EPFL

Plastics

MSE-433 Towards Sustainable Materials

Yves Leterrier, Martyn Wakeman
Spring 2025

Plastics

- Mr. McGuire: I just want to say one word to you - just one word.
- Ben: Yes sir.
- Mr. McGuire: Are you listening?
- Ben: Yes I am.
- Mr. McGuire: 'Plastics.'
- Ben: Exactly how do you mean?
- Mr. McGuire: There's a great future in plastics. Think about it. Will you think about it?
- Ben: Yes I will.
- Mr. McGuire: Shh! Enough said. That's a deal.

(The graduate, 1967)

slido

Please download and install the Slido app on all computers you use

What do you think about bioplastics?

ⓘ Start presenting to display the poll results on this slide.

Learning objectives

- What are plastics, their growth and global environmental impact
- How to create a circular plastics economy

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Outline

1. Plastics history, global production and impact
2. What are plastics
3. Roadmap towards sustainable plastics
4. Summary
5. Appendix

Historical perspective

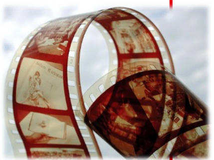
Pre-historic times
Wood, Bone (collagen), amber, horn, tortoise shell

-1600 Rubber from latex and Ipomoea alba

1847 Polyester resins

1862 Parkesine from plant cellulose

1870 Celluloïd



1907 Bakelite

1926 PVC

1930 Polystyrene (Styrofoam®)

Epoxy resins

1935 polyamide (Nylon®)

1938 PTFE (Teflon®)

1939 LDPE

1940 Silicone

1941 melamine-formaldehyde (Formica®)

