Plastics: production and recycling

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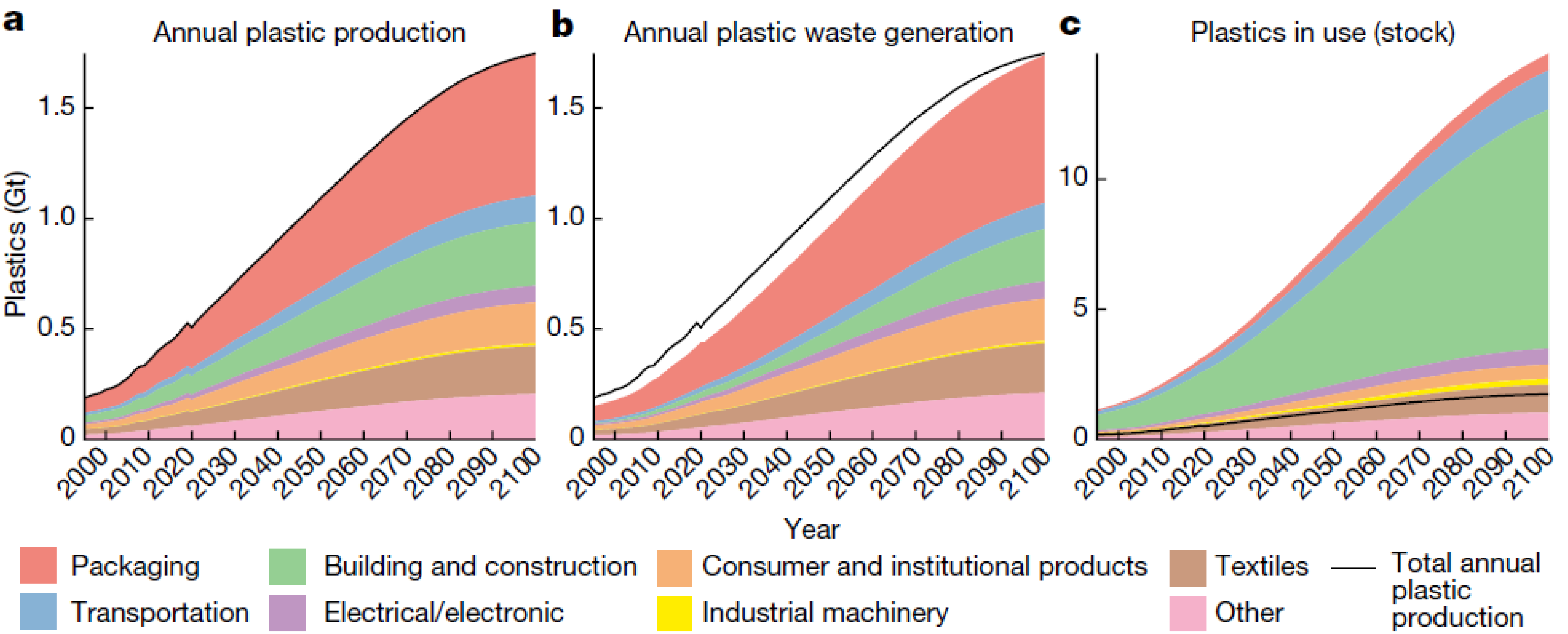
Context

Projections of global plastic production, waste generation and plastic stocks in use, by sector

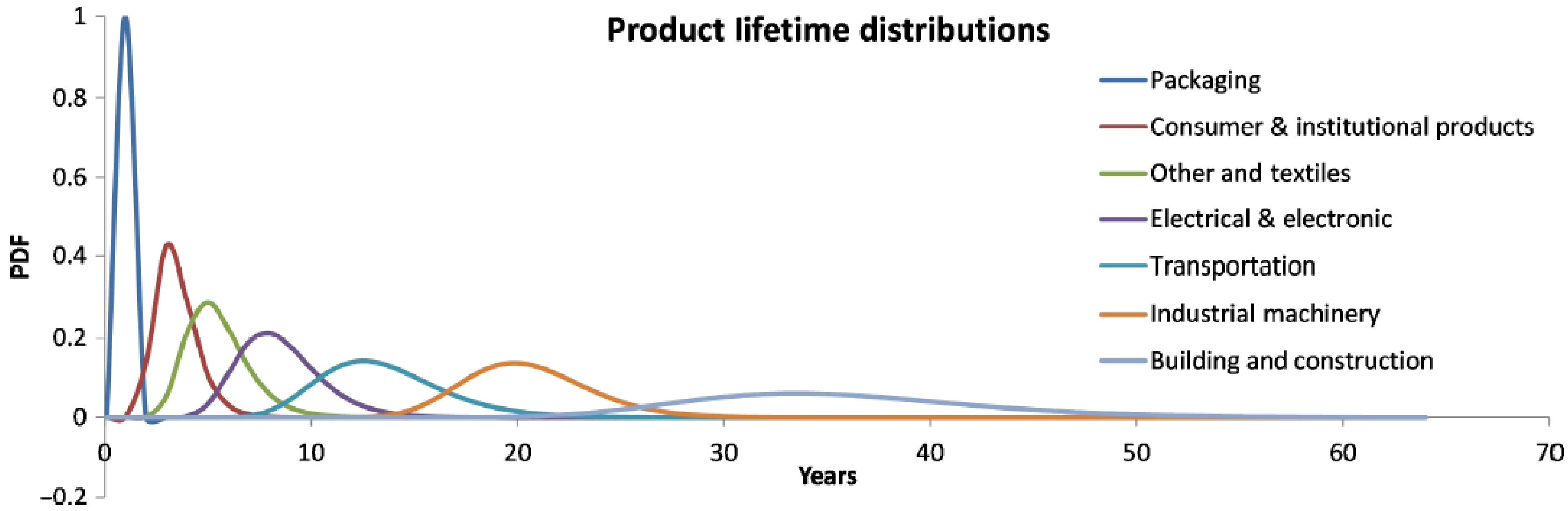


The growth in plastic demand shown in the figure implies a further increase in the GHG emissions of plastic production if there are no substantial changes in feedstock and process energy use.

Source: Stegmann *et al.*, "Plastic futures and their CO_2 emissions". Nature, Vol 612 (2022).

Context

Product lifetime distributions



Source: "Production, use, and fate of all plastics ever made", Geyer, Jambeck, Law, Sci. Adv. 2017;3: e1700782

Context

Plastic waste generated since 1950

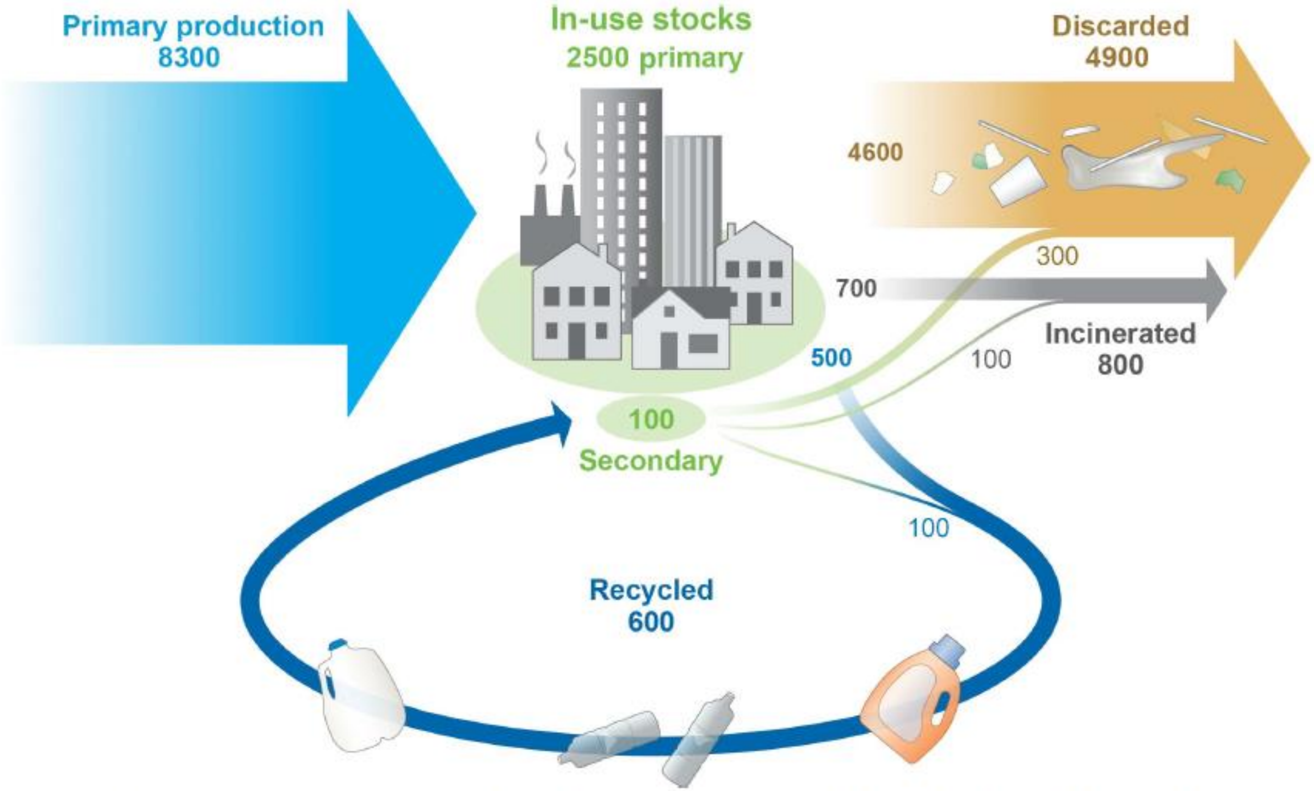


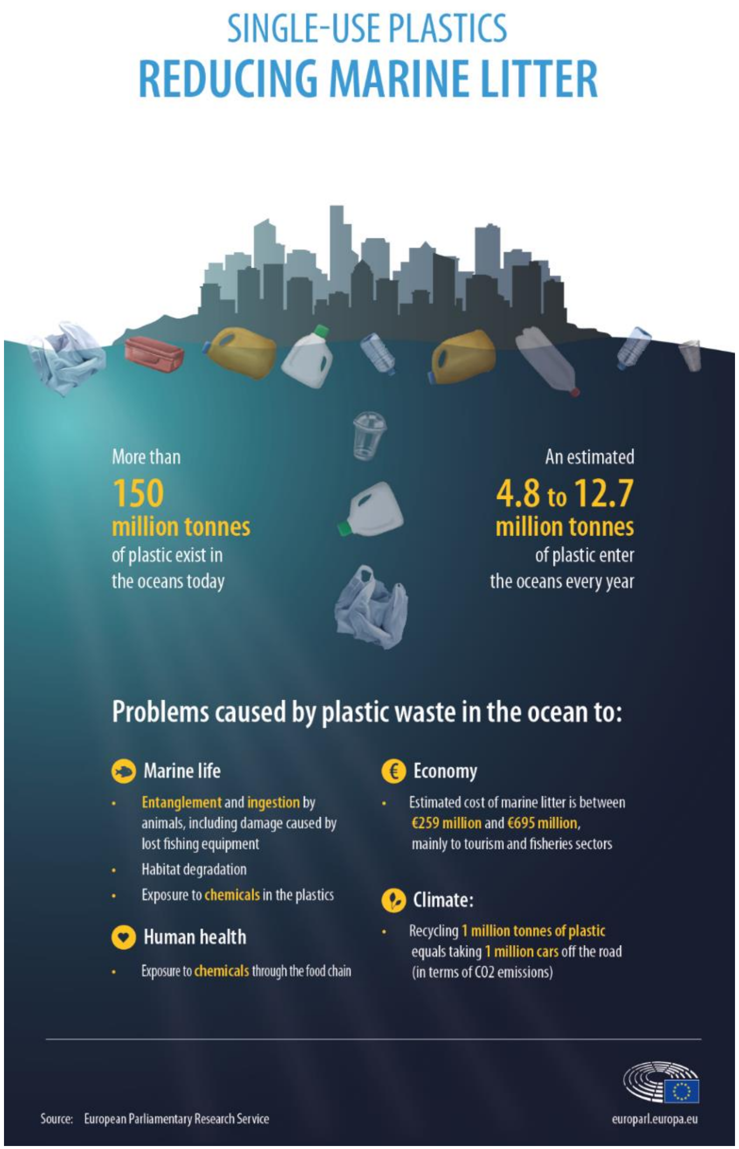
Fig. 2. Global production, use, and fate of polymer resins, synthetic fibers, and additives (1950 to 2015; in million metric tons).

“As of 2015: 6300 Mt of plastic waste had been generated.”

Source: “Production, use, and fate of all plastics ever made”, Geyer, Jambeck, Law, Sci. Adv. 2017;3: e1700782

Environmental impact of plastic

Source: "Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics", United Nations Environment Programme (2021).



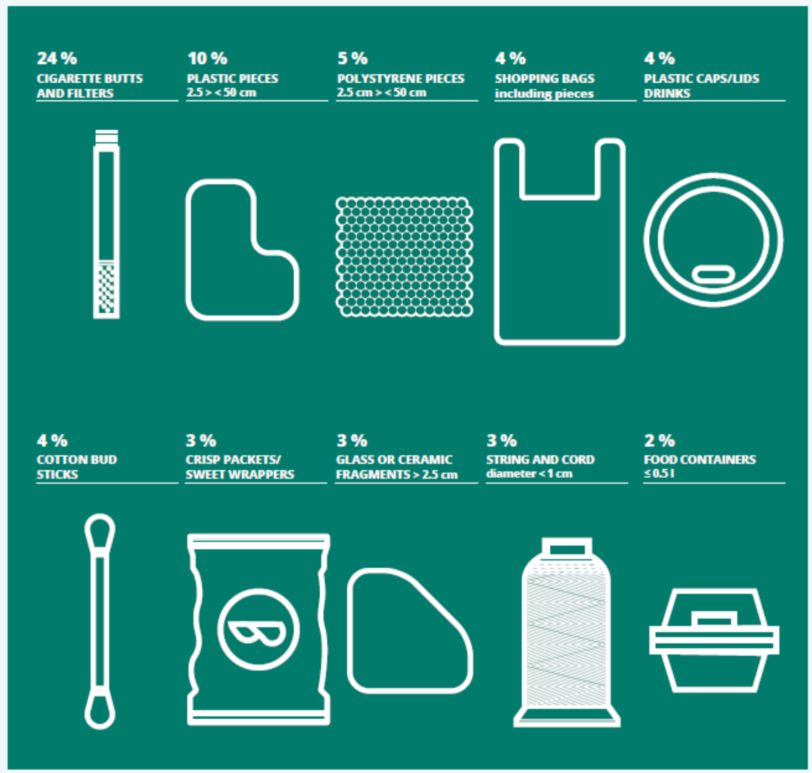
Source:https://www.europarl.europa.eu/news/en/headlines/society/20181005STO15110/plastic-in-the-ocean-the-facts-effects-and-new-eu-rules

Context

Environmental impact of plastic

"Marine Litter Watch is an ongoing EEA initiative launched in 2014 to better understand the composition, movement and origin of beach litter and to combat plastic litter. (...) The top 10 litter items reported to Marine Litter Watch between January 2014 and October 2020 are displayed in Figure 15 below. The percentages are calculated based on the total number of items collected. Together, these items represent 60 % of the litter reported (EEA, 2020c)."

