Plastics : A Rough Guide

Type & Uses | Manufacturing | Reuse & Recycling | Waste

References & Other Resources

Museums of the FutureNow

March 2023

Table of Contents

1. Background

In the course of developing the participatory museums that have contributed to the stories behind the exhibits in the Solway Hoard, the *Museums of the FutureNow* did a lot of reading.

The world of plastic is fascinating. This material is so widely used that it is almost invisible. Once you start looking though, it is everywhere; we depend on it for everything from packaging to heart valves. Unfortunately, once the polymers have been synthesised they are difficult to undo to different extents and are frequently simply discarded where they slowly disintegrate into smaller and smaller particles many of which never disappear.

We are interested primarily here in plastics synthesised from fossil fuels. According to market data from European Bioplastics, these account for 99% of the plastics produced annually. A very high level overview of bio-plastics as used in food contact materials is included in *Plastics :: Types & Uses*.

We felt that the materials we consulted may be of interest to others so we have collected them here under 4 broad categories:

(i) **Plastics :: Types & Uses** - types of plastic and their uses
(ii) **Plastics :: Manufacturing** - how plastics are made
(iii) **Plastics :: Reuse & Recycling** - opportunities for reuse and recycling
(iv) **Plastics :: Waste** - plastic waste and pollution

They are presented in the form of the notes that we took at the time with graphics and diagrams that either we created to help explain things to ourselves or were provided in the materials we used. In the latter case the source is cited in the notes for those interested in enquiring further.

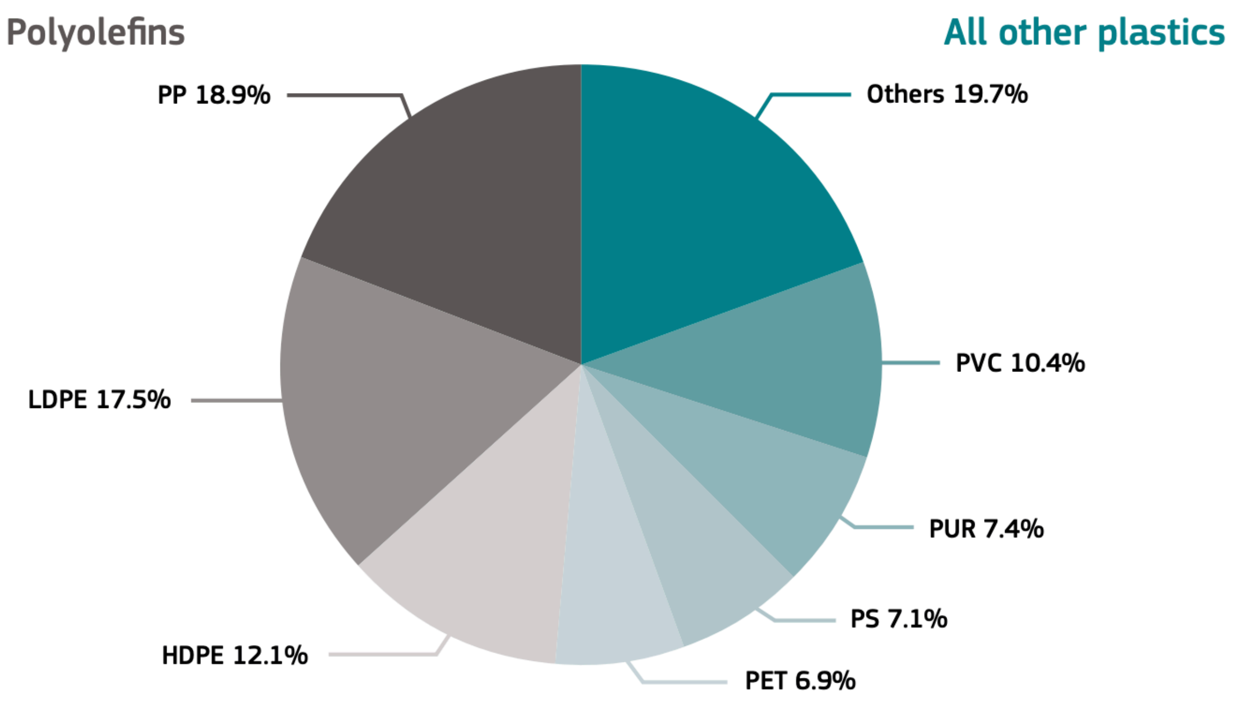
The final section - **Plastics :: Further Resources** - contains a full list of references to sources.

We hope you find (some of) these useful.

Museums of the FutureNow
March 2023

2. Plastics :: Type & Uses

Figure 12: The world plastics use is dominated by few main plastics classes of fossil-based plastics



Crippa, M. et al. (2019) p.57

Key to abbreviations:

PA:	polyamide (nylon)	$[C_{12}H_{22}N_2O_2]_n$
PP:	polypropylene	$[C_3H_6]_n$
PE:	polyethylene	$[C_2H_4]_n$
HDPE:	high density polyethylene	
LLDPE:	linear low density polyethylene	
EPE:	expanded polyethylene	
PS:	polystyrene	$[C_8H_8]_n$
PET:	polyethylene terephthalate	$[C_{10}H_8O_4]_n$
PVC:	polyvinyl chloride	$[C_2H_3CL]_n$
PU | PUR:	polyurethane (an elastomer)	$[C_{17}H_{16}N_2O_4]_n$
SBS:	styrene-butadiene-styrene	$[C_{20}H_{22}]_n$
SEBS:	styrene-ethylene-butadiene-styrene	$[C_{14}H_{18}]_n$

- Engineering plastics

  Engineering plastics exhibit higher performance than standard materials, making them ideal for tough engineering applications. They have gradually replaced traditional engineering materials such as wood or metal in many applications because, not only do they equal or surpass them in their weight/strength ratio and other properties, but they are also much easier to manufacture, especially in complicated shapes.

- Epoxy resins

  Epoxy resins have been around for more than 50 years, and are one of the most successful of the plastics families. Their physical state can be changed from a low viscosity liquid to a high melting point solid, which means that a wide range of materials with unique properties can be made. In the home, you'll find them in soft-drinks cans and special packaging, where they are used as a lining to protect the contents and to keep the flavour in. They are also used as a protective coating on everything from beds, garden chairs, office and hospital furniture, to supermarket trolleys and bicycles. They are also used in special paints to protect the surfaces of ships, oil rigs and wind turbines from bad weather.

- Fluoropolymers

  Fluoropolymers are renowned for their superior non-stick properties associated with their use as a coating on cookware and as a soil and stain repellent for fabrics and textile products. They also contribute to significant advancement in areas such as aerospace, electronics, automotive, industrial processes (chemical and power sectors, including renewable energy), architecture, food and pharmaceuticals and medical applications. The most well-known member of Fluoropolymers is PTFE (polytetrafluoroethylene).

- Polyolefins
  Polyolefins are a family of polyethylene and polypropylene thermoplastics. They are produced mainly from oil and natural gas by a process of polymerisation of ethylene and propylene respectively. Their versatility has made them one of the most popular plastics in use today.

  There are four types of polyolefins Low Density Polyethylene (LDPE) - food films and coatings, cable coatings etc.; Linear Low Density Polyethylene (LLDPE) - stretch films; High Density Polyethylene (HDPE) - crate, boxes and bottles - and Polypropylene (PP) - food packaging, carpet fibres, garden furniture, kitchen appliances, pipes - all with different strength to strength-to-density ratios.

- Polyvinyl Chloride
  Polyvinyl chloride (PVC) was one of the first plastics discovered, and is also one of the most extensively used. It is derived from salt (57%) and oil or gas (43%). It is the world's third-most widely produced synthetic plastic polymer, after polyethylene and polypropylene. PVC comes in two basic forms: rigid (sometimes abbreviated as RPVC) and flexible.

- Thermoplastics
  Thermoplastics are defined as polymers that can be melted and recast almost indefinitely. They are molten when heated and harden upon cooling. When frozen, however, a thermoplastic becomes glass-like and subject to fracture. These characteristics, which lend the material its name, are reversible, so the material can be reheated, reshaped, and frozen repeatedly. As a result, thermoplastics are mechanically recyclable. Some of the most common types of thermoplastic are polypropylene, polyethylene, polyvinyl chloride, polystyrene, polyethylene terephthalate and polycarbonate.

These plastics can be grouped into **2 main polymer** 'families' describing the way the plastic responds to heat:

- thermoplastics which soften on heating sand then harden again on cooling
- thermosets which never soften once they have been moulded.

Thermoplastics	Illustrative Uses	Thermosets	Illustrative Uses
Acrylonitrile butadiene styrene (ABS)	Lego bricks	Epoxide (EP)	adhesives, paints, composites,
Polycarbonate (PC)	Greenhouse 'glass'	Phenol-formaldehyde (PF)	moulded products
Polyethylene (PE)	HDPE: packaging (laundry detergent)	Polyurethane (PUR)	coatings, furniture, footwear, straps
	LDPE: packaging (plastic bags)		sanitary ware, tanks
Polyethylene terephthalate (PET)	water bottles	Unsaturated polyester resins (UP)	pipes, gratings
Polytetrafluoroethylene (PTFE)	non stick cookware		
Polyvinyl chloride (PVC)	construction		
Polymethyl methacrylate (PMMA)	optical devices (aka acrylic)		
Polypropylene (PP)	manufacturing		
Polystyrene (PS)	packaging, test tubes, petri dishes		
Expanded Polystyrene (EPS)	insulation		
Polylactic Acid (PLA)	3D printing filaments		
Polyhydroxyalkanoates (PHA)	medical applications		

Packaging is the largest plastics application, currently representing 26% of the total volume of plastics used globally and up to 40% in Europe (World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016 and PlasticsEurope, 2018)

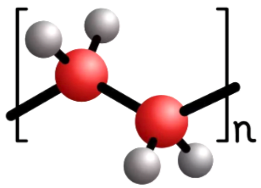
The four most important polymer types used in packaging and collected for recycling are PET mix, HDPE, LDPE and PP. But, of the total volume collected for recycling, only 13% reaches European converters and 30% is exported, with not much information on its final fate.