1947 Polyamide 11 (Rilsan®)

1949 PET (Mylar®)

1953 HDPE & PC

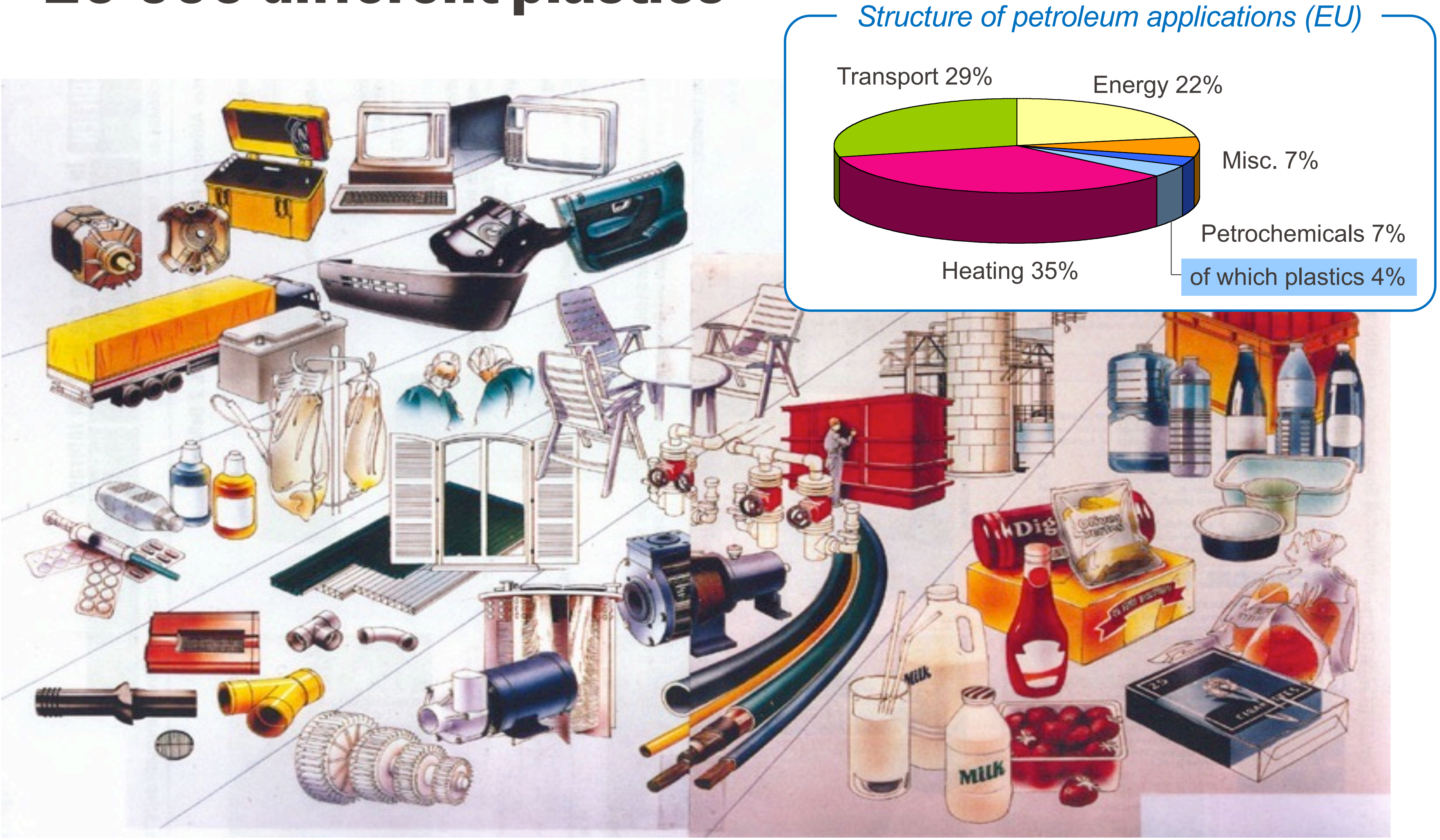
1954 Polypropylene

1990s Bioplastics (PLA, PHAs, and plasticized starches)

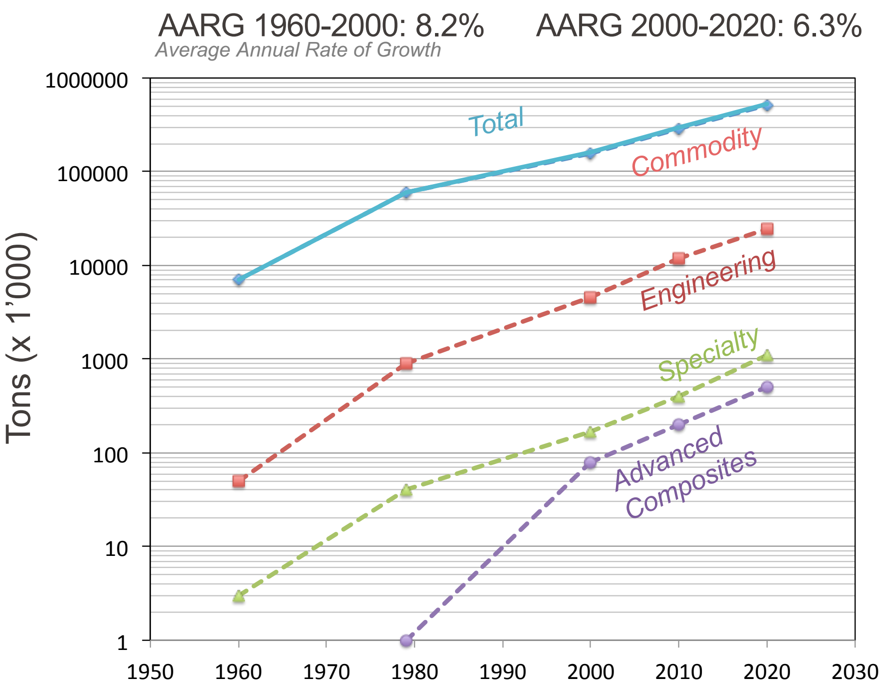
https://www.made-in-china.com/products-search/hot-china-products/HDPE_Bag.html
https://www.acmeplastics.com/what-is-hdpe
https://www.nonoilen.com/
https://www.carpartstuning.com/front-bumper-suitable-for-mercedes-e-class-w213-s213-c238-a238-facelift-2020-up-e63-design/6000940-3/
https://www.modelrckitsails.com/
https://www.mesdepanneurs.fr/blog/peindre-formica
https://www.esska-tech.co.uk/shop/Superflex-RTV-silicone-W-321-310-ml-white--9290WK321300-22430