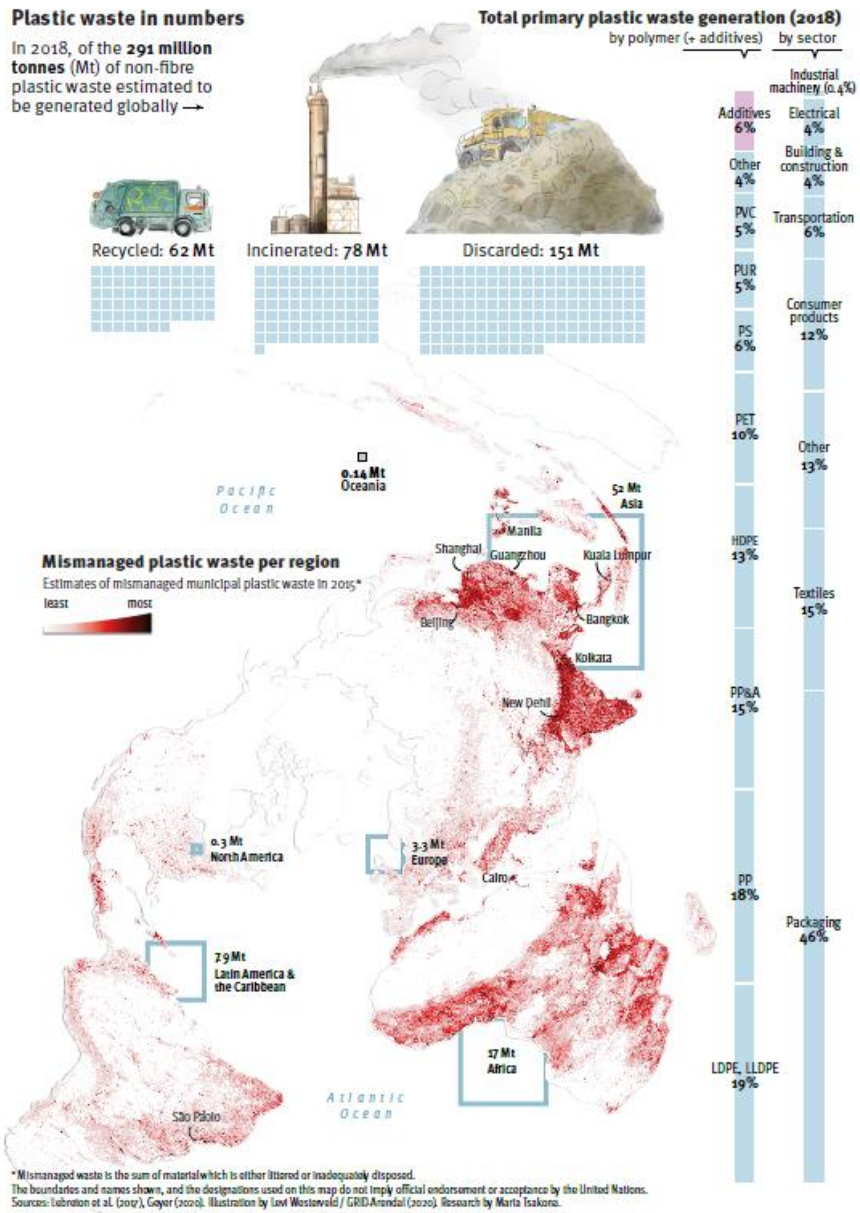
Figure 15. Top 10 items reported to Marine Litter Watch (January 2014 and October 2020)



Source: EEA (2020c).

Source: "Plastics, the circular economy and Europe's environment — A priority for action", European Environmental Agency (2021)

Environmental impact of plastic



Source: "Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics", United Nations Environment Programme (2021).

Environmental impact of plastic

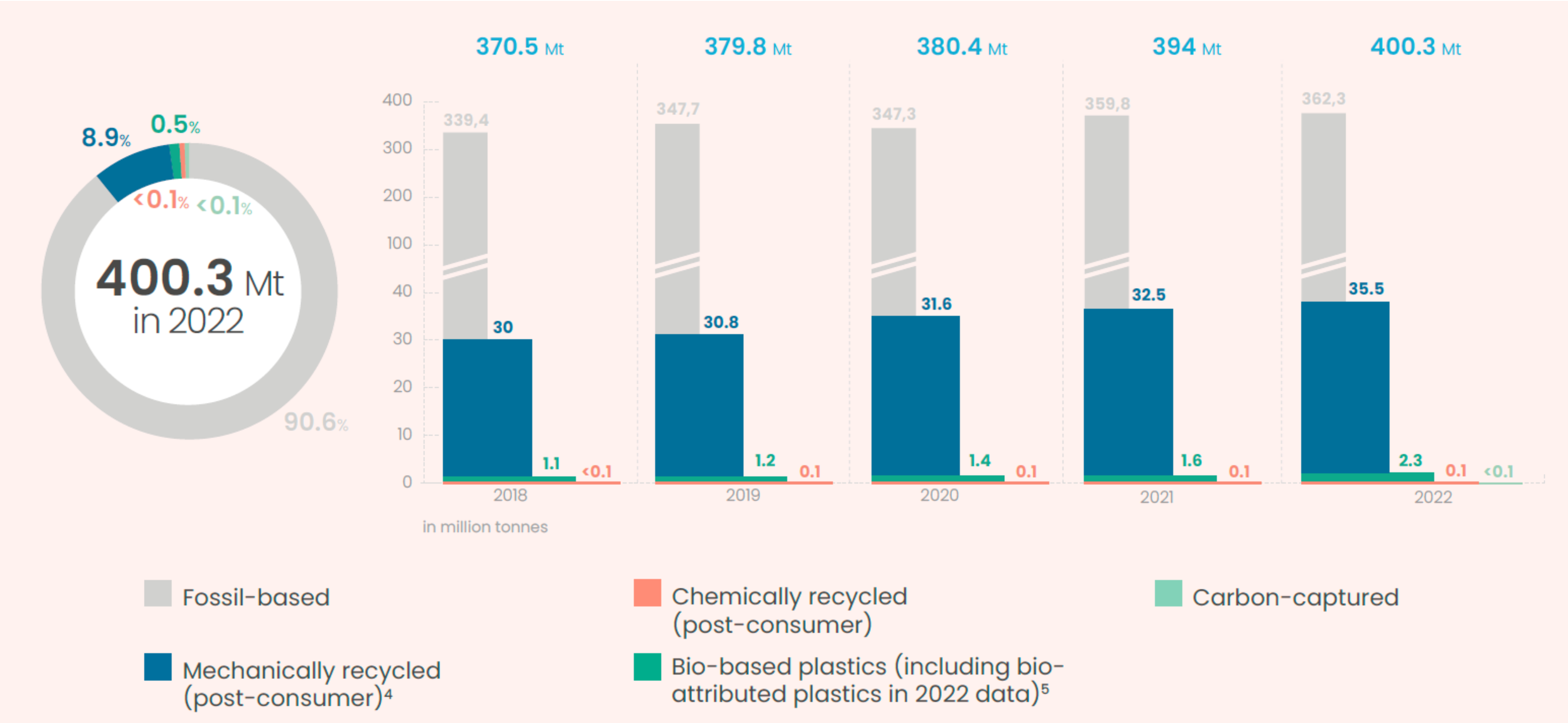
"We will not recycle our way out of the plastic pollution crisis: we need a systemic transformation to achieve the transition to a circular economy"

Inger Andersen

Under-Secretary-General of the United Nations and Executive Director of the UN Environment Programme

Source: https://www.unep.org/plastic-pollution

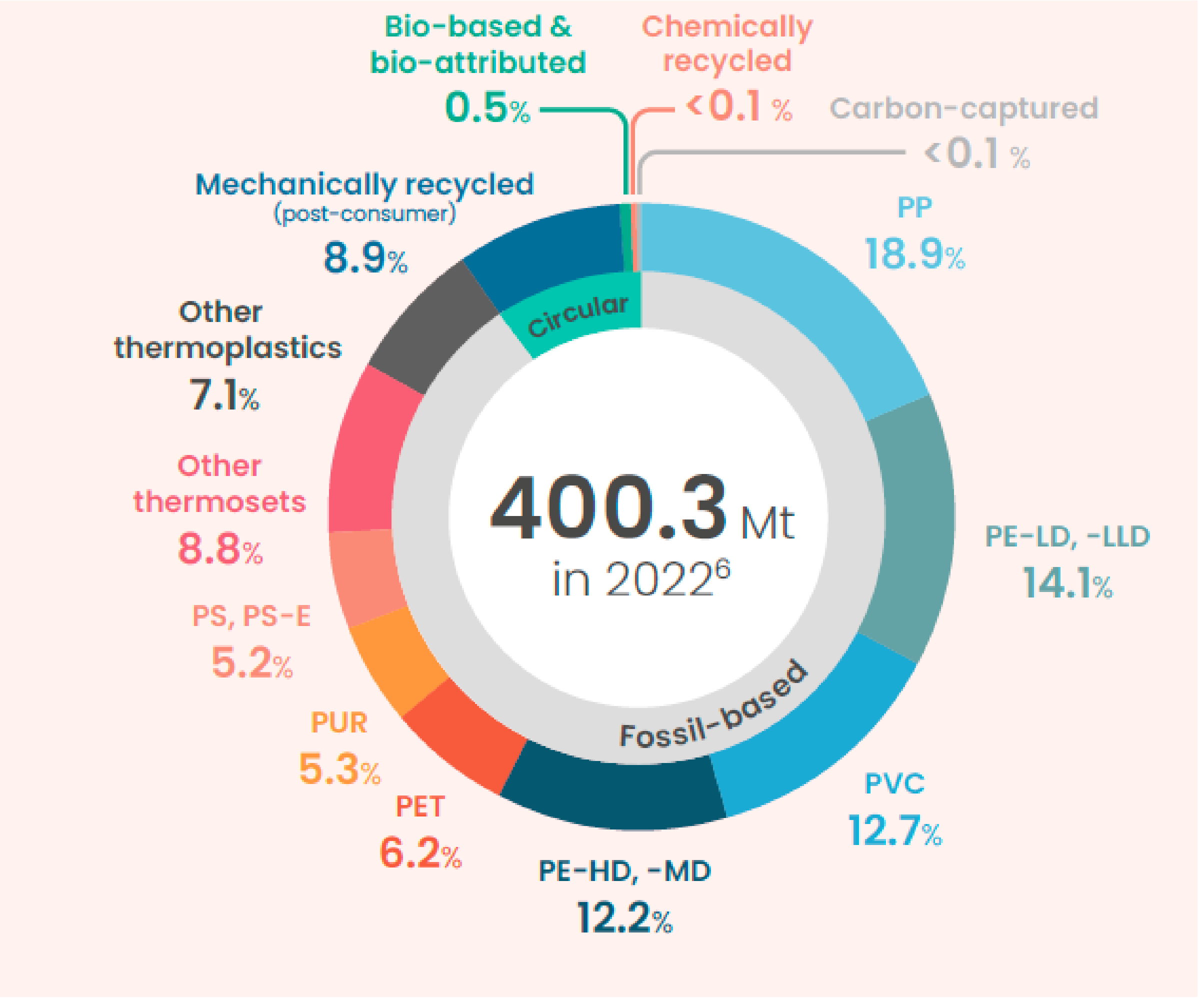
World plastics production (2022)



Source: “Plastics- the Facts 2023”, Report from the PlasticsEurope.

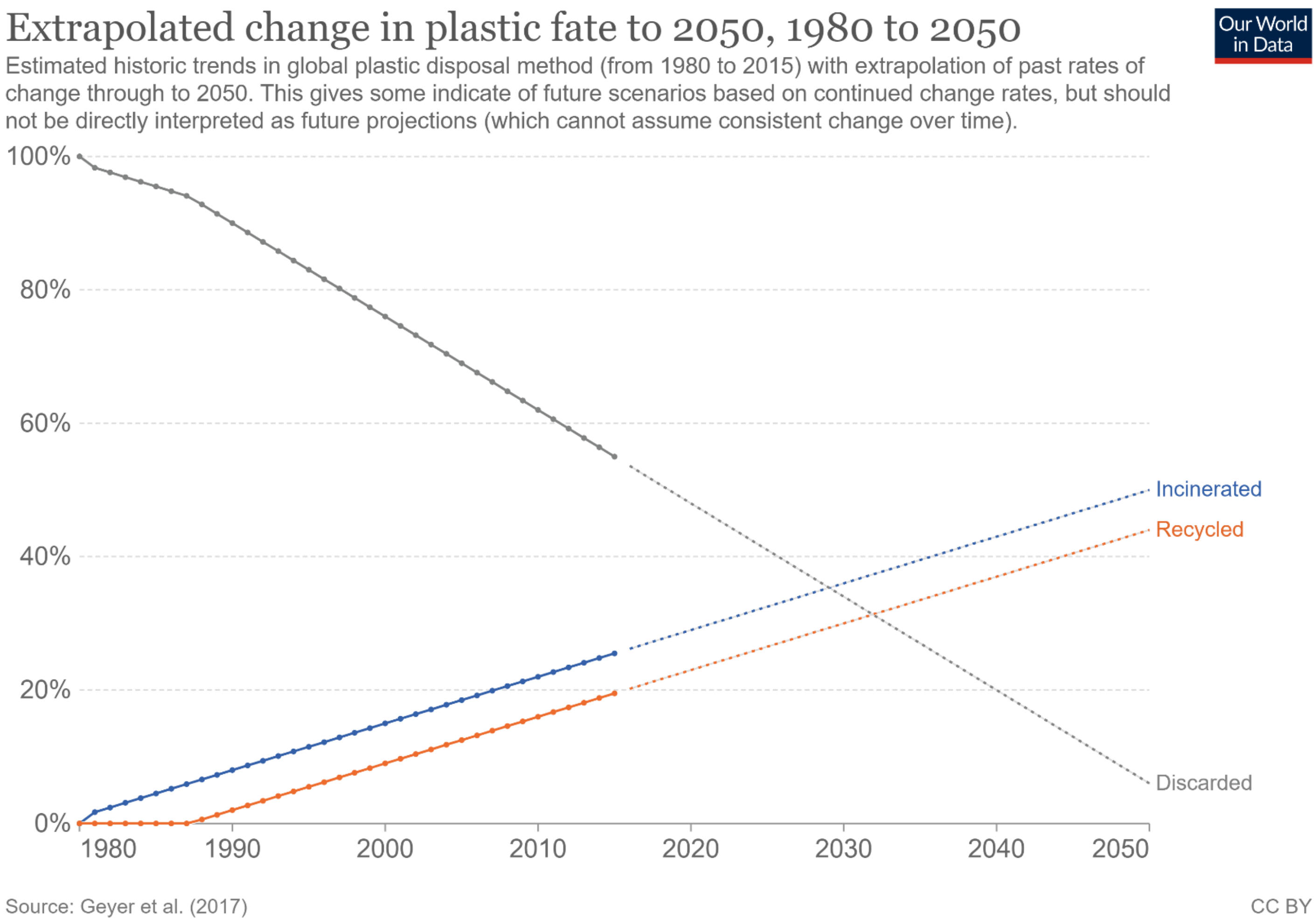
Context

Global plastics production by polymer (2022)