Type

Polyethylene

$[C_2H_4]_n$

Structure



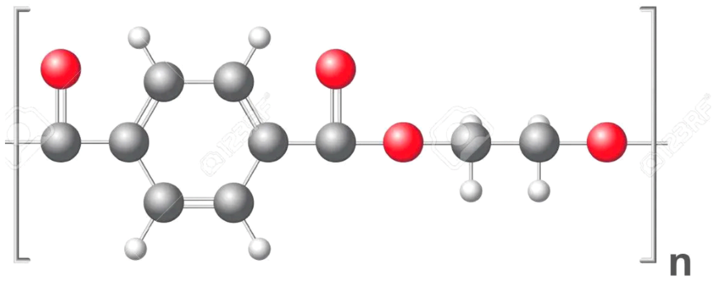
Uses

	LDPE [Low Density Polyethylene]	**HDPE [High Density Polyethylene]**
Uses	juice containers cling wrap bags trays can holders tubing prosthetics wash bottles ice cream lids extrusion moulding laminates	piping, sheeting fuel tanks food & beverage containers plastic bottles milk jugs, cups personal care products plastic containers: recycle bins bread bags, cereal box liners medical equipment 3D printing filament boating equipment cable insulators sewage mains pyrotechnic components
Recycling	4 rubbish bags | plastic lumber | furniture shipping envelopes | compost bins	2 detergent bottles | pipe | crates | decking | flower pots
Recycling complexity	easy with specialist equipment	easy with specialist equipment

Type

polyethylene terephthalate [PET]
aka polyester
$(C_{10}H_8O_4)_n$

Structure



Uses

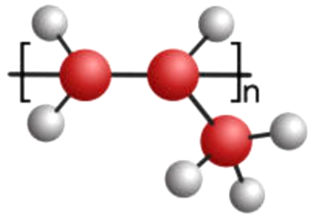
textiles
packaging
bottles
tennis balls
takeaway food containers
prepared food trays

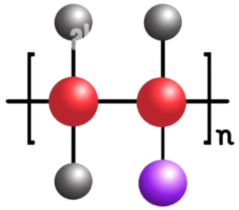
Recycling

most widely recycled plastic -> fashion items | carpet | bottles

Recycling complexity

easy with specialist equipment

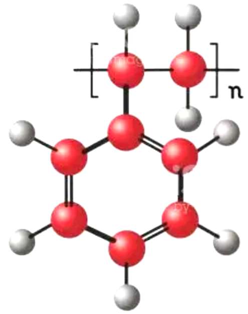
Type	**Polypropylene** $[C_3H_6]_n$
Structure	
Uses	material handling packaging medical devices clothing car parts houseware toys
Recycling	 paint cans | autoparts| food containers |razor handles | plant pots | speed bumps
Recycling complexity	difficult

Type	**polyvinyl chloride [PVC]** $(C_2H_3Cl)_n$
Structure	
Uses	construction insulation flooring piping insulation coatings & linings
Recycling	 carpet backing | flooring | pipe | wall siding | binders
Recycling complexity	hard: recycling is increasing

Type

polystyrene
$(C_8H_8)_n$

Structure



Uses

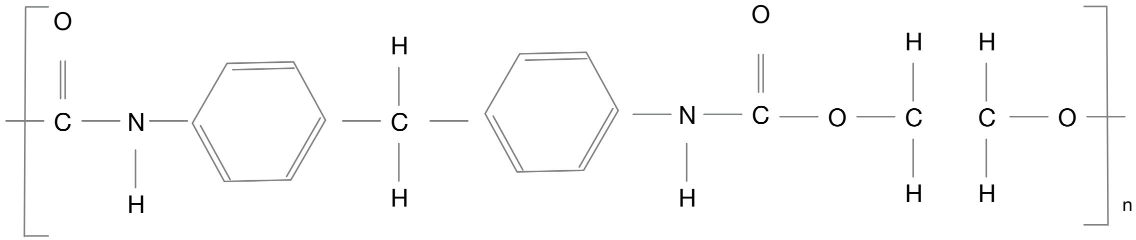
packaging
jewel cases [DVD]
containers
lids
bottles
trays
disposable cutlery

Recycling

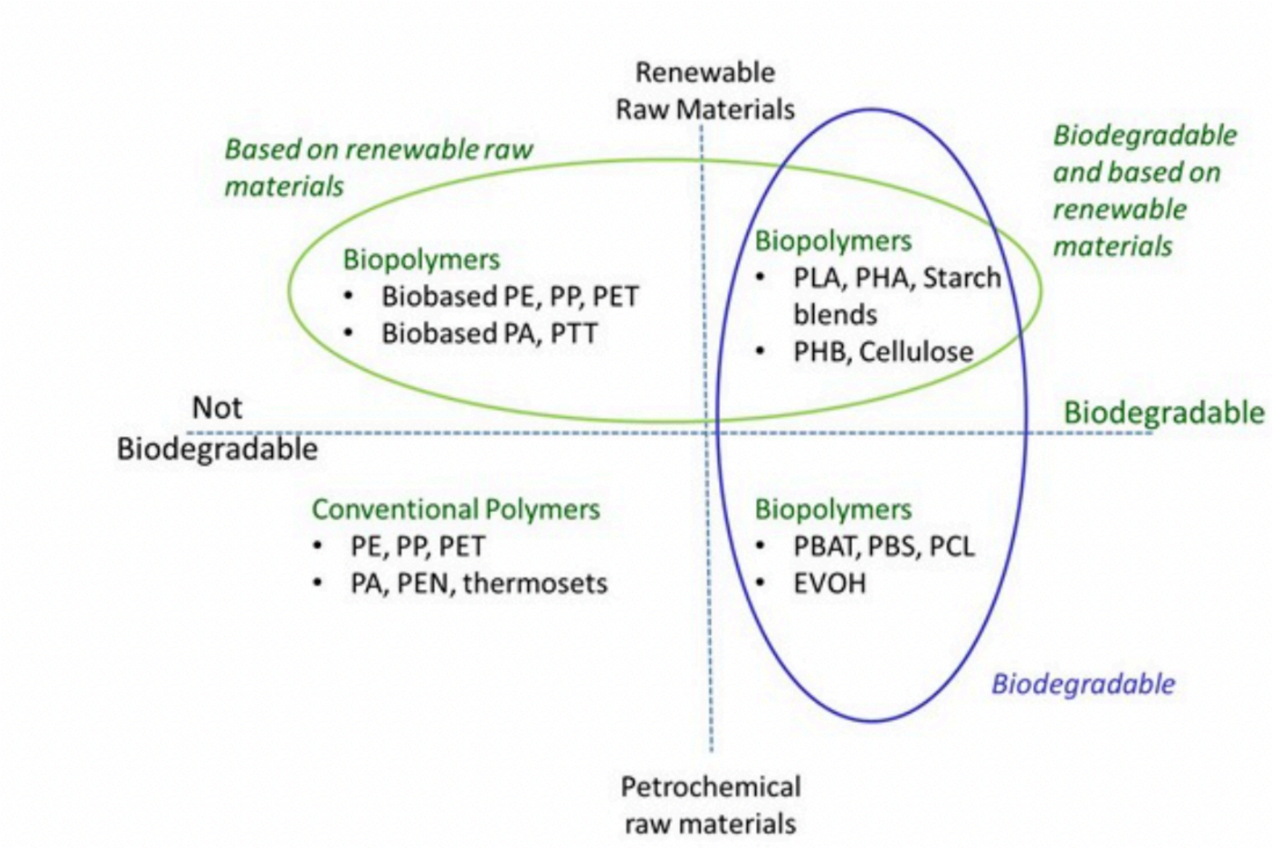
picture frames | crown moulding | flower pots | toys | hangers

Recycling complexity

hard: almost never recycled

Type	**Polyurethane [PUR]** (isocyanate + polyol)
Structure	
Uses	building insulation cooling devices e.g. refrigerators and freezers furniture and bedding footwear automative applications e.g. car seats and automotive parts paints, coatings and adhesives
Recycling	
Recycling complexity	difficult

Bio-plastics



Gotro, J. (2012)

Key to abbreviations:

PLA: polylactic acid
PHA: polyhydroxy alkanoate
PHB: polyhydroxy butyrate
PBAT: poly(butylene adipate-co-terephthalate)
PBS: poly(butylene succinate)
PCL: polycaprolactone
EVOH: ethylene vinyl alcohol
PE: polyethylene
PP: polypropylene
PET: polyethylene terephthalate
PA: polyamide (nylon)
PTT: poly trimethylterephthalate
PEN: polyethylene naphthalate

Bioplastics are used as alternatives to conventional fossil fuel based plastics and are increasingly being used in food contact materials (FCMs). For example, the Coca Cola Company has recently launched its Plant Bottle, which is partially made from bio-based plastics and Danone is using polyactide (PLA) for its yoghurt cups. Two different types of bioplastics exist: bio-based polymers and biodegradable plastics. Two further specific definitions for bio-related plastics are oxo-biodegradable plastics and bio-nanocomposites.