https://www.carbiolice.com/en/news/the-history-of-plastic-in-15-key-dates-2/
https://www.metmuseum.org/essays/the-mesoamerican-ballgame
https://wmuzeach.pl/all-objects/3NhC7JutWcfYhkTejqih_amber-figurine-of-a-bear-from-slupsk-/0
https://www.modip.ac.uk/artefact/bnsl-bar-119
https://www.planet-wissen.de/technik/werkstoffe/kunststoff/pwiebakeliturstoffdermodernenalltagskultur100.html
https://www.u-buy.ch/en/product/34HF72E-foam-rectangle-blank-polystyrene-sheet-boards-for-arts-and-crafts-blank-white-diy-project-party-decorations-16-x-11-x-2-inches-3
https://www.militarytimes.com/off-duty/military-culture/2023/11/01/its-raining-men-meet-the-man-behind-the-militarys-parachutes/

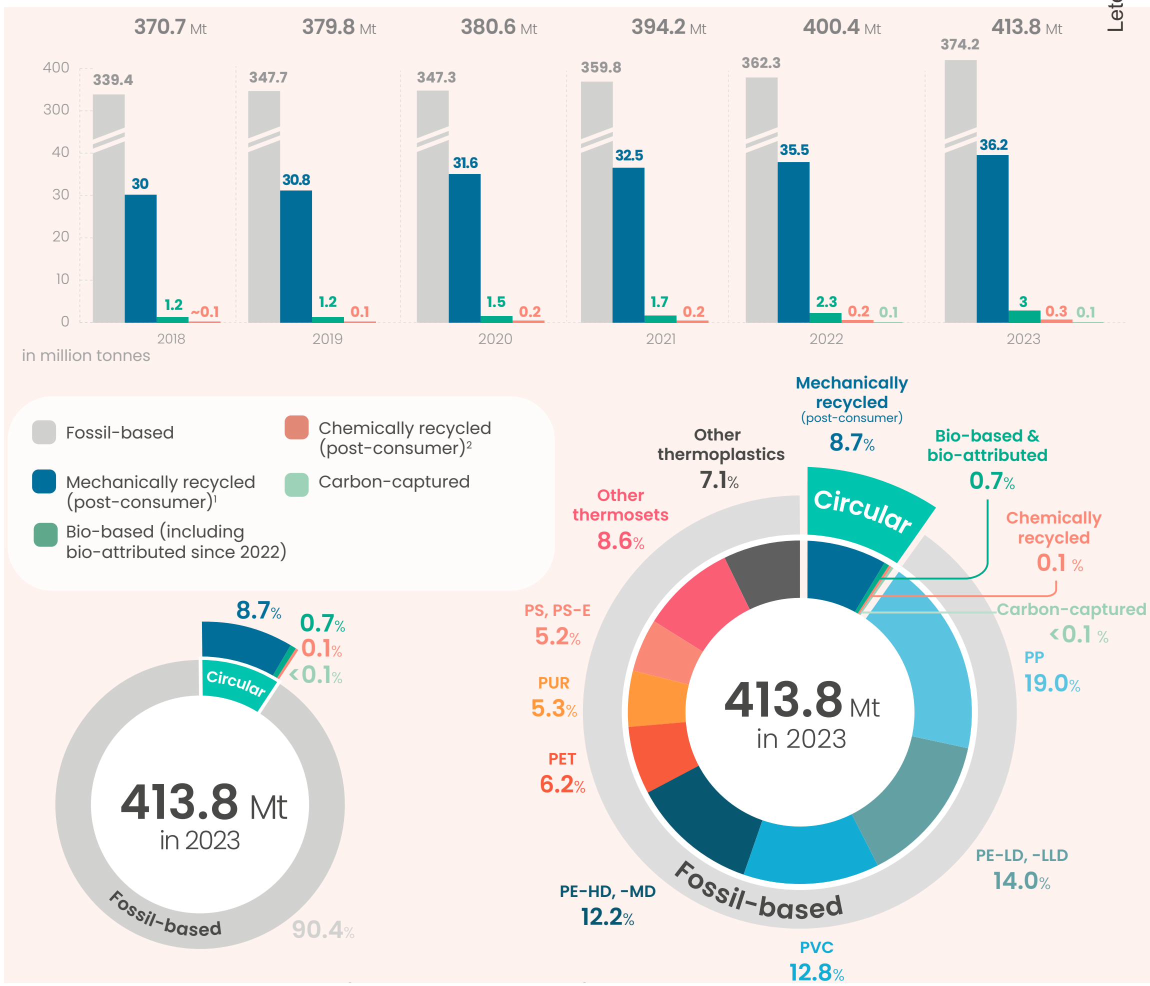