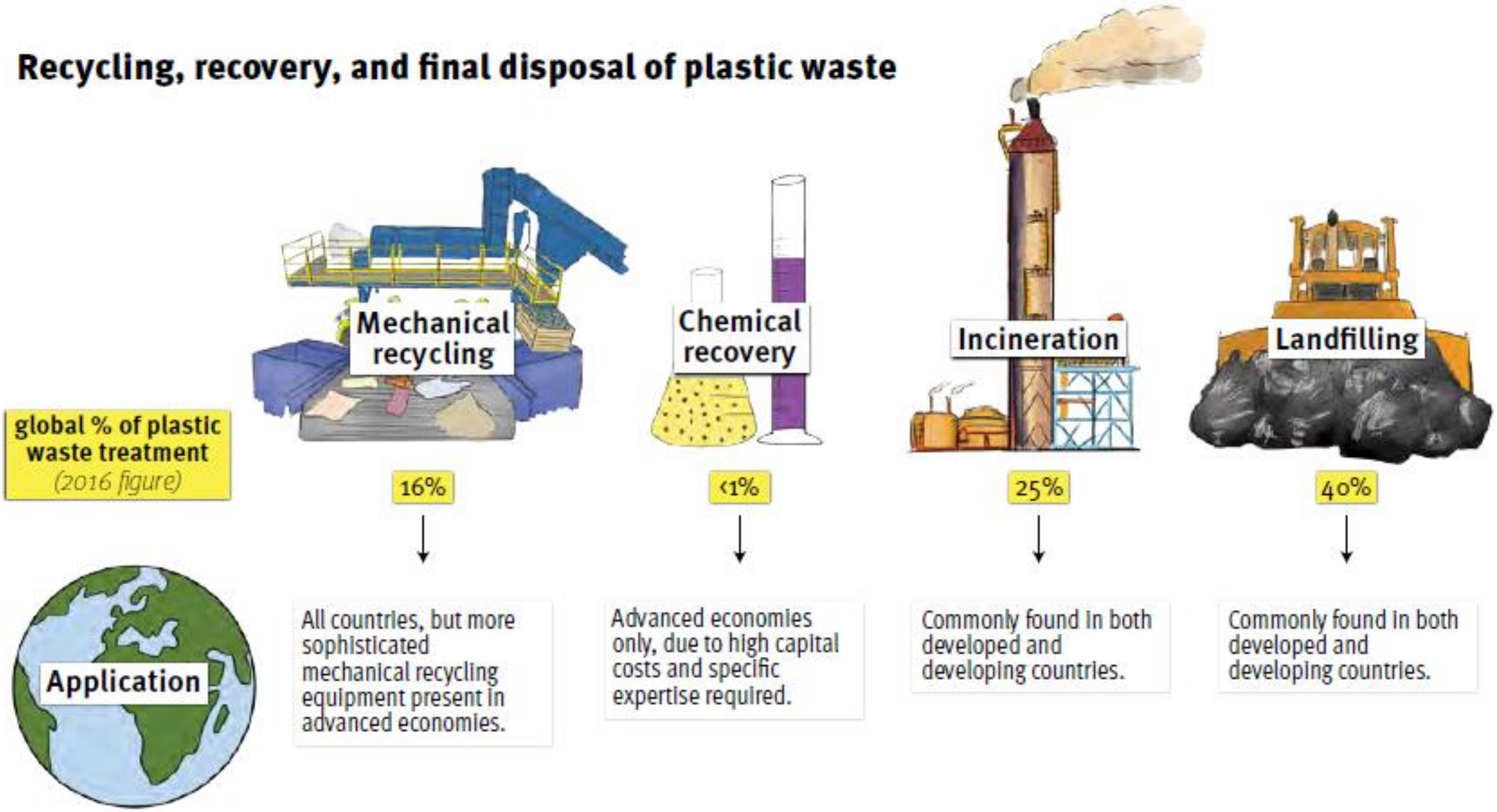
Source: "Plastics- the Facts 2023", Report from the PlasticsEurope.

Global plastic waste management rates



Source: https://ourworldindata.org/plastic-pollution

Global plastic waste management rates in 2016



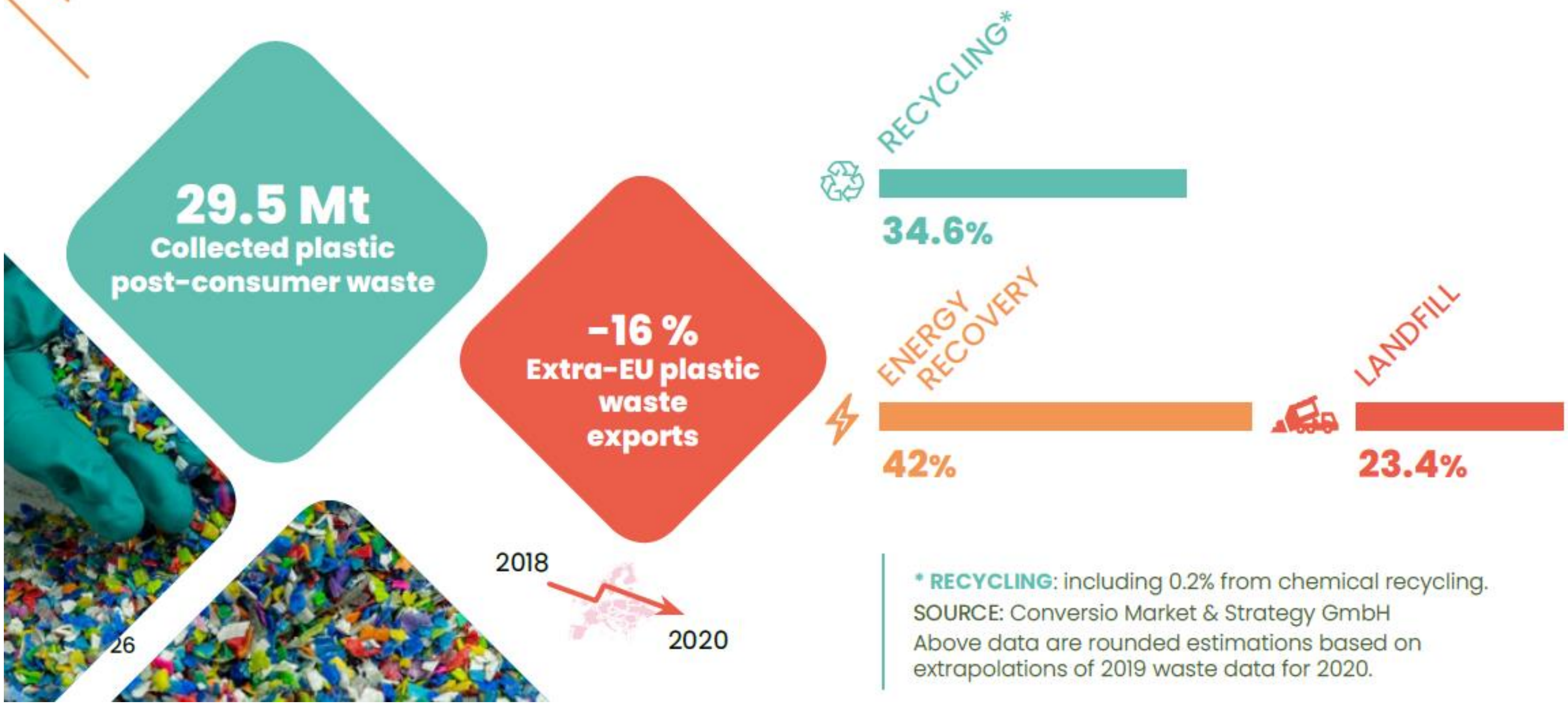
Source: “Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics”, United Nations Environment Programme (2021).

Context

Post-consumer plastic waste treatment in 2020 (EU context)

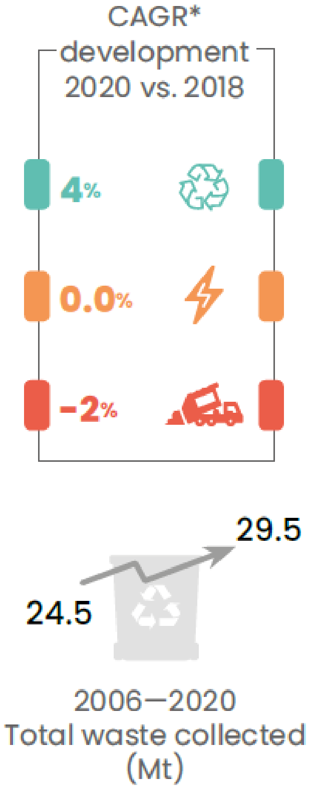
In 2020, more than 29 million tonnes of plastic post-consumer waste were collected in the EU27+3. Because plastics products have different life span (ranginging from 1 to 50 years or more), of post-consumer plastic waste collection figures do not match demand or consumption figures.

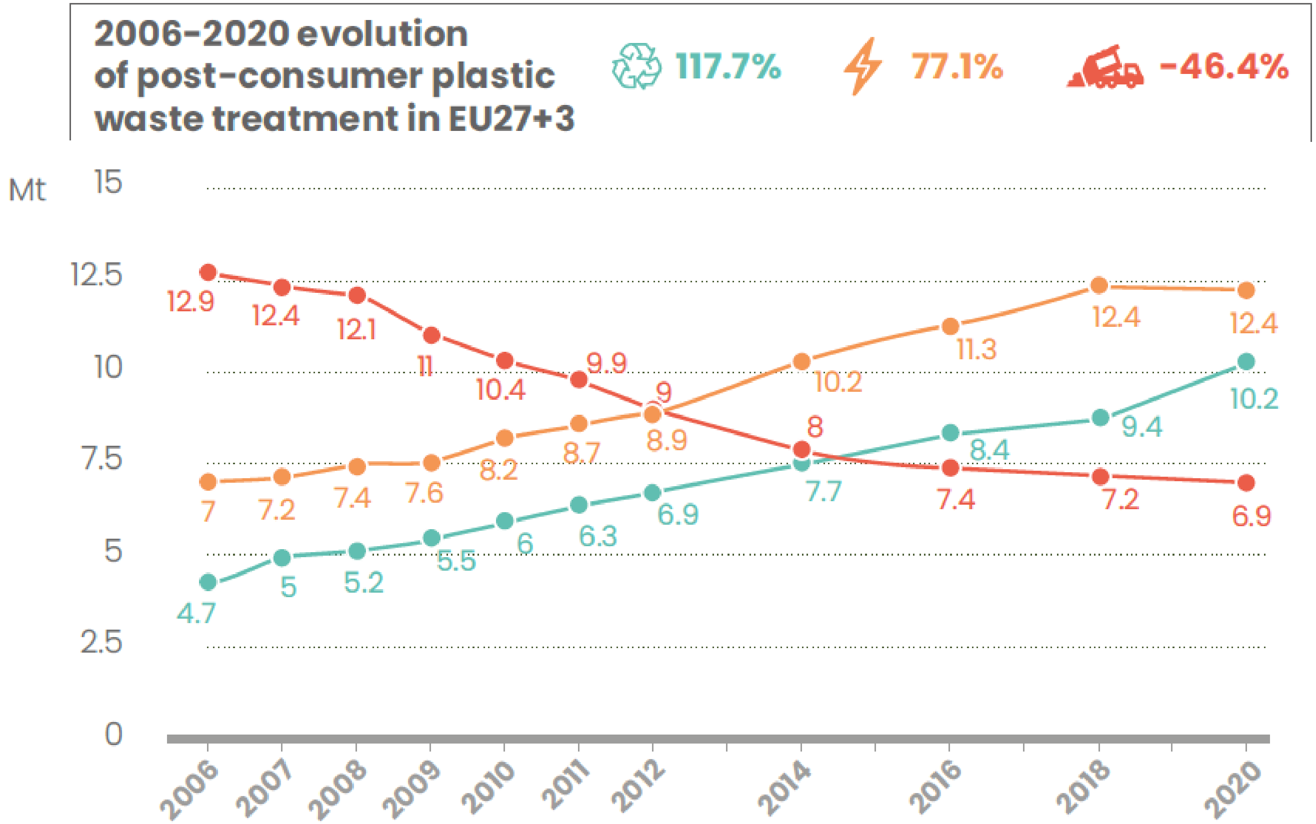
More than **one third was sent to recycling facilities inside and outside the EU27+3** but over 23% was still sent to landfill and more than 40% was sent to energy recovery operations.



Source: “Plastics- the Facts 2021”, Report from the PlasticsEurope.

Post-consumer plastic waste treatment between 2006-2020 (EU context)





Source: "Plastics- the Facts 2021", Report from the PlasticsEurope.

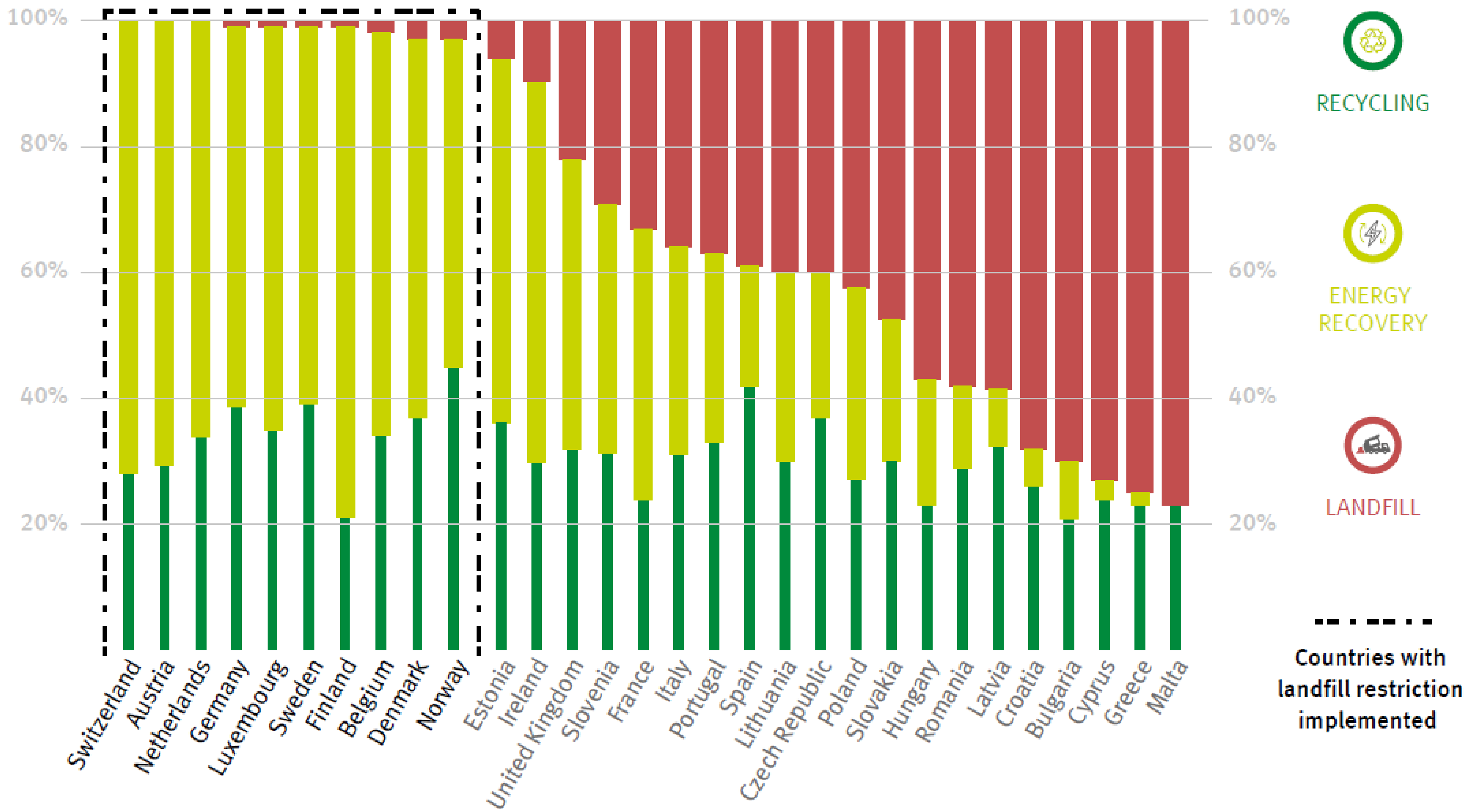
Plastic recycling?!

Miquel Roset, Director and Spokesperson at Retorna, states:
“The case of Spain, the home country of Vice-President designate Teresa Ribeira, is emblematic of the problem with falsified reporting on recycling results in Europe. Four months ago, we presented a report, together with Zero Waste Europe and Eunomia, to inform the Spanish government that the real figure for separated collection of plastic beverage bottles under three litters was 36%, almost half of the 71% claimed by the PRO Ecoembes. By the end of October, Spain must report whether this figure has reached 70% and, if that is not the case, the Spanish Waste Law dictates the implementation of a deposit and return system.”