Bio-based polymers are made from bio-based resources though in practice bio-based resource content may vary. Biomass used for the production of bioplastics may either be extracted directly from plants (starch, cellulose) or produced by microorganisms in fermentative processes (e.g. polyhydroxyalkanoates (PHA)). Biomass can either be from 1st generation feedstock (e.g. corn, sugar cane) or from non-food crops (2nd generation feedstock, e.g. lignocellulosic material). Bio-based polymers can also be produced by further chemical modifications and are not necessarily biodegradable.

Biodegradable plastics may be made from both natural and fossil resources and are biodegraded by microorganisms in their natural environment. The products of this process are energy, biomass, water and carbon dioxide or methane, depending of the presence or absence of oxygen. If biodegradable plastics are degraded in accordance with standards for compostability, e.g. the European standard EN 13432, they may be labeled compostable.

Oxo-biodegradable plastics are mainly composed of polyolefins such as polyethylene (PE) and polypropylene (PP), which contain further chemical additives intended to accelerate degradation. Oxo-biodegradable plastics do not degrade according to the previously mentioned standards.

Bio-nanocomposites are biopolymers which have been stabilised using nanoparticles. The nanoparticles enhance technical properties, such as barrier, thermal, chemical or mechanical stability and include nanoclays and nanosilver. The following bioplastics, which are to a varying degree bio-based and biodegradable, are relevant for FCMs :

Starch-based polymers	• Biodegradable polysaccharide • Alternative for polystyrene (PS) • Used in food packaging, disposable tableware and cutlery, coffee machine capsules, bottles
Cellulose-based polymers	• Biodegradable polysaccharide • Low water vapour barrier, poor mechanical properties, bad processability, brittleness (pure cellulosic polymer) • Regulated under 2007/42/EC • Coated, compostable cellulose films • Used in the packaging of bread, fruits, meat, dried products, etc.
Polylactide (PLA)	• Biodegradable, thermoplastic polyester • Possible alternative of low- and high-density polyethylene (LDPE and HDPE), polystyrene (PS), and poly terephthalate (PET) • Transparent, rigid containers, bags, jars, films
Polyhydroxyalkanoates (PHA)	• Biodegradable polyester • Family of many, chemically different polymers • Brittleness, stiffness, thermal instability
Biobased polypropylene (PP) and polyethylene (PE)	• Non-biodegradable vinyl polymer • Mainly based on sugar cane • Identical physicochemical properties
Partially biobased polyethylene terephthalate (PET)	• Alternative to conventional PET • Up to 30% bio-based raw materials • Used in bottles
Biobased polyethylene furanoate (PEF)	• Non-biodegradable polyester based on a heteroaromatic 5-ring structure • Better barrier function than PET • Up to 100% bio-based raw materials • May be used in the future in bottles, fibres, films

Aliphatic (co)polyesters	• Biodegradable polymers including e.g. polybutylene succinate (PBS), polyethylene succinate (PES), and polyethylene adipate (PEA) • Used in disposable cutlery
Aliphatic-aromatic (co)polyesters	• Biodegradable polymers including e.g. polybutylene adipate terephthalate (PBAT), polybutylene succinate terephthalate (PBST). • Used as fast food disposable packaging, PBAT for plastic films
Polycaprolactone (PCL)	• Biodegradable polyester • Low melting temperature, easily biodegradable • Used in medical applications, as PCL blends in FCMs
Polyvinyl alcohol (PVOH)	• Biodegradable vinyl polymer • Used for coatings, adhesives, and as additive in paper and board production
Polyamides (PA)	• Non-biodegradable polymer • Used in high-performance polymers, not commonly in FCMs
Others	• Animal (chitosan) and protein (soy protein isolate, gluten and zein) based bioplastics

Usually pure biodegradable plastics do not perform as well as conventional plastics. Material properties are enhanced by the addition of chemicals including antioxidants, light and UV stabilisers, releasing agents, cross-linking agents and many others.

[[Food Packaging Forum (2014) *Bioplastics: Types, applications, toxicity and regulation of bioplastics used in food contact materials*]]

3. Plastics :: Manufacturing

Annual global production of plastics doubled from 234 million metric tons in 2000 to 460 million metric tons in 2019. It is forecast to triple under a business-as-usual scenario to an estimated 1,231 million metric tons in 2060. Global plastic materials production in 2020 was dominated by the following regions: Asia (49 per cent), North America (19 per cent) and Europe (15 per cent).

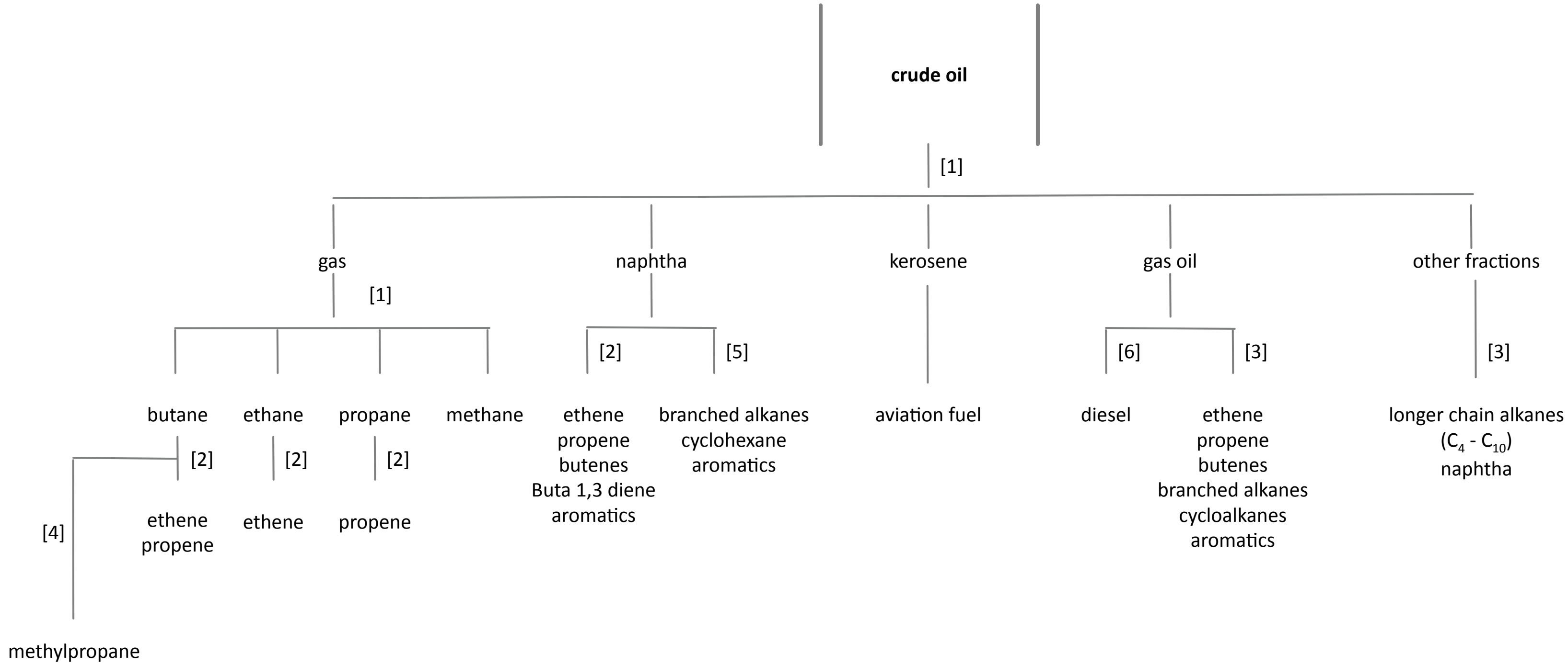
Up to 99 per cent of plastics are made from polymers derived from non-renewable hydrocarbons, mostly oil and natural gas. Some 86 per cent of the global market is dominated by thermoplastics.

Short-lived plastic products made up 66 per cent of plastics use in 2019. Short-lived plastic products include packaging made from LDPE (e.g., bags, containers, food packaging film), containers made from HDPE (e.g., bottles, shampoo bottles, ice cream tubs) and PET (e.g., bottles for fluids).

Durable or long-lasting plastic products found in buildings and construction, transportation, electronics and machinery made up around 35 per cent of plastic product use in 2019. Such items may be in use from around 8 years (in electronics, for example) to more than 20 years (in construction materials and industrial machinery).

Bio-based plastics are receiving growing attention. Bioplastics are plastics that are made from renewable resources, are biodegradable or are made through biological processes, or a combination of these. The term bioplastic should not be used without specification of the material's origin and biodegradability conditions.

