to Industrial Scale (Forthcoming)."

[31] Material Economics, 2022, "Scaling up Europe - Bringing Low-CO2 Materials from Demo to Industrial Scale (Forthcoming)."

[32] Material Economics, 2021, "EU Biomass Use in a Net-Zero Economy – A Course Correction for EU Biomass."

[33] Material Economics, 2020, "Preserving Value in EU Industrial Materials - A Value Perspective on the Use of Steel, Plastics and Aluminium."

[34] Pemal and Confederation of European Waste-to-Energy Plants (CEWEP), 2016, "Waste-to-Energy in Europe in 2016."

[35] See endnote 2 for details on sources used for lifetimes (including both the average lifetime and the lifetime distribution).

[36] Eriksen et al., 2020, "Dynamic Material Flow Analysis of PET, PE, and PP Flows in Europe: Evaluation of the Potential for Circular Economy," E*nvironmental Science & Technology*; Ciacci, Passarini, and Vassura, 2017, "The European PVC Cycle: In-Use Stock and Flows," *Resources, Conservation and Recycling*;

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EUROPE'S MISSING PLASTICS

Taking Stock of EU Plastics Circularity

Disclaimer: The analysis and conclusions of this report are those of Material Economics. Material Economics is solely responsible for the contents of this report and the views are those of the authors.

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