Source: https://zerowasteeurope.eu/press-release/retorna-stop-fake-reporting-zero-waste-europe/

The "circular economy" of plastics (EU context)

Plastic post-consumer waste rates (in 2018 per country)



ZERO LANDFILLING IS NEEDED TO ACHIEVE THE CIRCULAR ECONOMY OF PLASTICS!

Source: "Plastics- the Facts 2020", Report from the PlasticsEurope.

Context

Directive (EU) 2018/852

14.6.2018 EN Official Journal of the European Union L 150/141

DIRECTIVE (EU) 2018/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 30 May 2018

amending Directive 94/62/EC on packaging and packaging waste

(Text with EEA relevance)

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

(g) no later than 31 December 2025
regarding the following specific mat

(i) 50 % of plastic;

(ii) 25 % of wood;

(iii) 70 % of ferrous metals;

(iv) 50 % of aluminium;

(v) 70 % of glass;

(vi) 75 % of paper and cardboard;

(i) no later than 31 December 2030
regarding the following specific ma

(i) 55 % of plastic;

(ii) 30 % of wood;

(iii) 80 % of ferrous metals;

(iv) 60 % of aluminium;

(v) 75 % of glass;

(vi) 85 % of paper and cardboard.';

Plastics recycling rates

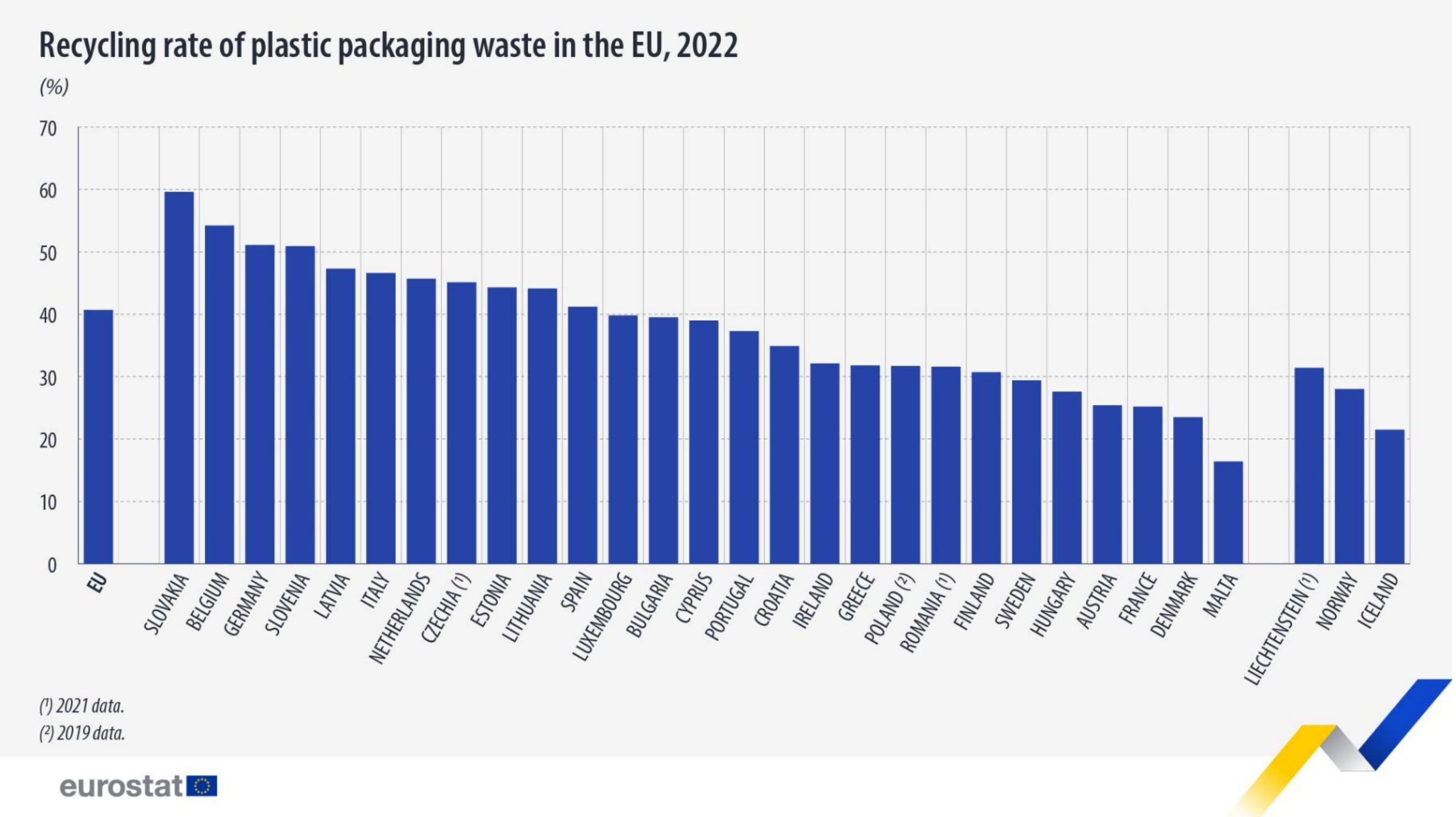
(packaging waste):

- 50% (2025)
- 55% (2030)

Source: "Plastics- the Facts 2020", Report from the PlasticsEurope.

Context

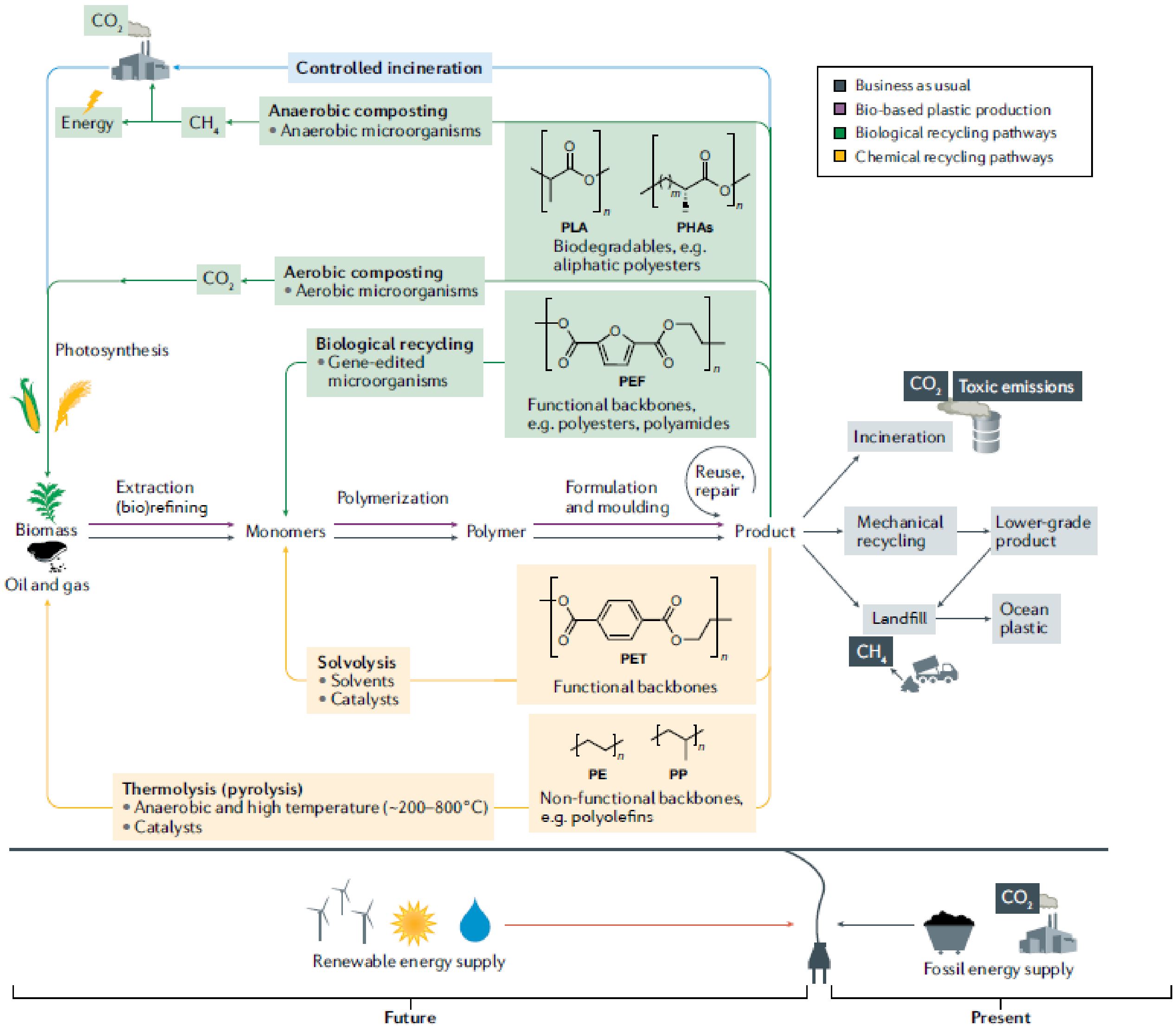
Recycling rate of plastic packaging waste in 2022 (EU context)



In 2022, the EU recycled 41% of all the generated plastic packaging waste, indicating a slight increase compared with 2012 when the rate stood at 38%

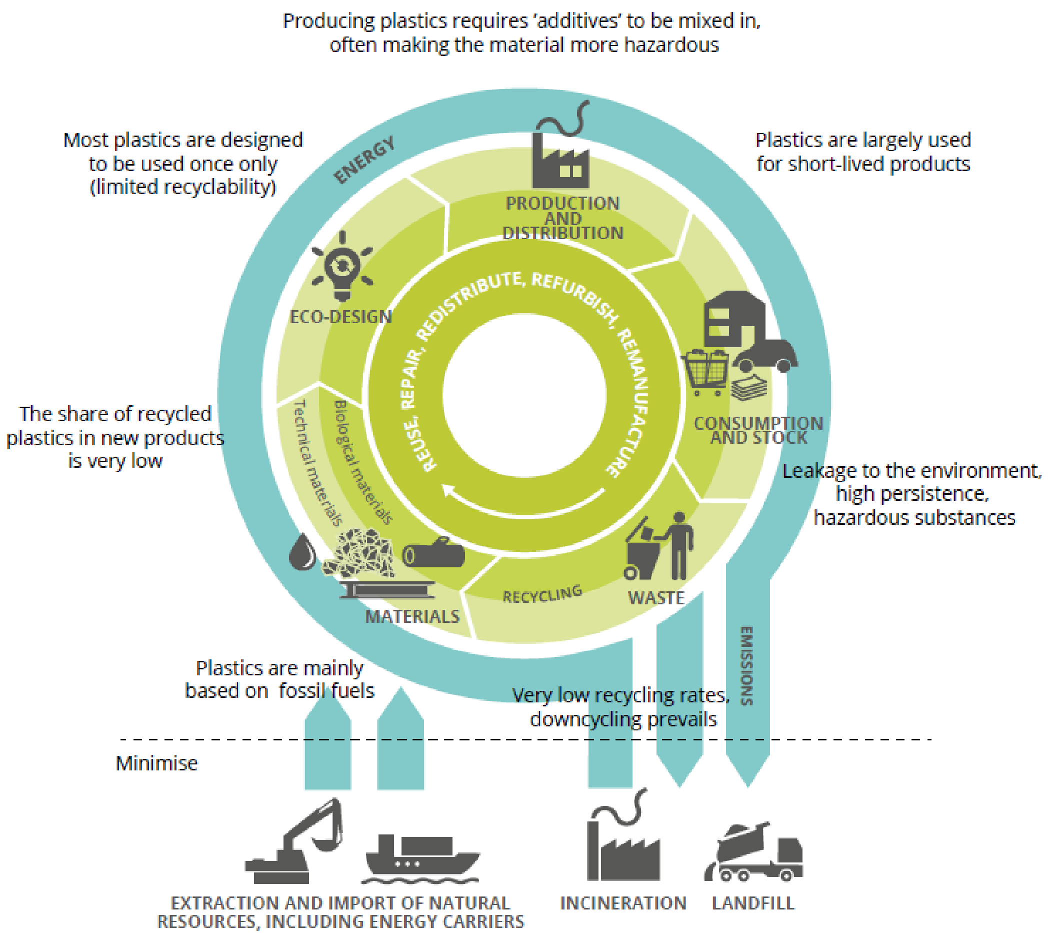
Source: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20241024-3

What is the scenario when considering plastics?



Source: "Bioplastics for a circular economy", Rosenboom, Langer, & Traverso. Nat Rev Mater 7, 117–137 (2022).

Circular economy of plastics: challenges



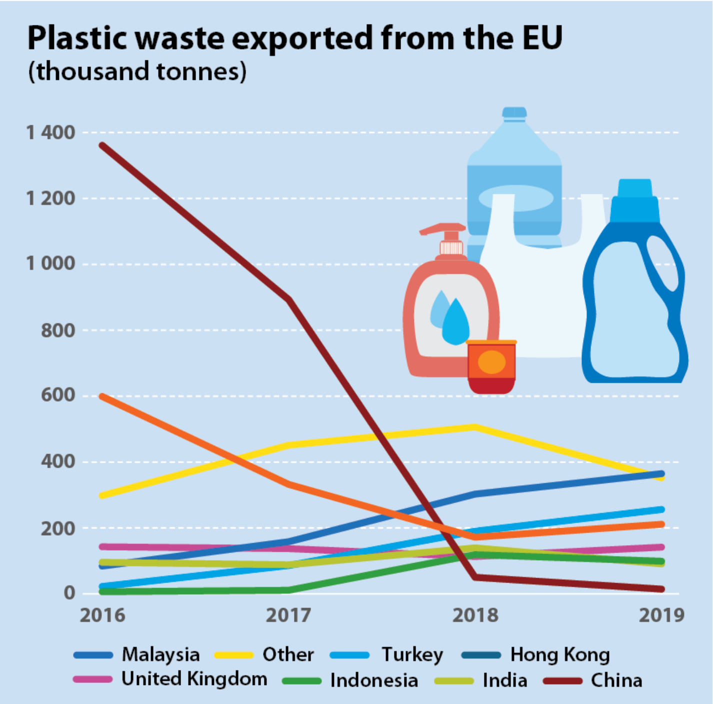
Source: "Plastics, the circular economy and Europe's environment — A priority for action", European Environmental Agency (2021)

Plastics: measures towards future circular economy

1. Ban exports of plastic waste to third countries

Rather than shipping huge amounts of plastic waste to third countries that often do not have the necessary capacity to deal with it in a sustainable way, Europe should manage its own plastic waste. This is better from both an environmental and an ethical perspective, even if part of the waste has to be recovered for energy.