Feedstocks, cracking and related refinery processes

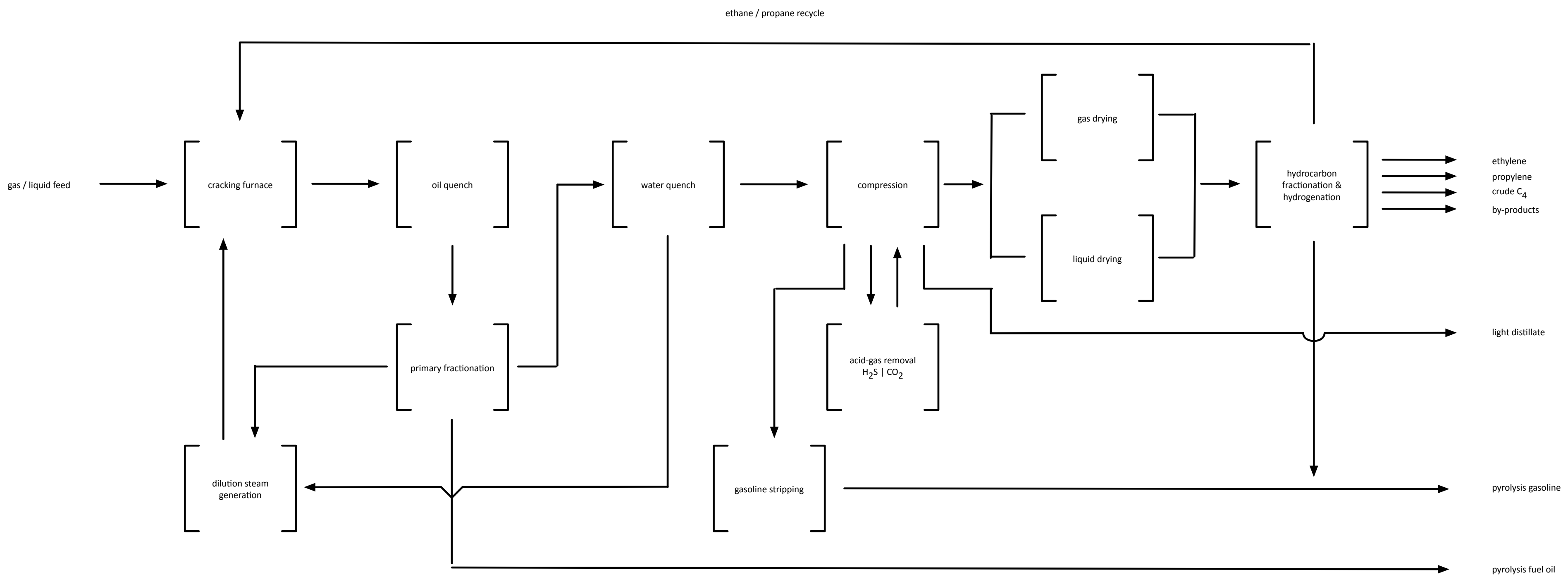


[1] Distillation | **[2]** steam cracking | **[3]** catalytic cracking (hydrocracking) | **[4]** isomerisation | **[5]** reforming (platforming) | **[6]** sulphur removal

aromatics : benzene | methylbenzene | dimethylbenzene | ethylbenzene

www.essentialchemicalindustry.org/processes/cracking-isomerisation-and-reforming.html

An example pathway: naphtha cracking for olefin production



www.semanticscholar.org/paper/Modelling-of-Naphtha-Cracking-for-Olefins-Marcos-Marcos

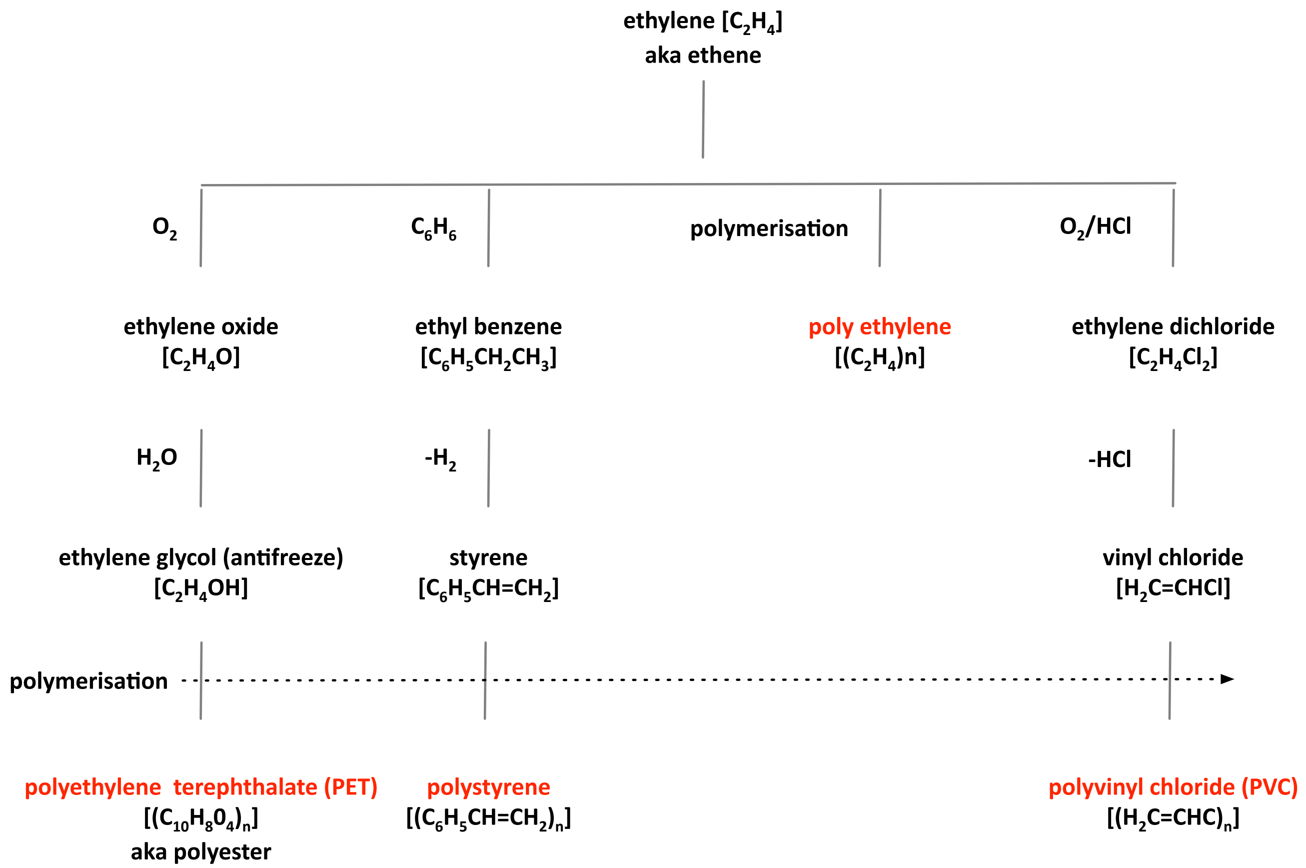
In steam cracking, a gaseous or liquid hydrocarbon feed like naphtha, LPG or ethane is diluted with steam and briefly heated in a furnace in the absence of oxygen. Typically, the reaction temperature is very high, at around 850 °C. The reaction occurs rapidly: the residence time is of the order of milliseconds. Flow rates approach the speed of sound.

After the cracking temperature has been reached, the gas is quickly quenched to stop the reaction in a transfer-line heat exchanger or inside a quenching header using quench oil.

The products produced in the reaction depend on the composition of the feed, the hydrocarbon-to-steam ratio, and on the cracking temperature and furnace residence time.

See for example: www.sciencedirect.com/topics/chemistry/steam-cracking

An example polyolefin pathway: ethylene → polyethylene | polyethylene terephthalate [PET] | polystyrene | polyvinyl chloride [PVC]



There are around 270 ethylene plants globally which produced 214 million tonnes of ethylene in 2021 at US$1,235 per tonne, creating a US$264Bn market which is forecast to grow by ~49% by 2030 (www.statista.com). Some of the largest include:

- **INEOS Grangemouth** www.ineos.com/globalassets/ineos-group/grangemouth/about/ineos-grangemouth-a5-visitor-welcome-bookletfinal-pdf.pdf

- **ExxonMobil /SABIC Portland, Texas** (February 2022) : The steam cracker has the capacity to produce 1.8 million metric tons per year of ethylene, a key feedstock for many plastics, from cling wrap to essential passenger vehicle components, sourced from the Eagle Ford Shale. www.texansfornaturalgas.com/texas_gulf_coast_continues_legacy_as_petrochemical_king_world_s_largest_ethane_steam_cracker_begins_operations_near_corpus_christi

- **Shell Singapore** (March 2010) : The cracker complex will produce 800,000 tonnes of ethylene per annum; 450,000 tonnes of propylene; and 230,000 tonnes of benzene. www.shell.com/business-customers/chemicals/factsheets-speeches-and-articles/factsheets/ethylene-cracker-complex.html