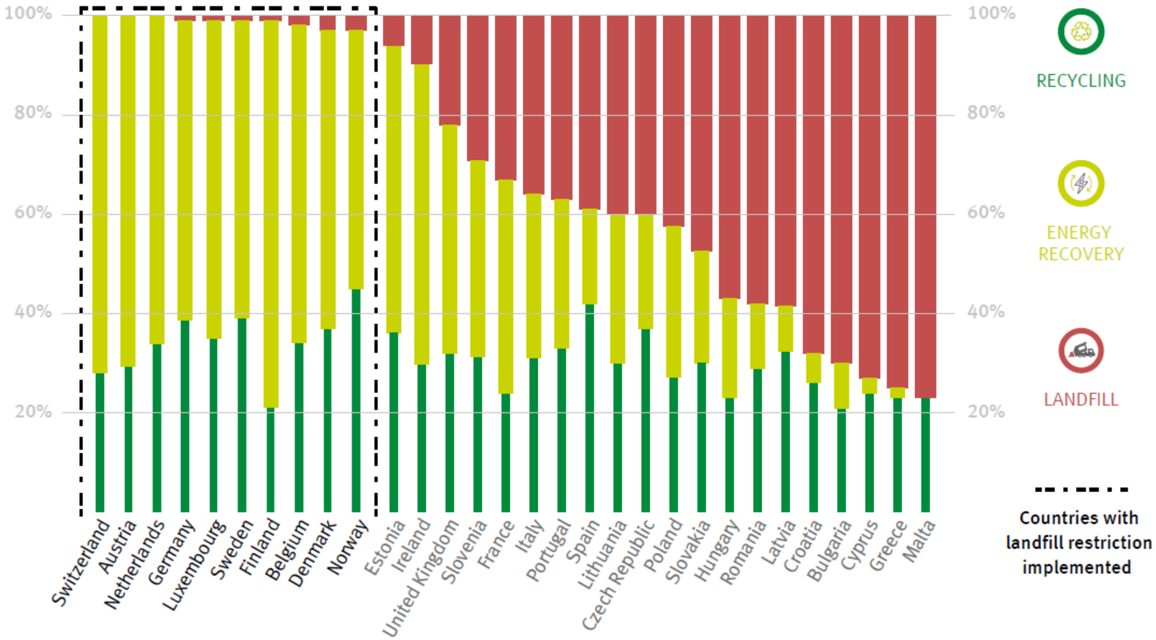
Source: "Plastics, the circular economy and Europe's environment — A priority for action", European Environmental Agency (2021)



Source:
https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200709-01

Plastics: useful measures towards future circular economy

2. Adopt a target of zero plastic waste to landfill, and minimise consumption and one-way use



Source: "Plastics- the Facts 2020", Report from the PlasticsEurope.

In addition to adopting a target of zero plastic waste to landfill and making reduction in consumption an explicit objective, policymakers should extend deposit refund schemes to cover a wider range of containers and single-use beverages.

Source: "Plastics, the circular economy and Europe's environment — A priority for action", European Environmental Agency (2021)

Plastics: useful measures towards future circular economy

3. Extend producer responsibility (EPR)

Ambitious EPR schemes should include measures that facilitate product design choices that consider end-of-life use and environmental impacts, such as toxicity, durability, reusability, repairability and recyclability/compostability.

Deposit-refund systems and EPR schemes can increase return and collection rates for post-consumer plastics and increase the quality of the plastic collected.

Source: "Bioplastics for a circular economy", Rosenboom, Langer, & Traverso. Nat Rev Mater 7, 117–137 (2022).

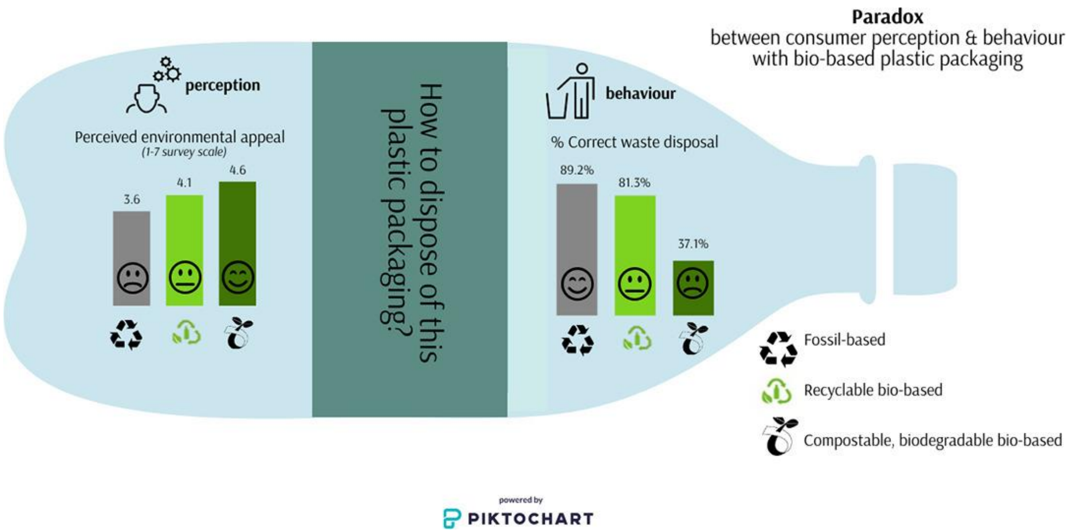
Source: "Plastics, the circular economy and Europe's environment — A priority for action", European Environmental Agency (2021)

Plastics: useful measures towards future circular economy

4. End misleading information about bio-based alternatives

“consumers may be misled by the diversity of existing labelling schemes and are often not aware of the environmental impacts associated with bio-based alternatives. A uniform European labelling scheme that relates to the actual rather than theoretical recyclability of bio-based plastics should therefore be created.”

Source: “Plastics, the circular economy and Europe’s environment — A priority for action”, European Environmental Agency (2021)



Source: “The paradox between the environmental appeal of bio-based plastic packaging for consumers and their disposal behaviour”, Taufik *et al., Science of the Total Environment* 705 (2020) 135820.

Plastics: useful measures towards future circular economy

5. Advanced recycling and reprocessing technology

To extract more value from plastic waste, advanced recycling and reprocessing technology must be developed. In addition, recycling for use in the same product (closed-loop recycling) must be prioritised over other options, such as recycling for use in the production of different products (open-loop recycling) or energy recovery.

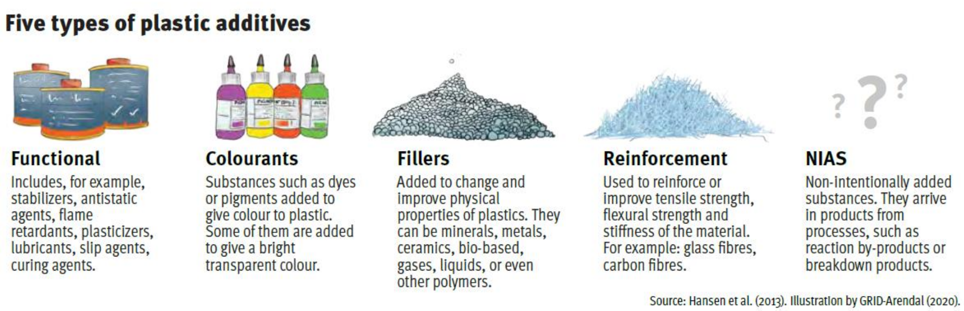
Source: “Plastics, the circular economy and Europe’s environment — A priority for action”, European Environmental Agency (2021)

Plastics: useful measures towards future circular economy

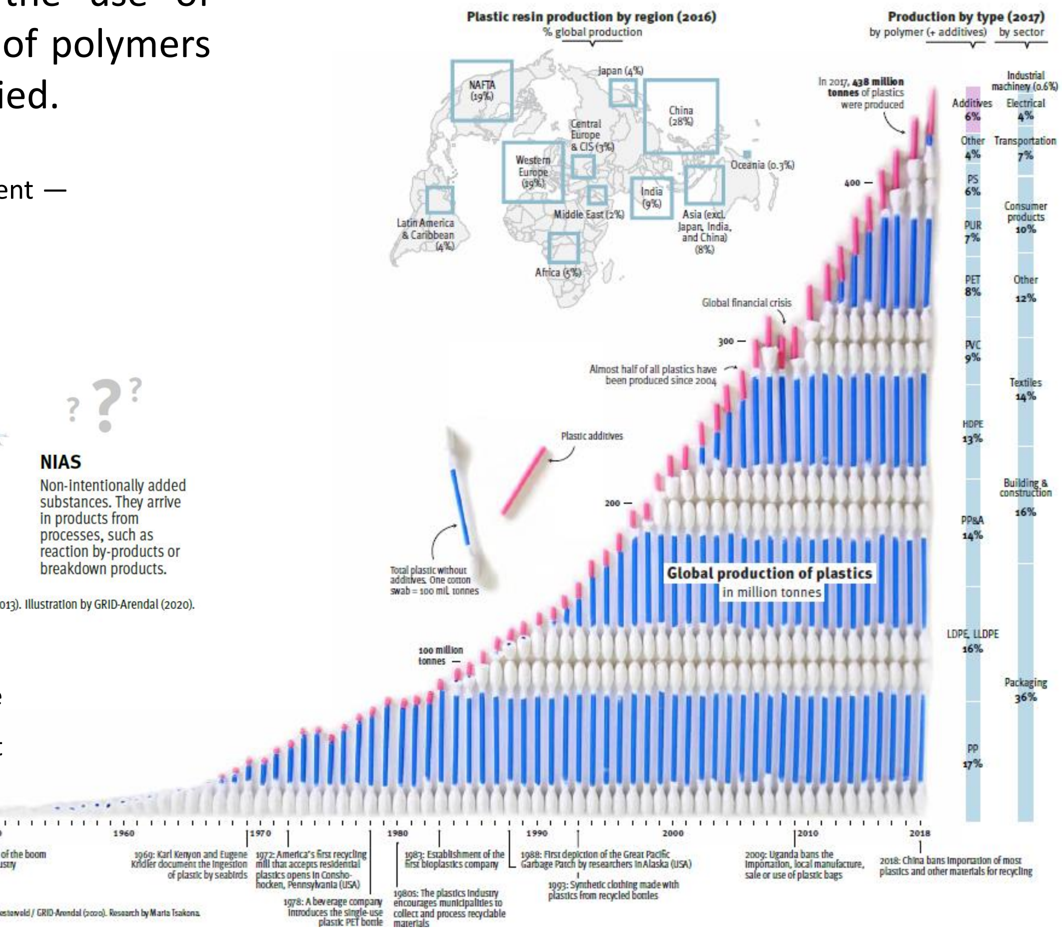
6. Limit additives and types of resin to improve recyclability

To increase the recyclability of plastics, the use of additives must be reduced and the number of polymers that can be used for specific products simplified.

Source: “Plastics, the circular economy and Europe’s environment — A priority for action”, European Environmental Agency (2021)



Images taken and adapted from: “Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics”, United Nations Environment Programme (2021).

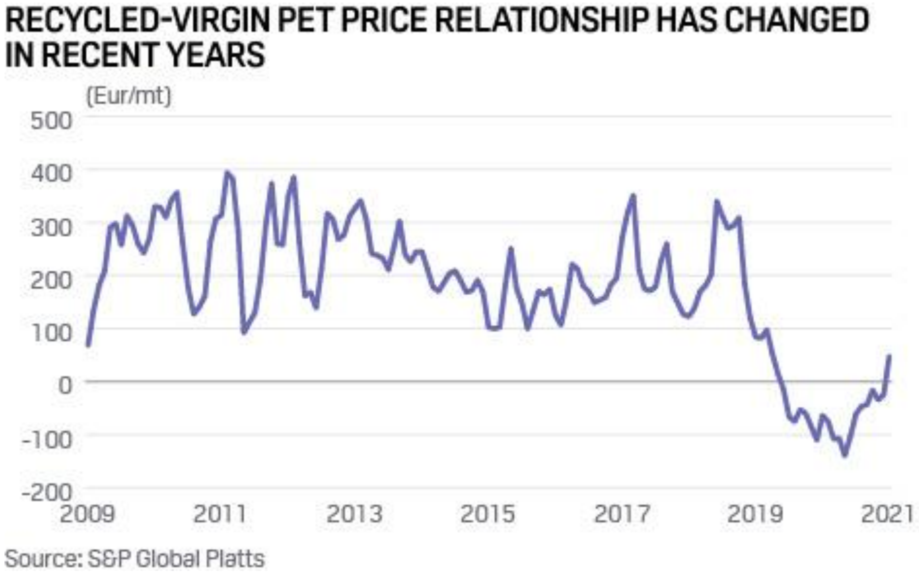


Plastics: useful measures towards future circular economy

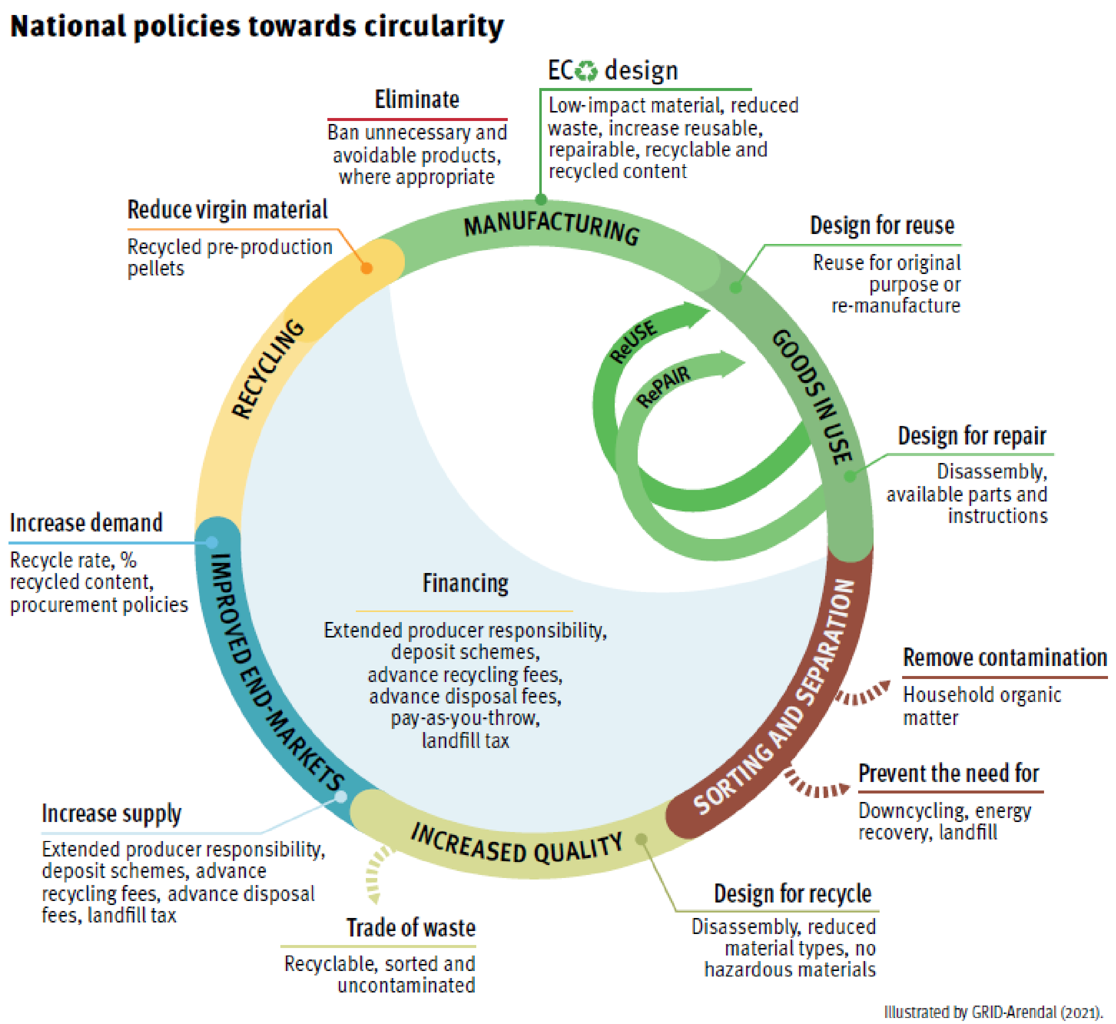
7. Price regulations and quotas for recycled content

The current cost of virgin plastic feedstock is very low and does not include costs to the environment and climate. Policymakers should therefore adopt a regulatory and financial framework, including, for instance, a plastics tax or a requirement for minimum recycled contents, that takes into account adverse impacts across the plastic product life cycle.

Source: "Plastics, the circular economy and Europe's environment — A priority for action", European Environmental Agency (2021)

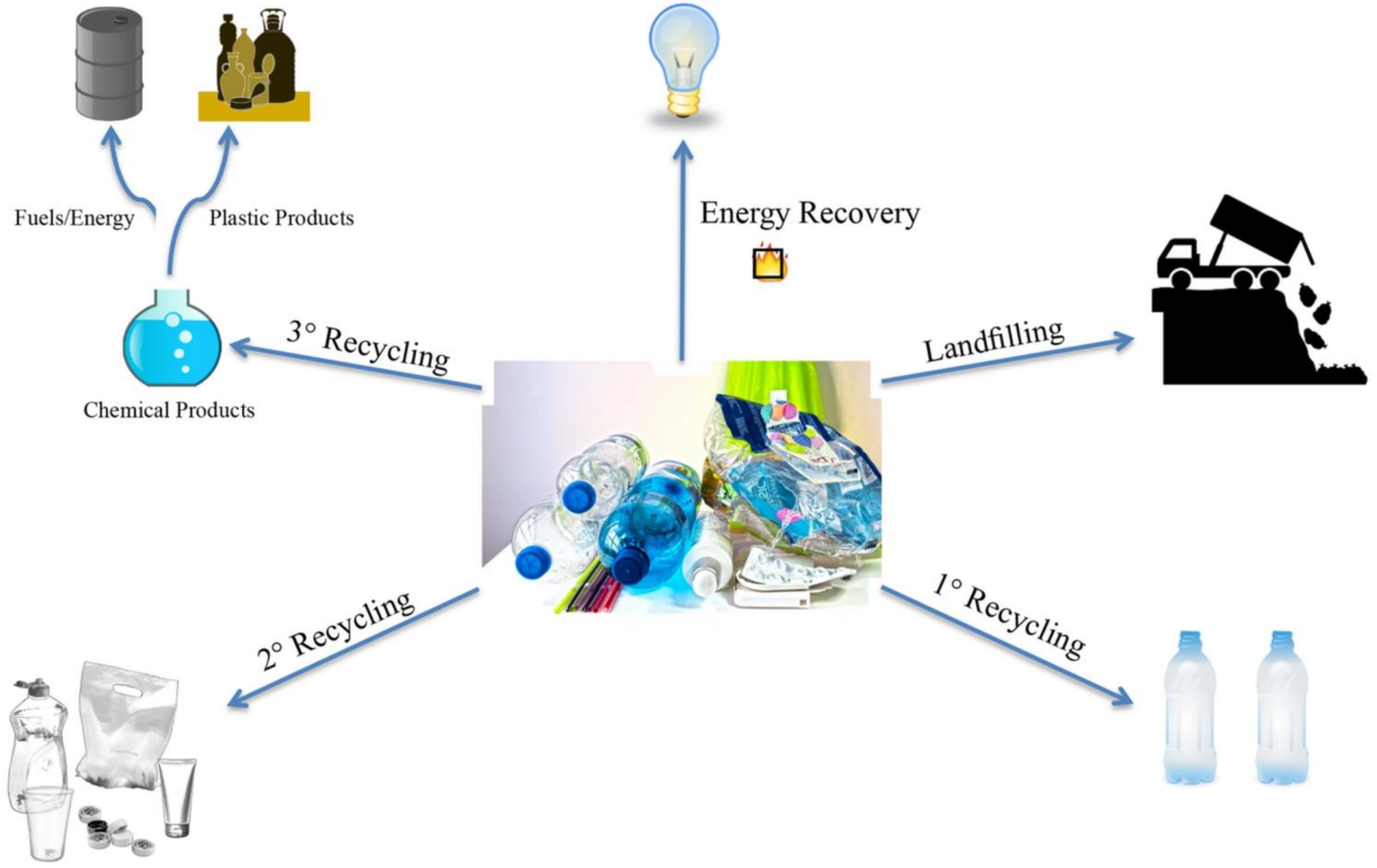


Circular economy of plastics

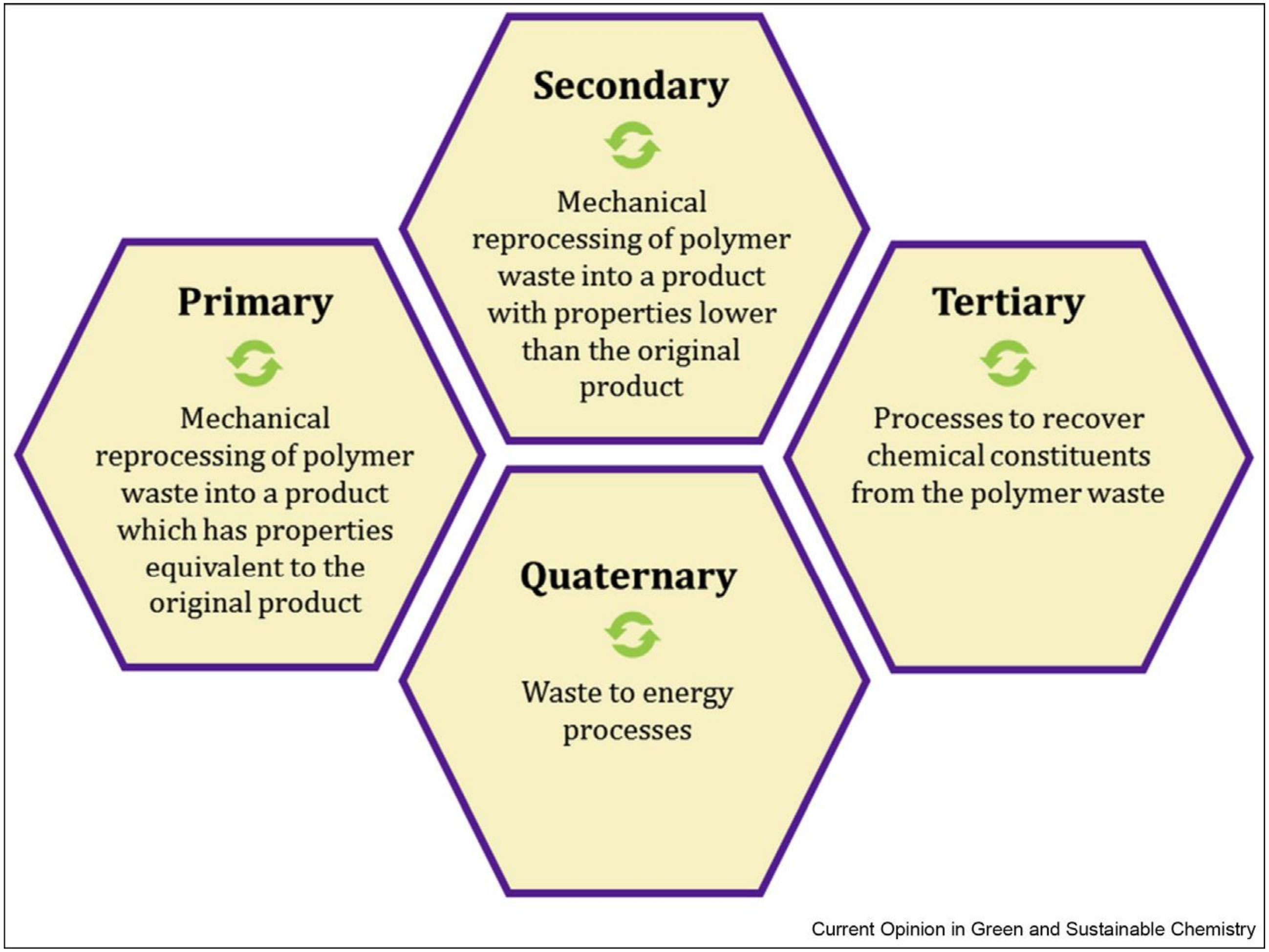


Source: "Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics", United Nations Environment Programme (2021).

Common fates for current plastic waste



Recycling options

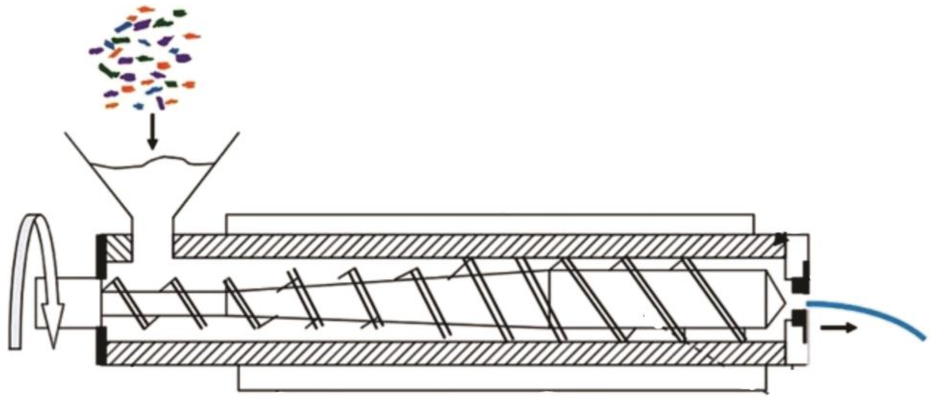


Primary Recycling

The first opportunity to practice recycling is at the processing facility, where no separation of the material is required: **considered a form of mechanical recycling.**

All major operations such extrusion, injection molding, calendaring, thermoforming, produces scraps.

Scraps can originate from rejected parts, sprues and runners generated during injection molding. In some cases, the scrap can represent 50% of the processed material (e.g.; thermoforming parts).
This scrap (or regrind) can be ground and combined with virgin resin to not only improve the economics of the process but prevent disposing of the material in landfills.



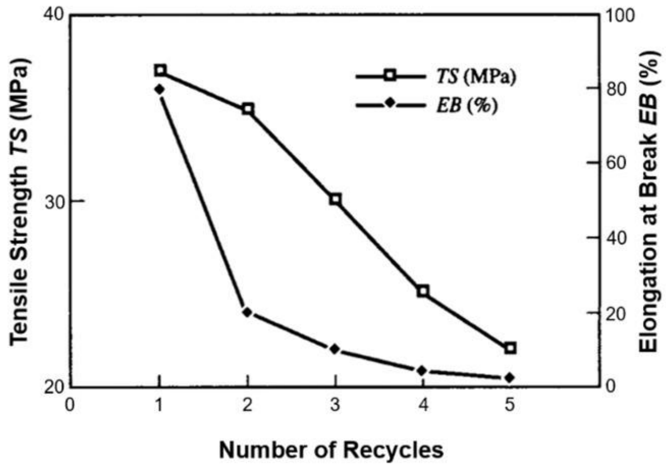
One cannot repeatedly process the polymer without consequences. It leads to degradation of the polymer (M_w), resulting in loss of mechanical properties, surface appearance and processability.

Primary Recycling

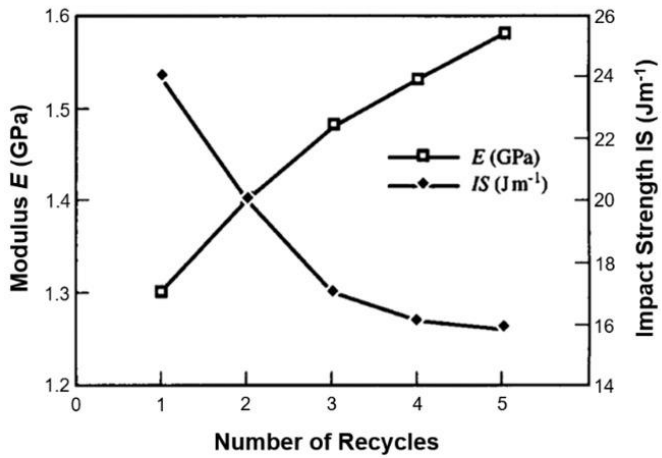
How much regrind can we use relative to virgin resin without losing performance?

One way is to study the effect of the number of regrinding and the number of recycling steps → **time consuming**

To expedite the process one can, estimate the number of regrind and resulting properties after n recycling steps. For that we need information about the original material left in the sample after n recycles steps, the decrease in the mechanical properties with each pass and the relationship between the properties and M_w, and a mixing rule for weighting the contributions from each fraction to the final mechanical properties.



Tensile strength and elongation at break versus number of recycles for PET



E and impact strength versus number of recycles for PET.

Mechanical or secondary recycling

Secondary recycling refers to the use of plastics unsuitable for primary recycling using standard plastics processing equipment.

Sources of plastic wastes potentially suitable for secondary recycling processes include:

I. post-consumer waste recovered from municipal refuse,

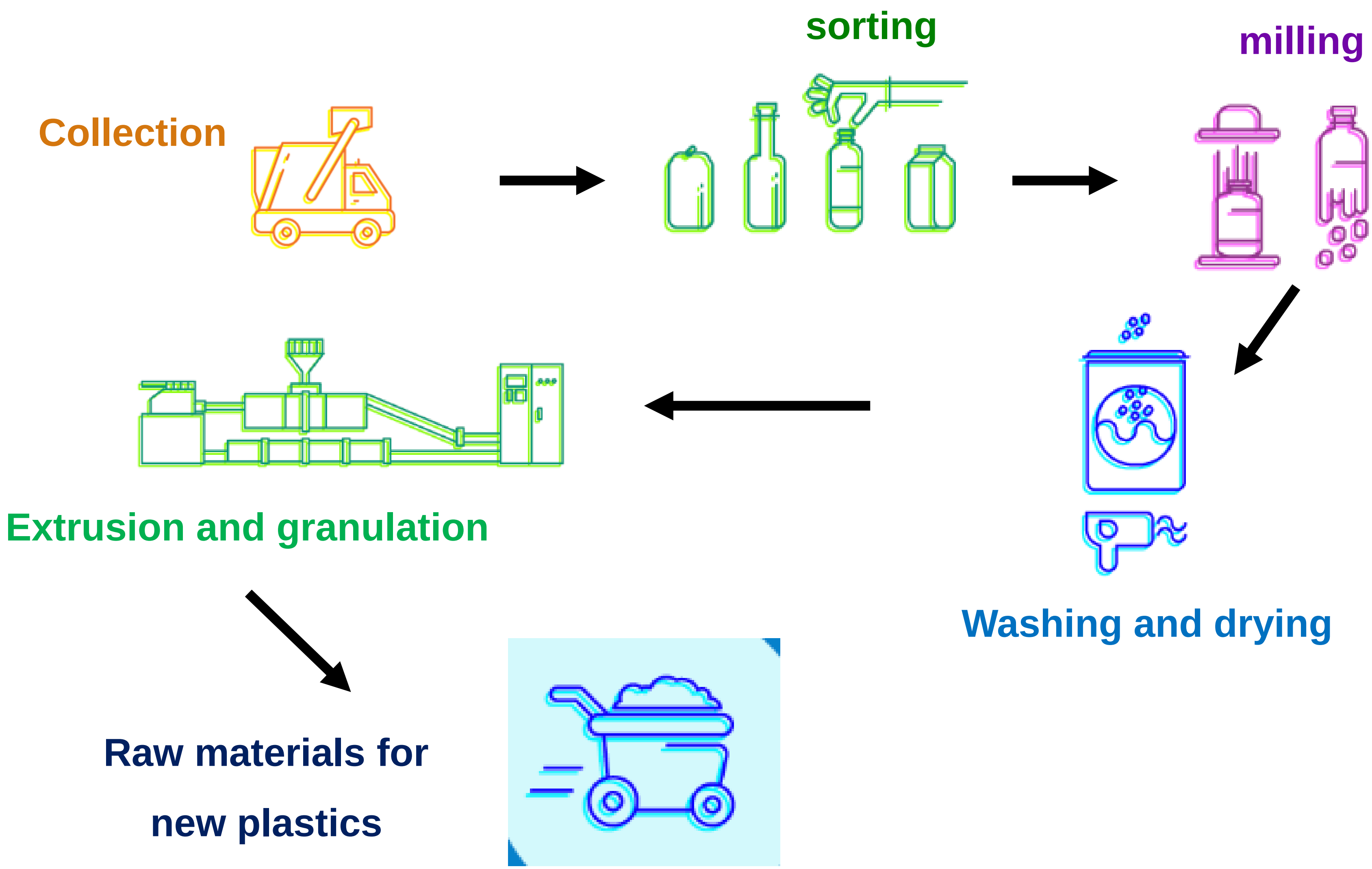
II. post-consumer waste obtained from returnable packages,

III. mixed industrial plastic waste,

IV. industrial plastic waste consisting of a single type of plastic

Sometimes secondary recycling is also referred to as mechanical recycling, which means reusing the recovered product as material for either the original purpose or for different ones.