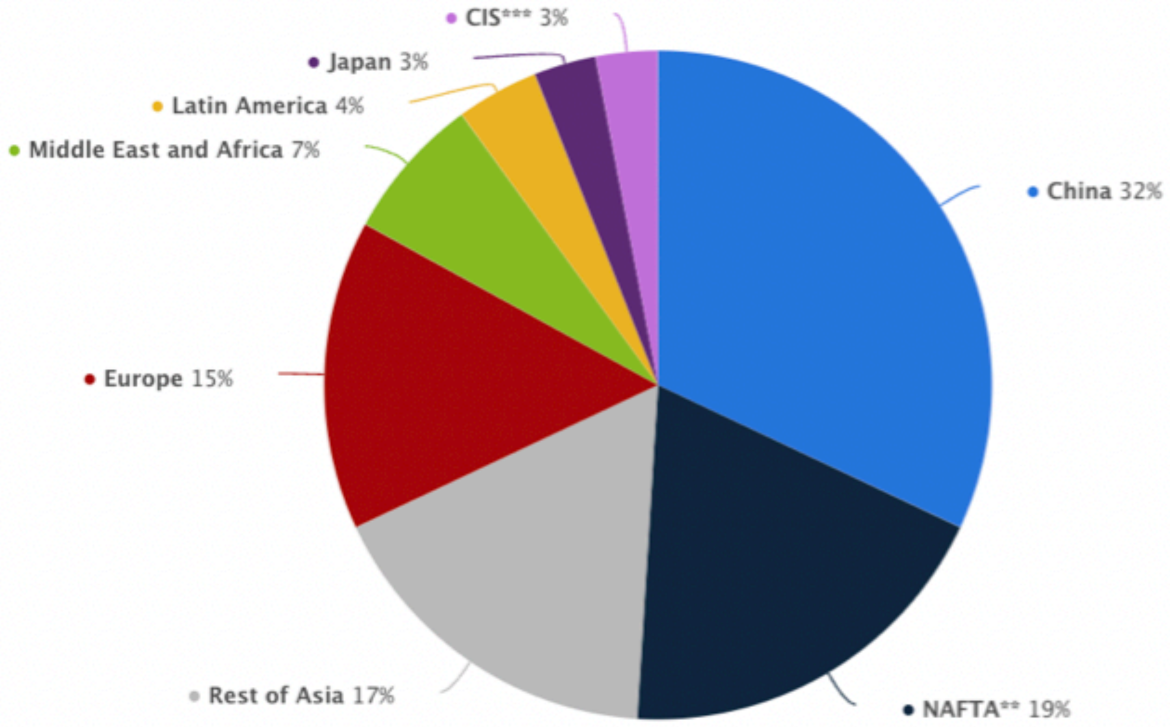
- **Qatar Energy and Chevron Phillips Chemical Co. Ras Laffan, Qatar** (June 2022) The RLPP will feature a 2 million tonnes per annum ethane cracking unit, making it the largest ethane cracker in the Middle East and one of the largest in the world. www.refiningandpetrochemicalsme.com/news/qatarenergy-starts-site-works-for-the-largest-ethane-cracker-in-the-middle-east

- **Dow LHC9 Freeport Texas** (2017) : The world-scale production unit – with a nameplate capacity of 1.5 million metric tons – is a central component of Dow's $6 billion U.S. Gulf Coast investment program. corporate.dow.com/en-us/news/press-releases/dow-ethylene-production-facility-freeport-texas.html

- **Sadara, Saudi Arabia** (2018) : The Sadara MFC is the only facility in Saudi Arabia with the flexibility to crack ethane/LPG and naphtha simultaneously. It is the heart of 26 world-scale manufacturing assets that were built for the Sadara Chemical Complex, the largest of its kind ever built in a single phase. The more than 3 million metric tons of performance-focused products from the Sadara complex will add new value chains to the Kingdom's vast petroleum reserves, resulting in the diversification of the economy and region. www.technipfmc.com/en/media/news/2018/03/sadara-world-s-largest-mixed-feed-cracker-passes-performance-tests

- **Technip Industries : DOW LHC9, Freeport USA**, Sadara KSA, Reliance, Dahej Gujurat, Etileno XXI Nanchital, Mexico www.technipenergies.com/en/markets/ethylene

Manufacturing locations



www.statista.com/statistics/281126/global-plastics-production-share-of-various-countries-and-regions

- **China** : the biggest exporter of plastics globally. In 2015, China made up 27.2% of all plastic goods exports, globally, which was around $18 billion in exported goods shipped around the world.
- **America** : plastics are the 3rd largest manufacturing industry across all 50 states, and in 2012, these manufacturers shipped more than $373 billion in goods worldwide.

- **Germany** : in the top 3 manufacturers. In 2015, the country had exported nearly 12% of the world's plastic goods. Coming second only to China in 2015; Germany accumulated more than $7.8 billion in exported goods.
- **Italy** : Making up almost 4% in the world's plastic exports, Italy is slowly on the economic rise in plastics manufacturing though the country's economy remains volatile, the plastics manufacturing industry is worth around $2.6 billion.

Major manufacturers:

Top 100 Polymer Producers (2021) www.minderoo.org/plastic-waste-makers-index/pwmi-2021/data/indices/producers, including the top 10:

- Exxonmobil (US) : corporate.exxonmobil.com
- Sinopec (PRC) : www.sinopecgroup.com/group/en
- Dow Chemical (US) : www.dow.com
- Indorama Ventures (Thailand) : www.indoramaventures.com
- SABIC (Saudi Arabia) [part of Saudi Aramco] : www.sabic.com
- Petrochina (PRC) : www.petrochina.com.cn
- Lyondellbasell (Netherlands) : www.lyondellbasell.com
- Reliance Industries (India) : www.ril.com/OurBusinesses/Petrochemicals/Polymers.aspx
- Braskem (Brazil) : www.braskem.com.br
- Aplek SA de CV (Mexico) : www.alpek.com

These 100 companies - of approximately 300 polymer producers operating globally- produce 90 per cent of all single-use plastic waste generated globally.

Top 100 Equity Owners of Polymer Producers www.minderoo.org/plastic-waste-makers-index/pwmi-2021/data/indices/investors. Twenty institutional asset managers hold over $300 billion worth of shares in the parent companies of polymer producers, of which an estimated $US10 billion comes from the production of virgin polymers for single-use plastics.

Top 100 Banks Financing Polymer Producers www.minderoo.org/plastic-waste-makers-index/pwmi-2021/data/indices/banks. Twenty of the world's largest banks, including Barclays, HSBC and Bank of America, have lent an estimated US$30 billion for the production of single-use plastic polymers since 2011.

Note: Minderoo Foundation is a philanthropic organisations founded by the Forrest family in Australia with AUS$2.6Bn funds invested including 'No Plastic Waste' www.minderoo.org/no-plastic-waste

The chemical industry absorbs 7-9 % of global oil supply, with 4-6 % being used to make plastic.

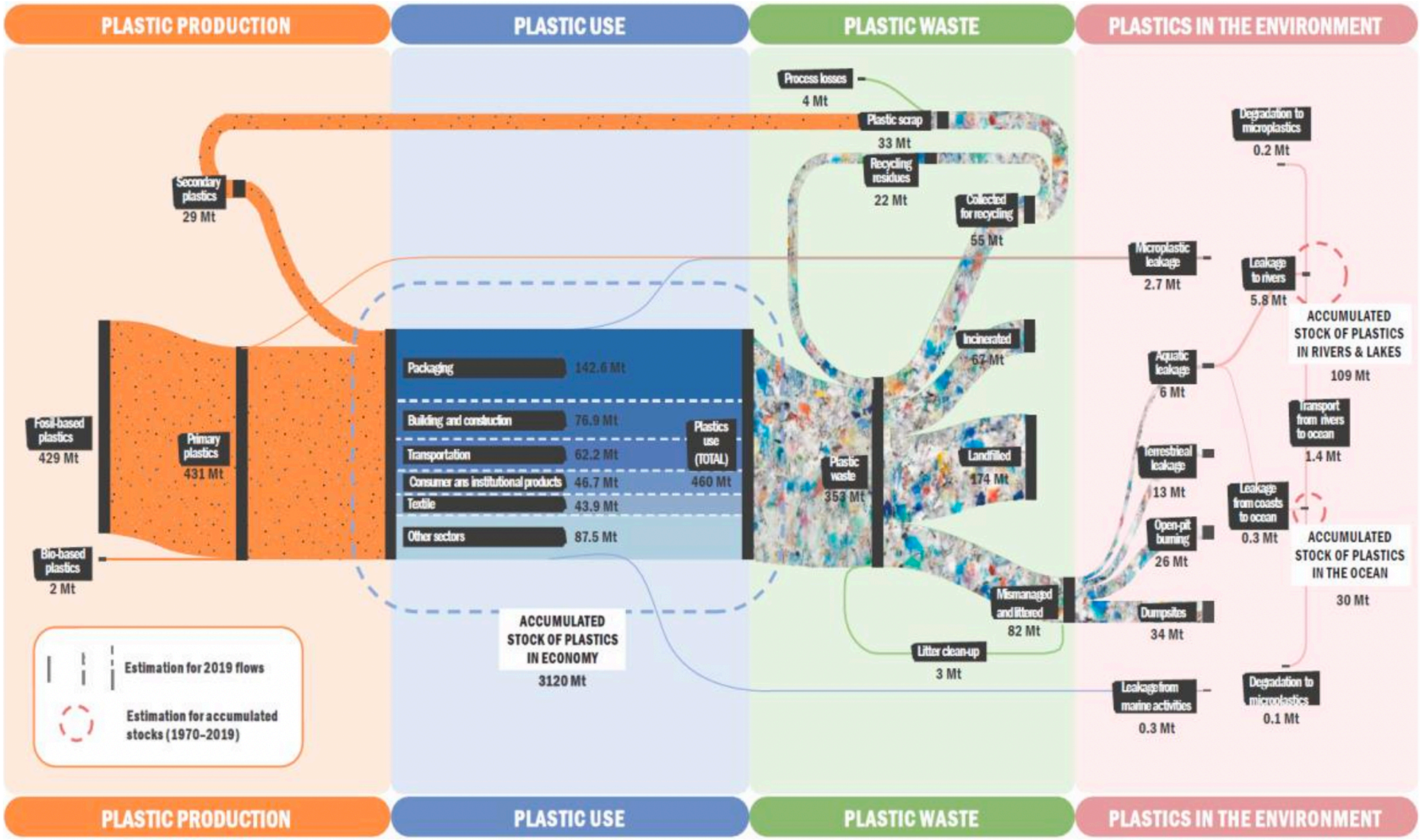
9.2 Bn tonnes of plastic manufactured since 1950, more than half of which has been produced since 2004. In 2020 alone 400m tonnes of plastic were manufactured. And this is projected to rise to 1,100 million [1.1Bn] tonnes per year by 2050.

4. Plastics :: Reuse & Recycling

it is estimated that about 5 800 million tonnes of plastics, representing 70 % of the total amount, have become waste, of which 84% or 4,900 million tonnes has been disposed of in landfills or in the environment

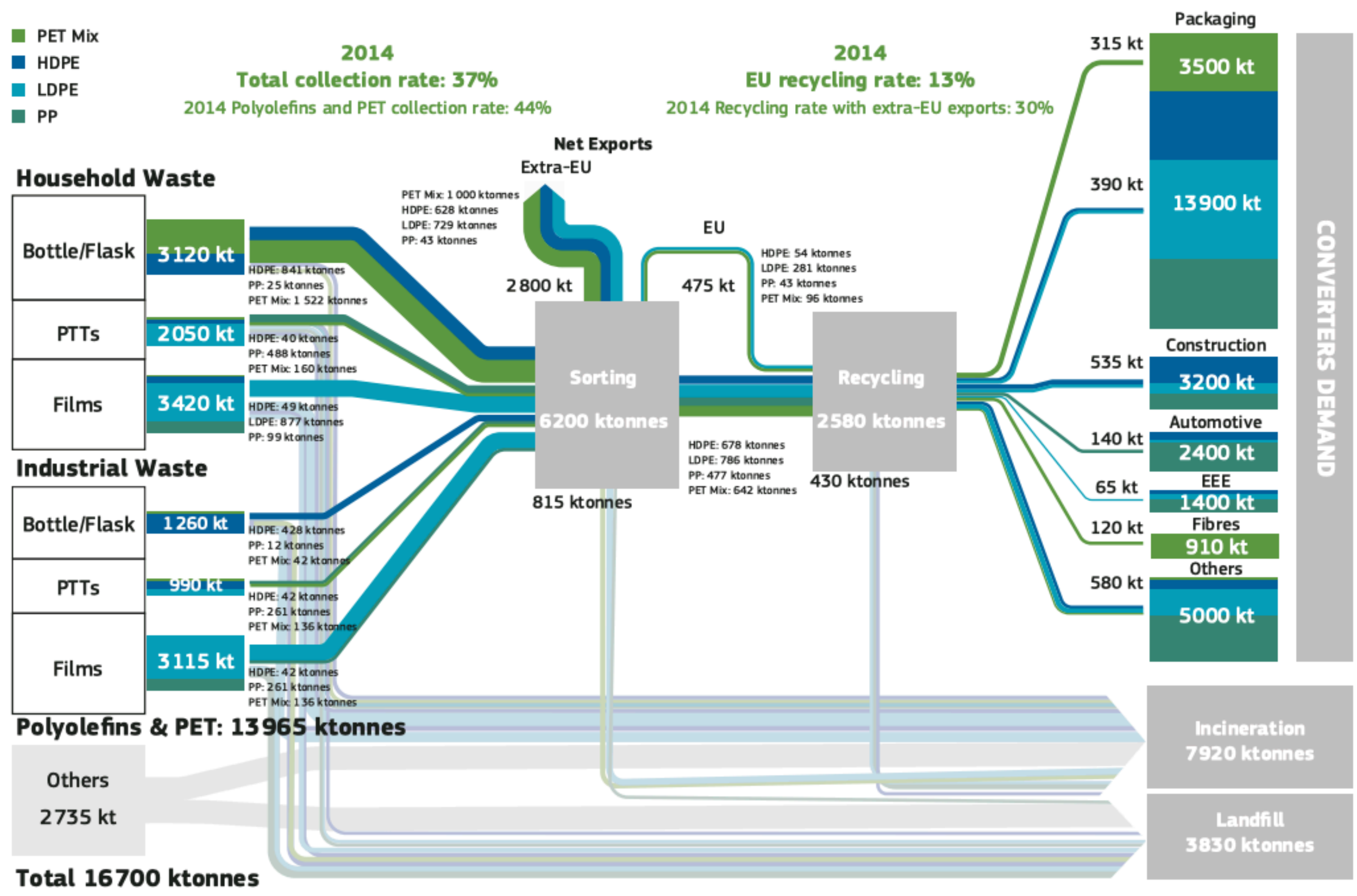
Global recycling rates are forecast to remain low over the coming decades, increasing from less than 9 per cent in 2019 (29 million metric tons), to 17 per cent in 2060 (176 million metric tons).   Global recycled (secondary) plastics are projected to make up 12 per cent of total plastics use in 2060, increasing from 6 per cent in 2019 [UNEP].

Global plastic streams



www.oecd-ilibrary.org/environment/global-plastics-outlook_de747aef-en

European plastic streams

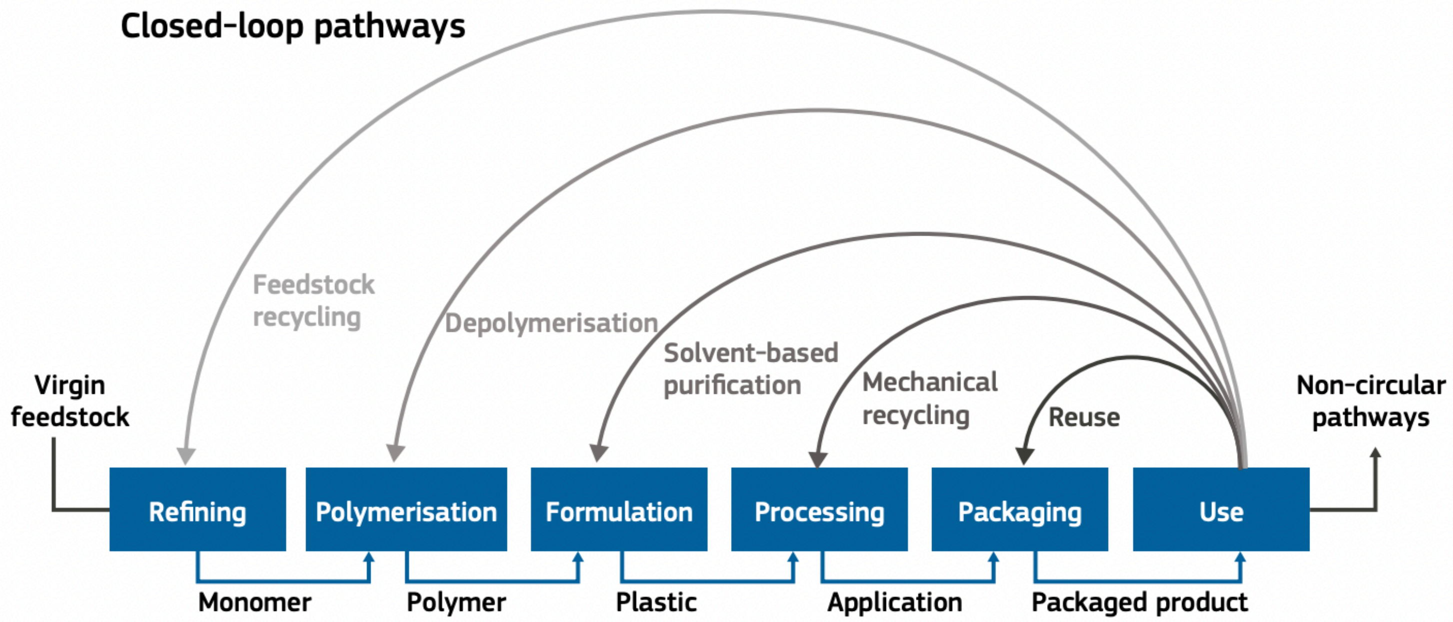


Source: Deloitte Sustainability, 2017

Figure 23: Overview of European plastics streams, 2014

Crippa, M. et al. (2019) p.125

Figure 24: Overview of different loops for plastics in a circular economy



Source: Drawing by Mats Linder

Crippa, M. et al. (2019) p.141

Mechanical, Chemical and Organic Recycling

Mechanical recycling is a robust and comparatively efficient way of reprocessing plastics into new resin that can be put back into the value chain [Crippa, M. (2019) §7].

Chemical Recycling (Crippa, M. (2019) §8) To realise the vision of an effective after-use plastics economy, significant improvement is needed in reprocessing methods for plastics so that they can remain in circular pathways. In line with the principles of a circular economy, 'inner loops' are more value preserving since they avoid the economic and environmental cost of breaking down and building up the material structure - 3 main types: solvent based purification, depolymerisation and feedstock recycling.

Organic recycling or biodegradation includes home and industrial composting, aerobic and anaerobic digestion.

Barriers to organic recycling

While biodegradable and compostable plastics have already been on the market for more than 25 years, a significant market breakthrough has not taken place yet. Information for citizens is limited, generic, and sometimes contradictory, misleading or false. For a good understanding it is important to note that a compostable plastic is more than just a biodegradable plastic, because besides ultimate and complete biodegradability it also entails timely disintegration and the absence of toxicity. As biodegradation depends on the specific environmental habitat, the environment should always be mentioned when making a claim about biodegradability. Because of the difference in properties, useful applications, and potential benefits and disadvantages, definitions must make a clear distinction between compostable plastics and environment-specific biodegradable plastics, as discussed in the above sections. Besides these nuances on environmental habitat, it is also important that standards on acceptance criteria for biodegradability should include requirements regarding environmental safety (chemical analyses and toxicity tests). [Crippa, M. et al. (2019) pp.159-161]:

It is a misunderstanding that biodegradable plastics offer a solution to the littering problem.