Mechanical or secondary recycling



Adapted from: https://bluevisionbraskem.com/en/intelligence/mechanical-energy-or-chemical-the-different-types-of-recycling-work/

Mechanical or secondary recycling

The complications arise as a result of the **mixing of polymer types and the presence of impurities** (metal, sand, glass, paper, etc.). The problem with mixed polymer types is that polymers are highly incompatible, and their properties are significantly lower than those of the pure components (*thermodynamics of mixing*). In some cases, such as in the generation of parts with thick walls (e.g., plastic lumber), mixed polymers can be tolerated.

Not only a wide variety of plastics is present in the MSW, but a wide variety of other materials are present as plastics make up only 6.2% (see table below).

Plastic Type (SPI #)[a]	Percent by Weight in MSW	Percent by Weight of Plastics
PS (6) foam	0.5	8.0
PET (1) soda bottles	1.0	16.0
HDPE (2) milk/water bottles	0.7	11.0
Bags (4) LDPE film	1.8	29.0
Other (LDPE (4), PVC (3) bottles, PS (6) caps, and other (7) plastics)	2.2	36.0
Total	6.2	100.0

Plastic in Municipal Solid Waste (MSW) of Hamilton, Ohio

The incompatibility of polymers and differences in their melting and processing temperatures, it is difficult to directly reprocess a polymeric mixture.

Technical approaches to secondary recycling include direct reprocessing, reprocessing using specialized equipment, chemical modification of mixed plastic waste (compatibilizers), using recycled in the core, using waste as a filler, and using waste as a binder for a low-cost filler.

Mechanical or secondary recycling

Barriers/challenges:

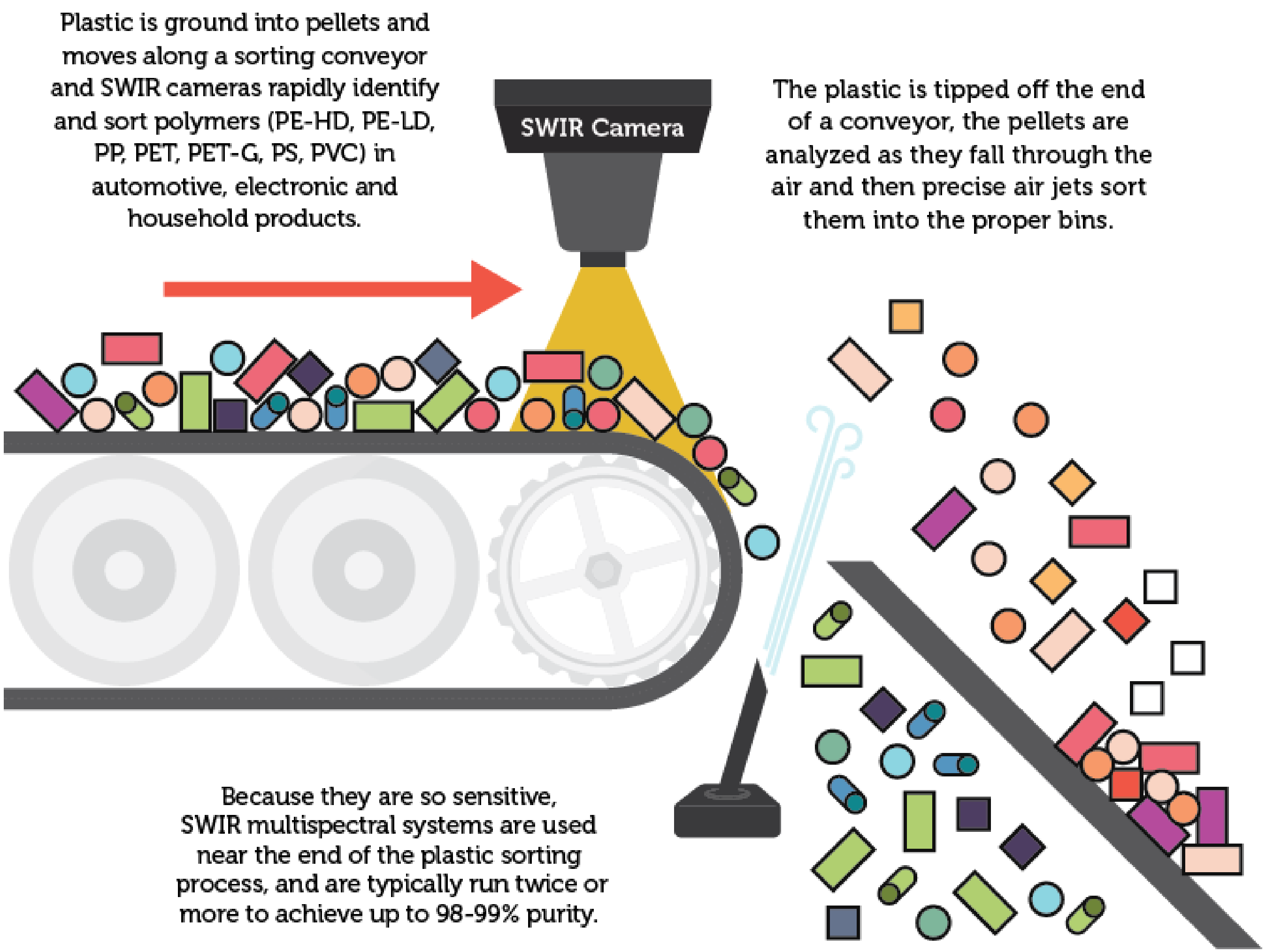
- The purity of the materials is not known;
- The contamination of the matrix with other polymers reduces the mechanical properties. Most polymers are not compatible with each other. Examples are the presence of PET impurities in a PVC matrix.

Separation techniques:

- Fourier-transform and near-infrared spectroscopy
- X-ray detection
- Optical color recognition cameras to separate clear and colored materiais from each other.

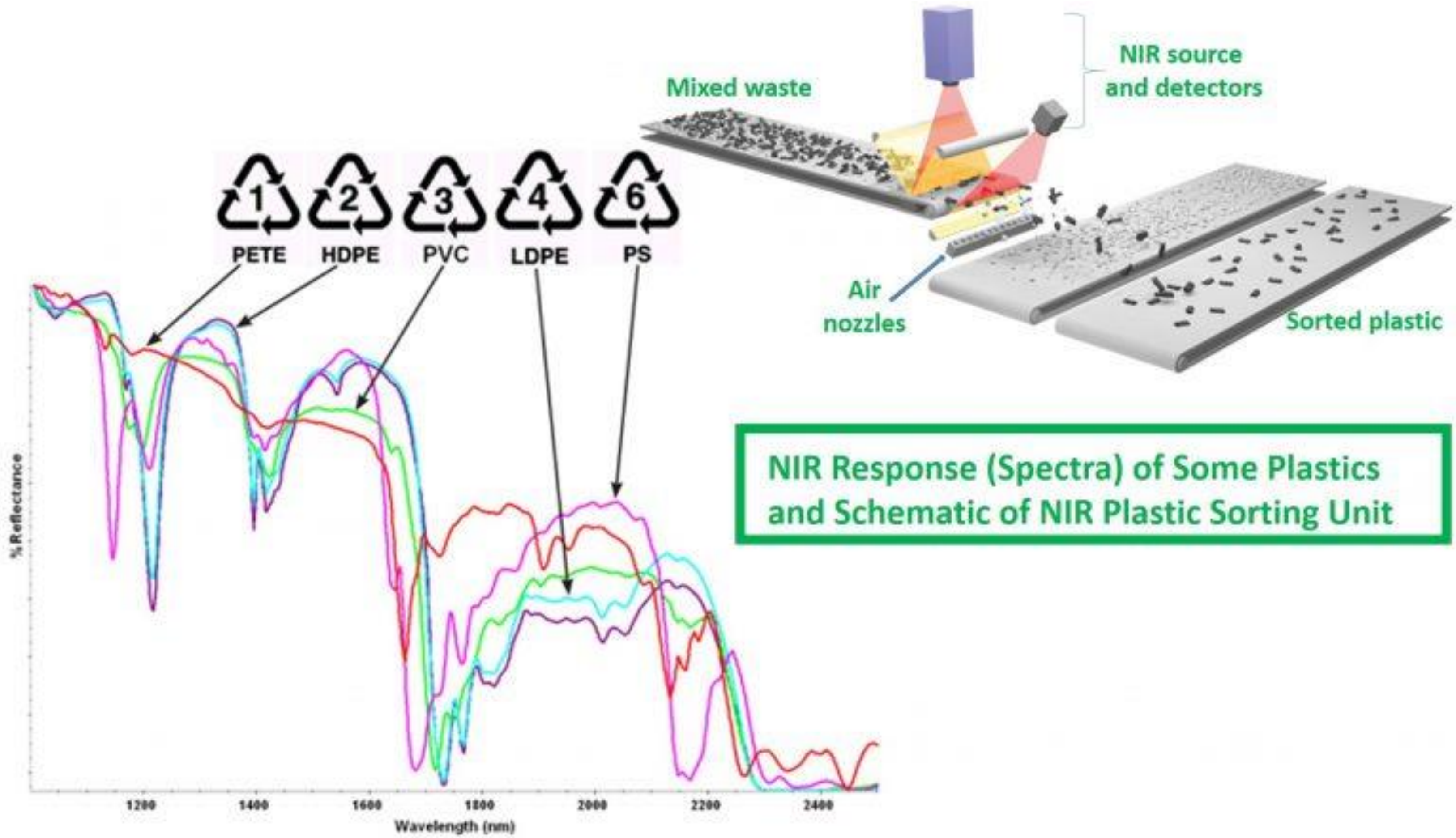
Mechanical or secondary recycling

Fourier-transform and near-infrared spectroscopy



Mechanical or secondary recycling

Fourier-transform and near-infrared spectroscopy

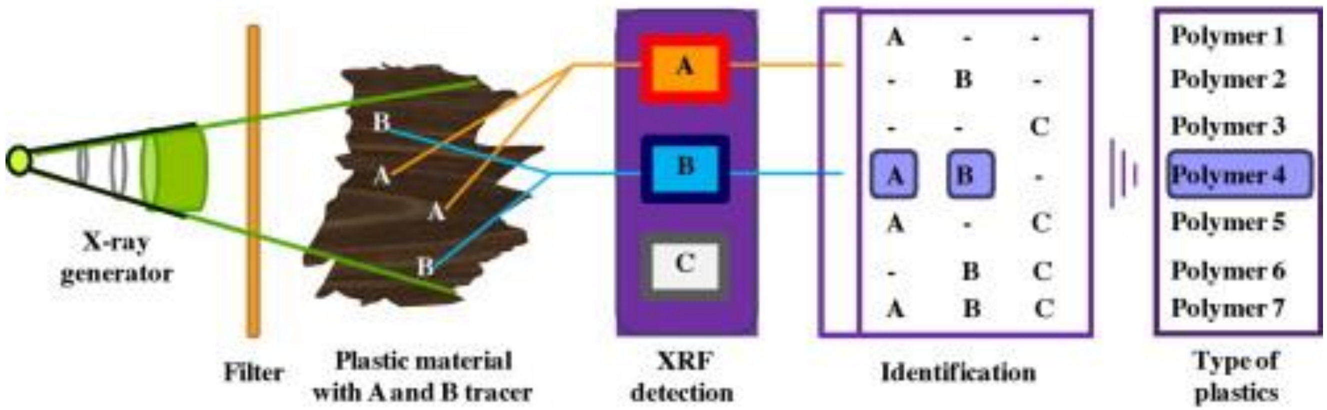


Mechanical or secondary recycling

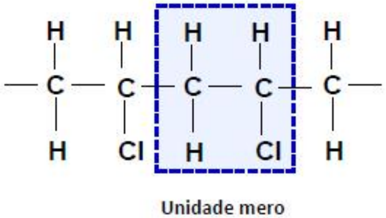
Ambigroup: http://www.ambigroup.com/

Mechanical or secondary recycling

X-ray fluorescence



PVC



Tertiary of feedstock recycling

Chemical recycling

In contrast to mechanical recycling, chemical recycling offers the potential for making high-quality polymers from waste — termed ‘upcycling’. Plastic products are depolymerized into their monomeric subunits, which can then be repolymerized through controlled polymerization mechanisms into polymers of desired quality

Solvolysis

In solvolysis, polymers with cleavable groups along their backbone, such as ester bonds in PET and PLA, can be subjected to solvent-based depolymerization processes such as hydrolysis, glycolysis or methanolysis.

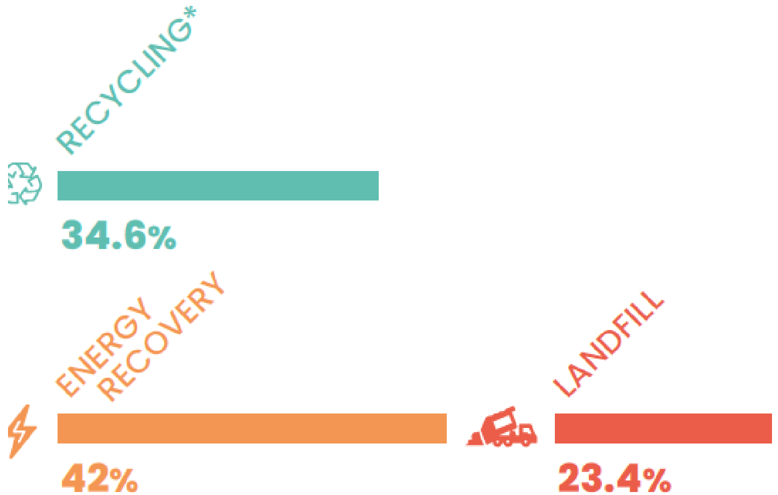
Thermolysis

In thermolysis, typically polyolefins, which do not possess hydrolysable functional groups, are pyrolyzed at temperatures of ~200–800 °C (depending on the polymer and catalyst used) in the total or partial absence of O_2. Under these conditions, the C–C bonds break, converting the polymer back into feedstock in the form of hydrocarbon oil or gas, or directly into olefin monomers.

Quaternary recycling

Incineration as a method to recover energy may be also classified as a form of recycling. Incineration (or quaternary recycling) still remains a very popular method for waste volume reduction and for energy recuperation.

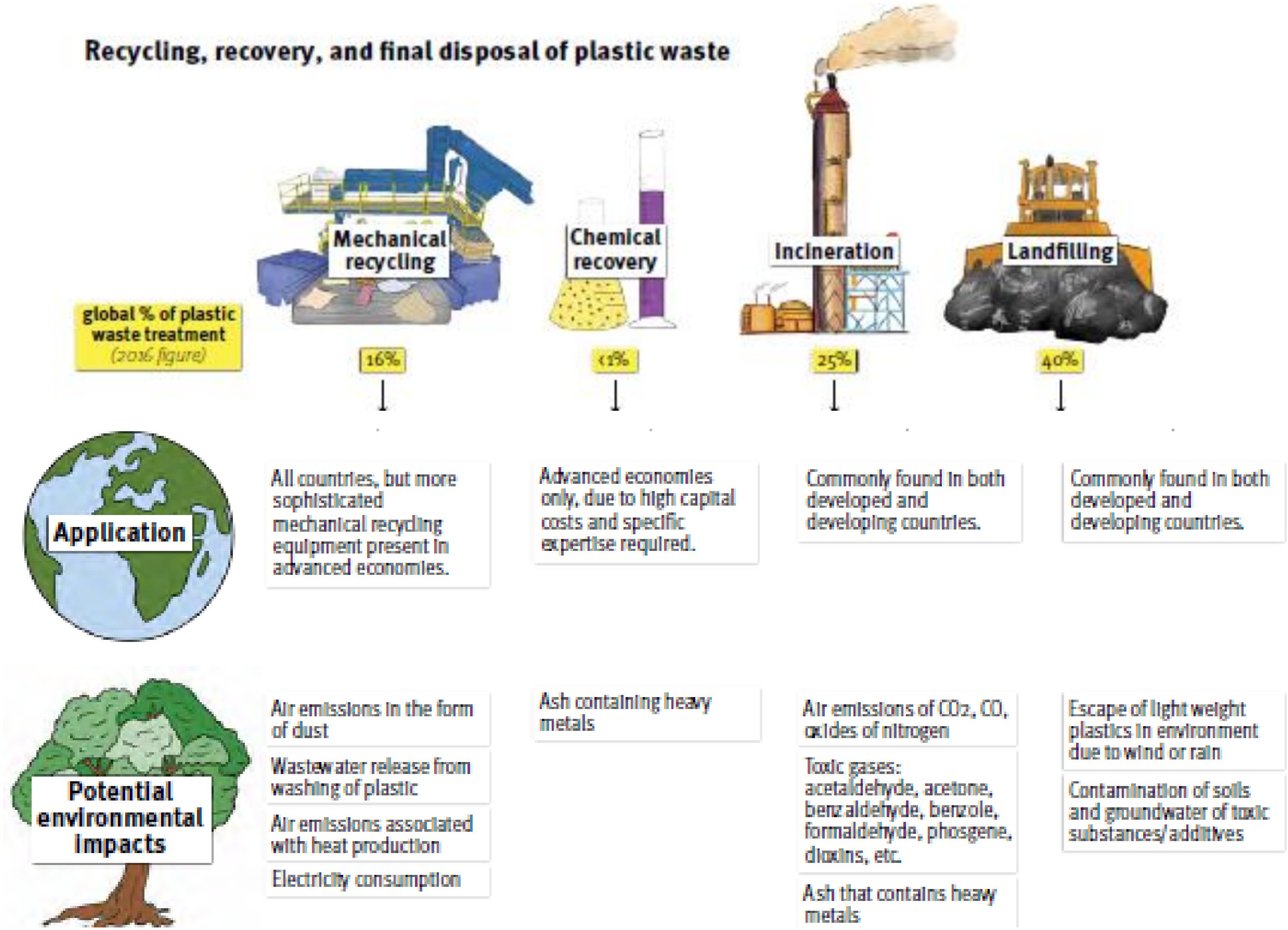
In Europe, it is the most common method of utilizing discarded plastic.



This method is especially used for processing of mixed and heavily contaminated wastes, which cannot be easily and/or economically recycled by any other method. Burning of energy-dense waste can create heat, electricity, or other forms of energy, which can be directly used in technological processes or for heating of buildings.

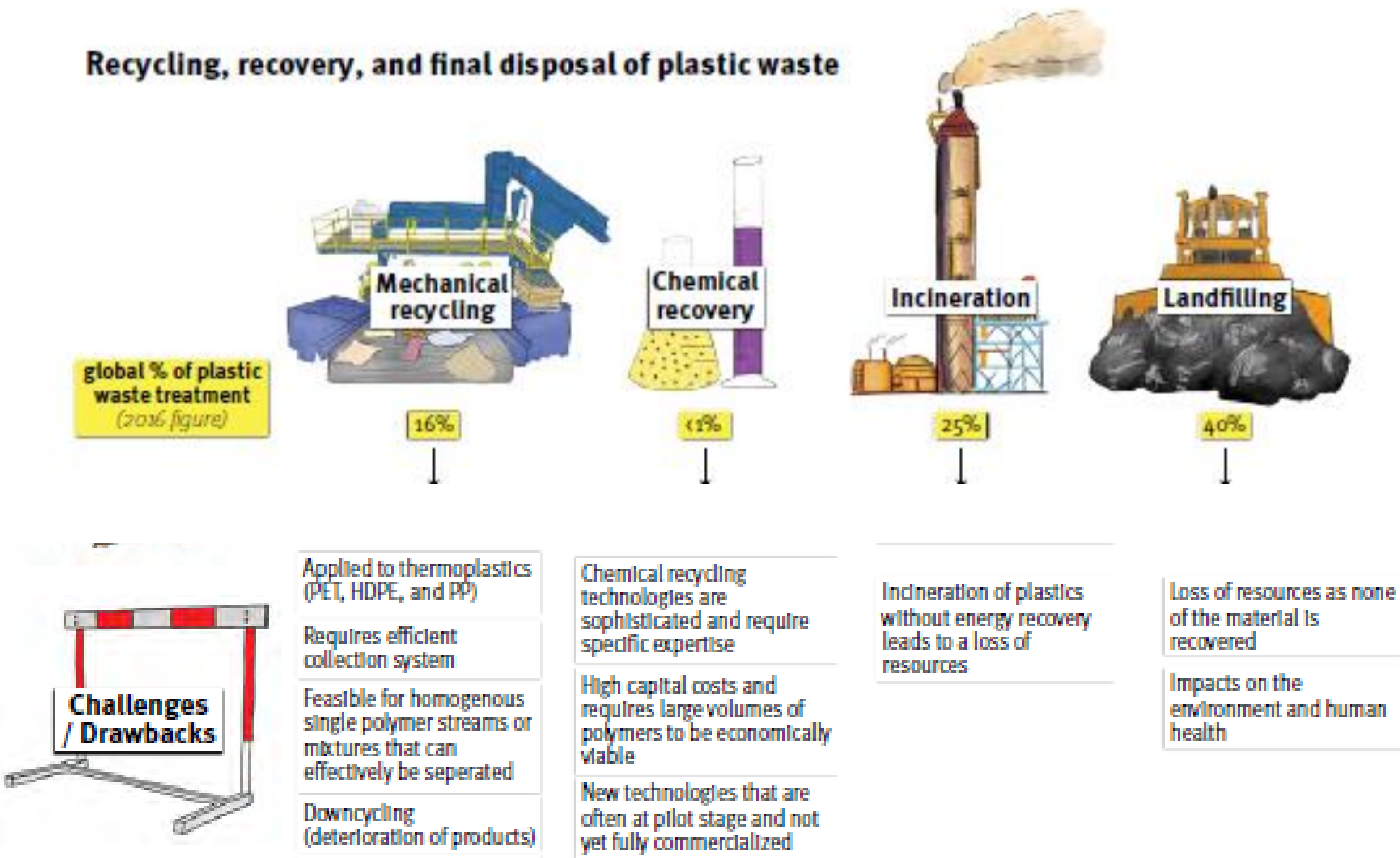
Source: Ignatyev et al., “Polymers recycling: a review”, ChemSusChem 2014, 7, 1579-1593.

Recycling options



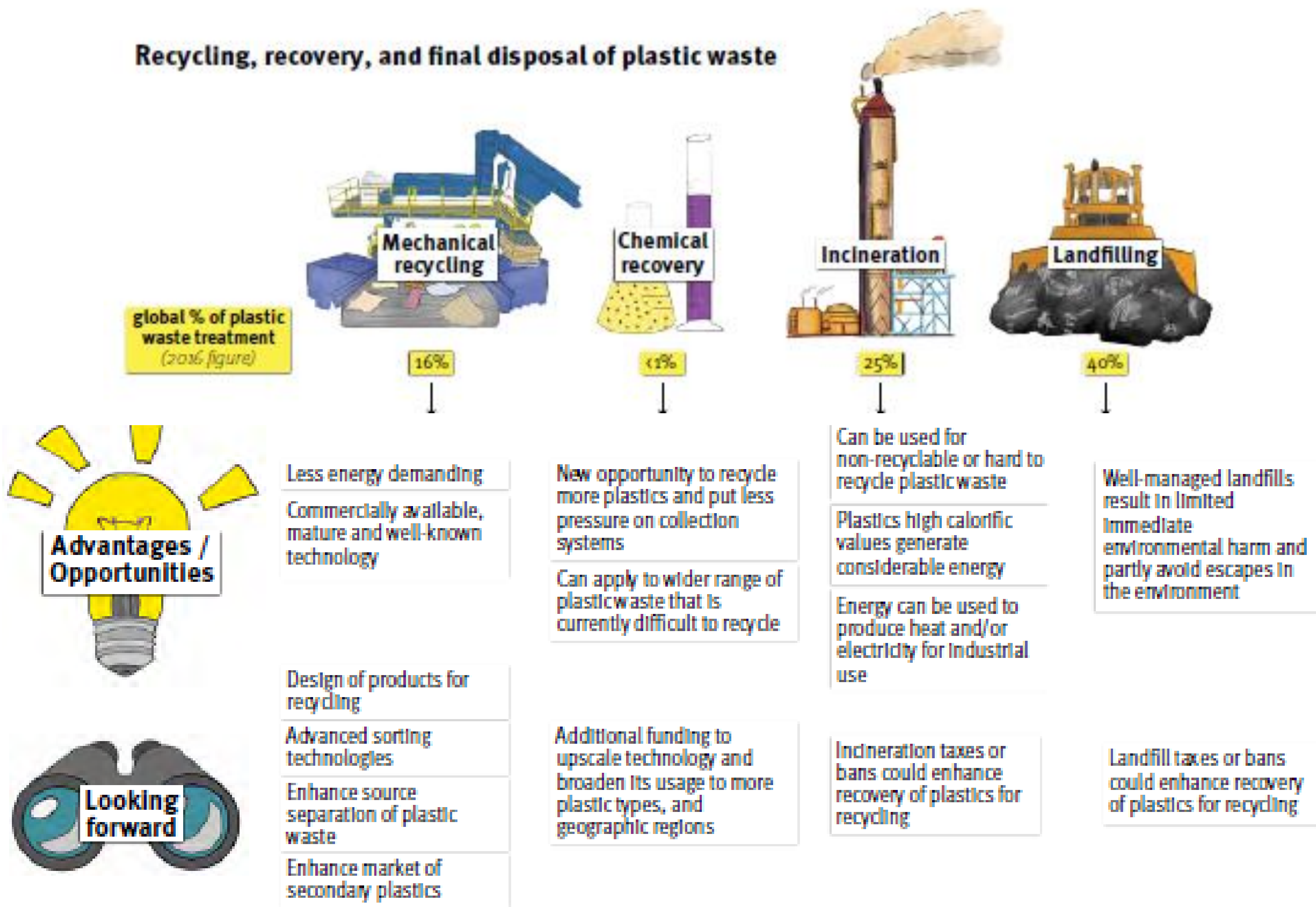
Source: “Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics”, United Nations Environment Programme (2021).

Recycling options: summary



Source: "Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics", United Nations Environment Programme (2021).

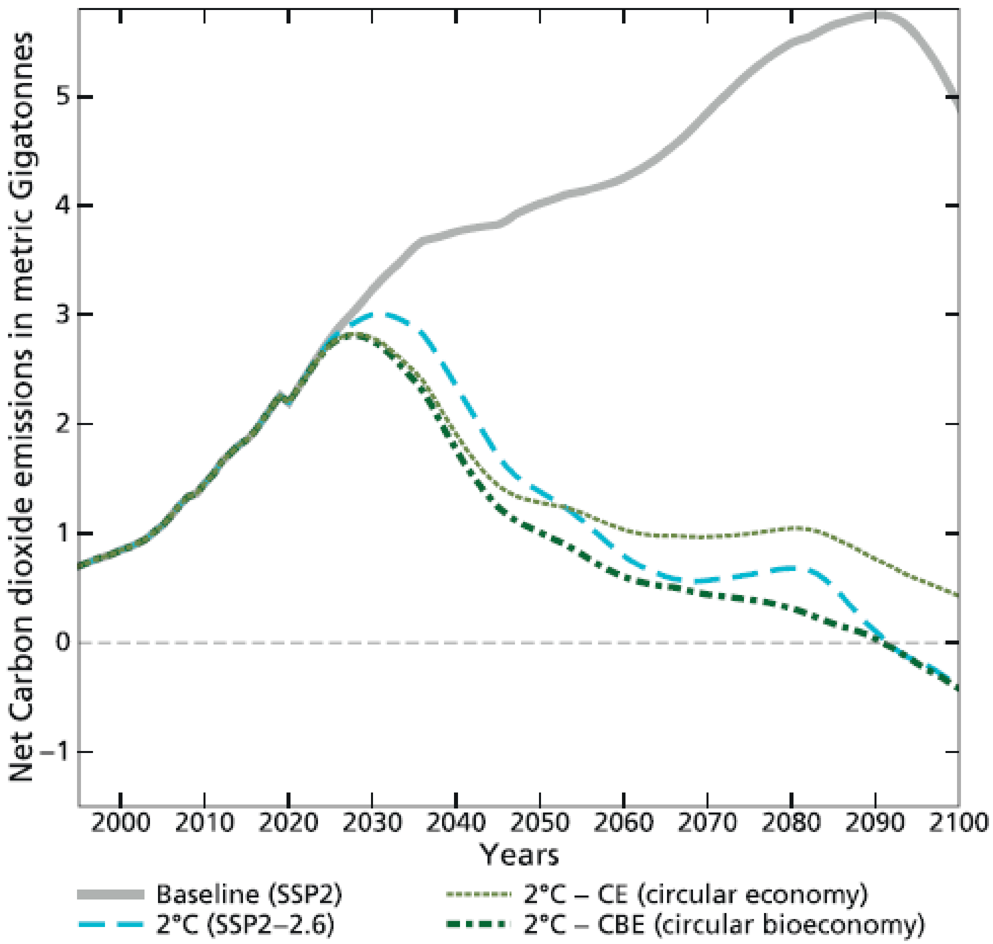
Recycling options : summary



Source: "Drowning in plastics – Marine Litter and Plastic Waste Vital Graphics", United Nations Environment Programme (2021).

Global carbon balance of the plastics sector over the entire life cycle

Projections under different scenarios



SSP2: middle-of-the-road socioeconomic path that results in a continued focus on fossil resources and only a small uptake of biomass as feedstock.

SSP2-2.6°C: 2°C global mean temperature change target by 2100.

CE & CBE: a global paradigm shift toward a CE involving all relevant actors is assumed. Next to gradually phasing out landfilling, the authors assume that policies incentivizing circular product design, standardized plastic types and avoidance of additives, opaque colours and multimaterial plastic products will increase sorting and recycling efficiencies.

Extended Data Fig. 3 | Comparing the net CO_2-emissions of the four scenarios for the global plastic sector. These emission lines are the same as the solid net emission lines of Fig. 3; biogenic emissions are assumed to be renewable and therefore have no net contribution to climate change.

Source: Stegmann *et al.*, “Plastic futures and their CO_2 emissions”. Nature, Vol 612 (2022).

Overview

Plastics are the most complicated material family. It will be very difficult to make a 50% cut in CO_2 emissions while predicted demand doubles. Here are some suggestions:

- ❑ Reduce the variety of plastics in use to simplify recycling and increase recovery rates.
- ❑ Replace all possible disposable packaging with long life packaging in continuous re-use and extend the life of all non-disposable plastic goods.
- ❑ Promote life extension for other products, including vehicles, which contain many plastic components, as part of a general strategy for reducing demand for new materials (economic impact?)
- ❑ Development of bio-based plastics.