It is a misunderstanding that bio-based materials are inherently biodegradable (although PLA and PHA[1] are).

---

[1] PHA: Polyhydroxyalkanoates en.wikipedia.org/wiki/Polyhydroxyalkanoates

It is a misunderstanding that biodegradable plastics, by definition, contribute to the problem of microplastics in the environment. (Correct disposal, standards, specifications and communication about biodegradation should be clear and sufficiently stringent to illustrate and make sure that biodegradable plastics do not contribute to microplastics in the environment).

(some) recycling options by type

Thermoset plastics such as epoxy resins are **generally not recyclable**. They are hard and very durable plastics that are meant to be heat-resistant. Once the hardening process has taken place after mixing the two components together, it is irreversible, so it's virtually impossible to separate them again.

Fluoropolymers There is no industrial recycling facility for fluoropolymers anywhere in the world at the present time - and the problem is becoming ever more acute.

Polyolefins (polyethylene and polypropylene) can be chemically recycled by pyrolysis (cracking) or gasification.

As **polystyrene** is a plastic formed from styrene (a liquid hydrocarbon), it’s not recyclable. However, EPS can and should be recycled. It’s 98% air and only 2% plastic, which makes it possible to recycle. EPS can be reused for the manufacture of new poly boxes or compacted and turned into rigid plastic products.

Polyurethane can be recycled in one of two ways: either mechanically, in which it’s reused in its polymer form, or chemically, in which it’s broken back down into its chemical components. Common uses for recycled polyurethane include carpet padding, boards and mouldings that can be used in soundproofing and flooring, and even as raw material for new polyurethanes.

PVC can be recycled several times, thanks to its polymer structure that withstands mechanical stress during recycling operations while keeping its key physical properties. The feasibility of PVC recycling is demonstrated by increased quantities of recycled PVC – amounting to 731,461 tonnes in 2020 in Europe and 6.5 million tonnes in total over the past 20 years. Therefore, improving the scope of recycling technologies for PVC is important.

Today PVC end-of-life products are recycled mainly by mechanical recycling. New technologies for chemical (feedstock) recycling of mixed PVC wastes are under development.

5. Plastics :: Waste

Environmental plastics are materials containing synthetic polymers as an essential ingredient that are found in natural environments without fulfilling an intended function.' Environmental plastics can then be further classified according to origin, shape (beads, pellets, fragments, films, fibres), colour and size. The latter descriptor is used to differentiate between nano-plastics (< 1 µm), microplastics (< 5 mm), meso-plastics (< 2.5 cm), macro-plastics (< 1 m), and mega-plastics (> 1 m).

It is estimated that about 5 800 million tonnes of plastics, representing 70 % of the total amount, have become waste, of which 84% or 4 900 million tonnes has been disposed of in landfills or in the environment. Collectively the 23 coastal EU countries would rank 18th in a table of estimates of mismanaged waste.

The UK is responsible for 0.21% of global plastic waste [UNEP] and has the largest per capita plastic waste in Europe. UK supermarkets dispose of 800,000 tonnes of plastic annually

In 2021, approximately 2.5 million metric tons of plastic packaging waste was created by households in the United Kingdom - a small increase over the previous year. The UK recycling rate for waste in 2021 was 44%, down from 47% in 2020 [UNEP and Statista]

Ocean plastic

Around 20% of plastic in the ocean comes from human activities at sea – mostly fishing. In 2019, a Greenpeace report found that each year, 640,000 tonnes of "ghost gear" – abandoned, lost or discarded fishing equipment – enters the ocean and is left there. 9.4 million tonnes of plastics are expected to sink too the seabed each year. Accordingly, the seafloor will be an important hotspot of plastic pollution. [Greenpeace 2019]

The estimated cost of marine plastic pollution is US$19Bn covering only government spending, economic loss in fisheries and aquaculture and tourism in 87 (coastal) countries [Deloitte]. A 1 per cent decline in annual marine ecosystem services could equate to an annual loss of $500 billion in global ecosystem benefits [UNEP].

In 2019, plastics generated 1.8 billion metric tons of greenhouse gas emissions – 3.4 per cent of global emissions – with 90 per cent of those emissions coming from plastics production and conversion from fossil fuels [UNEP].

The inaugural meeting of the International Negotiating Committee on developing a global plastics treaty is taking place in Punta del Este, Uruguay, from 28 November to 2 December 2022.

6. Plastics :: Further Resources

a. Plastics

- Plastics Europe plasticseurope.org the plastics trade association in Europe
- Plastics Information Europe pieweb.plasteurope.com
- *The Eleven Most Important Types of Plastic* www.creativemechanisms.com/blog/eleven-most-important-plastics
- *Everything You Need to Know about Polylactic Acid [PLA]* www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes
- *Everything You Need to Know About Polypropylene Plastic (PP)* www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic
- *Everything You Need to Know About ABS Plastic* www.creativemechanisms.com/blog/everything-you-need-to-know-about-abs-plastic
- *Everything You Need to Know About PVC Plastic* www.creativemechanisms.com/blog/everything-you-need-to-know-about-pvc-plastic
- *Everything You Need to Know About the World's Most Useful Plastic (PET and Polyester)* www.creativemechanisms.com/blog/everything-about-polyethylene-terephthalate-pet-polyester
- *Everything You Need to Know about Polyhydroxyalkanoates (PHA)* www.creativemechanisms.com/blog/everything-you-need-to-know-about-pha-polyhydroxyalkanoates
- The Discovery of Nylon edu.rsc.org/download?ac=11184
- *Polyurethanes* www.polyurethanes.org/en & www.madehow.com/Volume-6/Polyurethane.html
    - toluene https://en.wikipedia.org/wiki/Toluene produced as a by-product from styrene manufacturing and from coke-oven operations
    - toluene di-isocyanate https://en.wikipedia.org/wiki/Toluene_diisocyanate

Bio-plastics

- European Bioplastics (2023) Bioplastics Market Data www.european-bioplastics.org/market
- Food Packaging Forum (2014) *Bioplastics: Types, applications, toxicity and regulation of bioplastics used in food contact materials.* www.foodpackagingforum.org/food-packaging-health/bioplastics
- Gotro, J. (2012) Do you know the three key aspects of bio-plastics? Polymer Innovation Blog: polymerinnovationblog.com/do-you-know-the-three-key-aspects-of-bioplastics

Other

- A range of resources on different plastics www.xometry.com/resources/materials
- Statista : www.statista.com/statistics/281126/global-plastics-production-share-of-various-countries-and-regions
- Plastic manufacturing by country - fun facts dolphinplastics.com.au/blog/plastic-manufacturing-country-fun-facts

- Top 100 Polymer Producers (2021) www.minderoo.org/plastic-waste-makers-index/pwmi-2021/data/indices/producers
- Marcos, J. & Marcos, J. (2017) *Modelling of Naphtha Cracking for Olefins Production;* www.semanticscholar.org/paper/Modelling-of-Naphtha-Cracking-for-Olefins-Marcos-Marcos/6d77b3af5c11b88c97c8c910b82628cab7885abd

b. Global controls

- EU (2023) Bio-based, biodegradable and compostable plastics. The EU's policy framework on the sourcing, labelling and use of bioibased plastics, and the use of biodegradable and compostable plastics. environment.ec.europa.eu/topics/plastics/biobased-biodegradable-and-compostable-plastics_en
- UN (2022) Fifth Session of the United Nations General Assembly, Nairobi. www.unep.org/environmentassembly/unea5

  - Approximately 7 billion of the 9.2 billion tonnes of plastic produced from 1950-2017 became plastic waste, ending up in landfills or dumped.
  - Includes the Resolution adopted by the United Nations Environment Assembly on 2 March 2022 (in Nairobi).
  - Includes the Marine Litter and Plastic Pollution Toolkit leap.unep.org/knowledge/toolkits/plastic

- UNEP (2022) **The first session of the INC to develop an international legally binding instrument on plastic pollution, including in the marine environment.** Punta del Este, Uruguay www.unep.org/events/conference/inter-governmental-negotiating-committee-meeting-inc-1. Inaugural meeting towards a legally binding instrument.
- UNEP (2022) *Draft decision on the draft provisional agenda of the second session of the intergovernmental negotiating committee to develop an international legally binding instrument on plastic pollution, including in the marine environment.* wedocs.unep.org/bitstream/handle/20.500.11822/41338/ProvisionalAgendaINC2E.pdf
- UNFCCC (2022) Plastic Promise? Oceans and Coastal Zones unfccc.int/blog/sea-change-0
- OECD (2022) *Global Plastics Outlook: economic drivers, environmental impacts and policy options*. www.oecd-ilibrary.org/environment/global-plastics-outlook_de747aef-en
- UNFCCC (2021) Sea Change. Oceans and Coastal Zones unfccc.int/blog/plastic-promise
- UNEA (2019) Resolution 4/9 addressing single use plastic pollution wedocs.unep.org/bitstream/handle/20.500.11822/28473/English.pdf
- UNEA (2019) Resolution 4/6 addressing marine plastic litter and microplastics wedocs.unep.org/bitstream/handle/20.500.11822/28471/English.pdf
- IPBES Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019) ipbes.net/sites/default/files/downloads/spm_unedited_advance_for_posting_htn.pdf

c. Science

- UNEP (2022) Plastics Science *UNEP/PP/INC.1/7* wedocs.unep.org/bitstream/handle/20.500.11822/41263/Plastic_Science_E.pdf
- Ford, H.V. et al (2022) The fundamental links between climate change and marine plastic pollution. *Science of the Total Environment* . 806 (1) doi.org/10.1016/j.scitotenv.2021.150392

d. Impact

- Zheng, J. & Suh, S. (2019) Strategies to reduce the global carbon footprint of plastics. *Nat. Clim. Change*. 9, 374-378 doi.org/10.1038/s41558-019-0459-z
- Centre for International Environmental Law (CIEL) Fossil Fuels & Plastics www.ciel.org/issue/fossil-fuels-plastic
- CIEL (2019) *Plastic & Climate : The Hidden Costs of a Plastic Planet* www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf
- ClientEarth: *Plastics: A Carbon Copy of the Climate Crisis* www.clientearth.org/latest/latest-updates/stories/plastics-a-carbon-copy-of-the-climate-crisis

By 2050, the [cumulative] greenhouse gas emissions from plastic could reach over 56 gigatonnes – 10-13 percent of the entire remaining carbon budget", wrote the Centre for International Environmental Law (CIEL), in their "Plastic and Climate" report of 2019. By 2050, the emissions from the lifecycle of plastics could be equivalent to 615 large coal-fired power stations - 2.8 gigatonnes of CO2 per year.

- Canada's National Observer Investigation (2021) www.nationalobserver.com/2021/03/10/canadas-east-coast-researchers-look-plastic-and-new-way-do-science
- OnlyOne (2022) *My blood tested positive for plastic and now I want answers - and action*. www.only.one/read/my-blood-tested-positive-for-plastic-now-i-want-answers-and-action
- Natural History Museum (2017) *Just How Bad is the World's Plastic Problem* www.nhm.ac.uk/discover/the-plastic-problem.html
- HuffPost (2014) *Plastiglomerate: The New & Horrible Way Humans are Leaving their Mark on the Planet* www.huffpost.com/entry/plastiglomerate_n_5496062

Fossil Record

- The Guardian (2019) *After bronze and iron, welcome to the plastic age, say scientists* www.theguardian.com/environment/2019/sep/04/plastic-pollution-fossil-record
- EarthSky (2019) *Plastic pollution has entered fossil record, says study* earthsky.org/earth/plastic-pollution-fossil-record

- Global CO_2 emissions ourworldindata.org/co2-emissions

e. Recycling and Reuse

- Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. (2019) *A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions*, M. De Smet & M. Linder (Eds.), European Commission, Brussels, Belgium; available at www.hbm4eu.eu/wp-content/uploads/2019/03/2019_RI_Report_A-circular-economy-for-plastics.pdf
- BBC (2018) *Why Plastic Waste Recycling is So Difficult;* www.bbc.co.uk/news/science-environment-45496884
- Race to Zero (2022) 2030 Breakthrough Agenda [COP27] www.racetozero.unfccc.int/system/breakthroughs
- Verra Plastic Waste Reduction Standard (for recycling, reuse) https://verra.org/programs/plastic-waste-reduction-standard

Recycling specific plastics:

- Fluoropolymers www.chemanager-online.com/en/topics/chemicals-distribution/new-process-recycling-fluoropolymers
- Polystyrene: www.businesswaste.co.uk/plastic-recycling/is-polystyrene-recyclable
- Epoxy / silicon resins coolmag.net/recycling-epoxy-silicon-resins
- EEA (2020) *Biodegradable and compostable plastics — challenges and opportunities*; www.eea.europa.eu/publications/biodegradable-and-compostable-plastics

f. Waste and Pollution (including marine pollution)

- Greenpeace (2019) *Ghost Gear: the abandoned fishing nets haunting our oceans* www.greenpeace.de/sites/default/files/publications/20190611-greenpeace-report-ghost-fishing-ghost-gear-deutsch.pdf
- UNEP *Our Planet is Choking on Plastic*: www.unep.org/interactives/beat-plastic-pollution
- UNEP (2021) *Drowning in Plastics Marine Litter & Plastic Waste*: wedocs.unep.org/bitstream/handle/20.500.11822/36989/VITGRAPH_ES.pdf
- International Union for the Conservation of Nature (2021) *Marine Plastic Pollution* www.iucn.org/resources/issues-brief/marine-plastic-pollution
- Statista (2021) *Plastic waste in the UK* www.statista.com/topics/4918/plastic-waste-in-the-united-kingdom-uk and plastic waste in Europe www.statista.com/topics/5141/plastic-waste-in-europe
- Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L. and Suh, S. (2020) Degradation Rates of Plastic in the Environment. *ACS Sustainable Chemistry* 8, 3494-3511.
- Petten, L. et al. (2020) *Marine Plastic Pollution.* Deloitte; www2.deloitte.com/uk/en/insights/topics/strategy/marine-plastic-pollution.html
- *The Ocean Cleanup : the price tag of plastic pollution;* theoceancleanup.com/the-price-tag-of-plastic-pollution
- National Geographic (2019) *The World's Plastic Pollution Crisis Explained* www.nationalgeographic.com/environment/article/plastic-pollution

- Minderoo Foundation *Sea The Future* www.minderoo.org/no-plastic-waste
- Plastic pollution (UK) www.greenpeace.org.uk/challenges/plastic-pollution
- Marine Litter : *AWI Litterbase* litterbase.awi.de
- UN Environment Programme www.unep.org/interactives/beat-plastic-pollution .
- Oceans' plastics plasticoceans.org

g. Technology will save us (*maybe*)

- Prof. Kimura and *Ideonella sakaiensis* a PET-eating enzyme
  - Medium (2018) *2050 : A World without plastic* medium.com/age-of-awareness/2050-a-world-without-plastic-4acc3ac81892
  - The Conversation (2016) New Plastic Munching Bacteria could Fuel a Recycling Revolution theconversation.com/new-plastic-munching-bacteria-could-fuel-a-recycling-revolution-55961

- WRAP International Circular Plastics Flagship Competition. Funding new innovations to tackle plastic pollution in India, Chile, South Africa and Kenya wrap.org.uk/what-we-do/our-services/grants-and-investments/international-circular-plastics-flagship-competition

h. (Some) Exhibit information sources

Exhibit 6

- Geological time:
  - en.wikipedia.org/wiki/International_Commission_on_Stratigraphy
  - en.wikipedia.org/wiki/Geologic_time_scale

- Håkon Mosby vulcano:
  - www.mindat.org/maps.php?id=208360 | Tromsø 69.6492° N, 18.9553° E
  - cage.uit.no/2015/01/19/scientists-intrigued-by-a-unique-volcano-on-the-ocean-floor
  - www.uib.no/en/geobio/56662/haakon-mosby-mud-volcano

Exhibit 8

- Gulf stream collapse: www.theguardian.com/environment/2021/aug/05/climate-crisis-scientists-spot-warning-signs-of-gulf-stream-collapse
- East Greenland currents: en.wikipedia.org/wiki/East_Greenland_Current

- Norse traditions
  - www.smithsonianmag.com/history/why-greenland-vikings-vanished-180962119
  - en.wikipedia.org/wiki/Valkyrie

Exhibit 9

- Submarine cables:
  - www.submarinecablemap.com
  - www2.telegeography.com/submarine-cable-faqs-frequently-asked-questions
  - Shanghai landing: www.submarinecablemap.com/submarine-cable/seamewe-3
  - Scotland-Ireland www.submarinecablemap.com/submarine-cable/scotland-northern-ireland-3 [42km Donaghadee - Port Patrick]
  - Manufacturing subsea cables www.jdrcables.com/manufacturing-subsea-cable
  - Subsea composite cables www.subsea-composite-cables.com and www.subsea-composite-cables.com/pdf/subsea-fibre-optic-composite-cables/subsea-fibre-optic-cables-HS-SK813.pdf
  - Quintis Fibre Optic Cable specifications, applications etc. mh-fiberoptics.com/sites/default/files/downloads/quintis_fiber_optic_cable_v2.pdf

- Fibre communications:
  - Fibre optic communication en.wikipedia.org/wiki/Fiber-optic_communication
  - NANOG77 *Everything you always wanted to know about Optical* Richard Steenbergen www.youtube.com/watch?v=nKeZaNwPKPo
  - Optical Fibre Capacity Limits - where do we go next? www.youtube.com/watch?v=prC-1lZ_wdk&t=549s

- Quantum networks:
  - Quantum entanglement in Optical Fiber www.optica-opn.org/home/articles/volume_19/issue_3/features/quantum_entanglement_in_optical_fiber
  - Quantum networks: en.wikipedia.org/wiki/Quantum_network
  - What is a quantum network? www.symmetrymagazine.org/article/what-is-a-quantum-network
  - Envisioning quantum networks pie.org/news/photonics-focus/novdec-2022/envisioning-quantum-networks
  - Quantum teleportation: en.wikipedia.org/wiki/Quantum_teleportation

    One of the first scientific articles to investigate quantum teleportation is *Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels* published by C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters in 1993, in which they proposed using dual communication methods to send/receive quantum information. It was experimentally realised in 1997 by two research groups, led by Sandu Popescu and Anton Zeilinger, respectively.