20'000 different plastics



Global plastic production and accumulation



Courtesy Pardos Marketing



https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2024/

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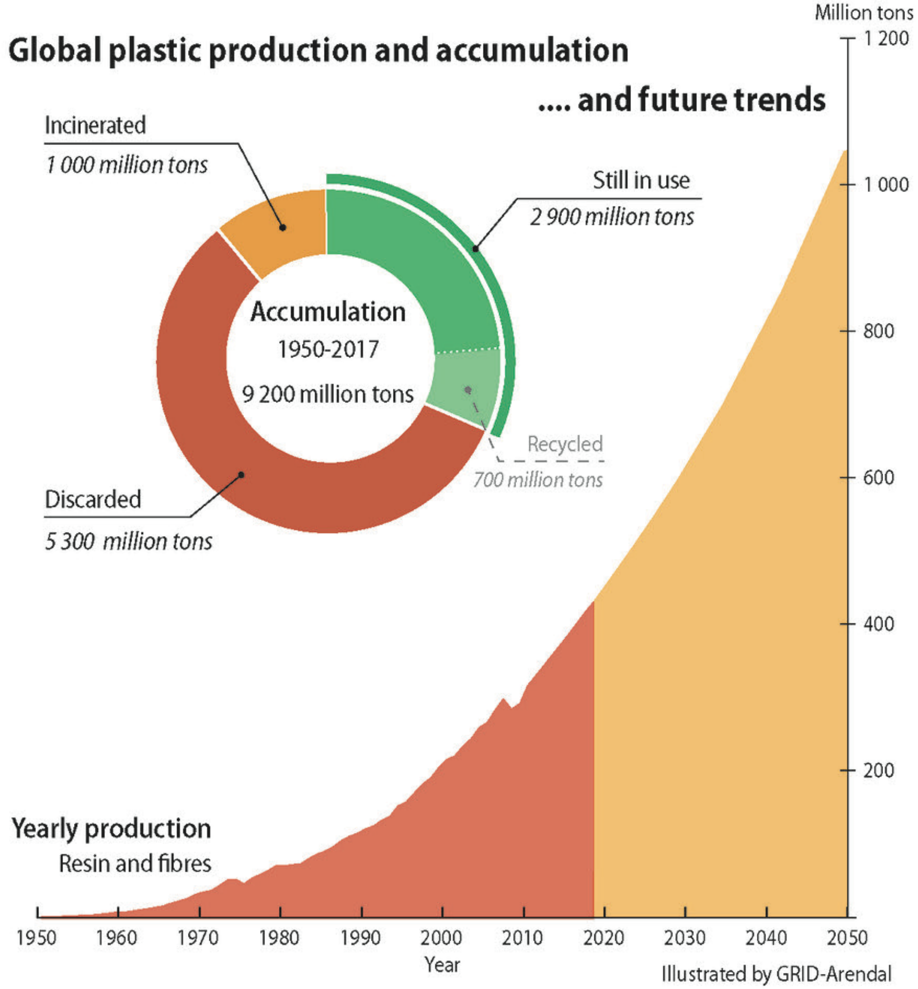
Global plastic production and accumulation

- Global cumulative production of plastics since 1950 is forecast to grow from 9.2 billion tons in 2017 to 34 billion tons by 2050.
- Therefore, it is urgent to “turn off the tap” in regard to the production of virgin plastics, reduce the volumes of uncontrolled or mismanaged waste entering the oceans, and increase the level of plastic waste recycling, currently estimated at less than 10%.

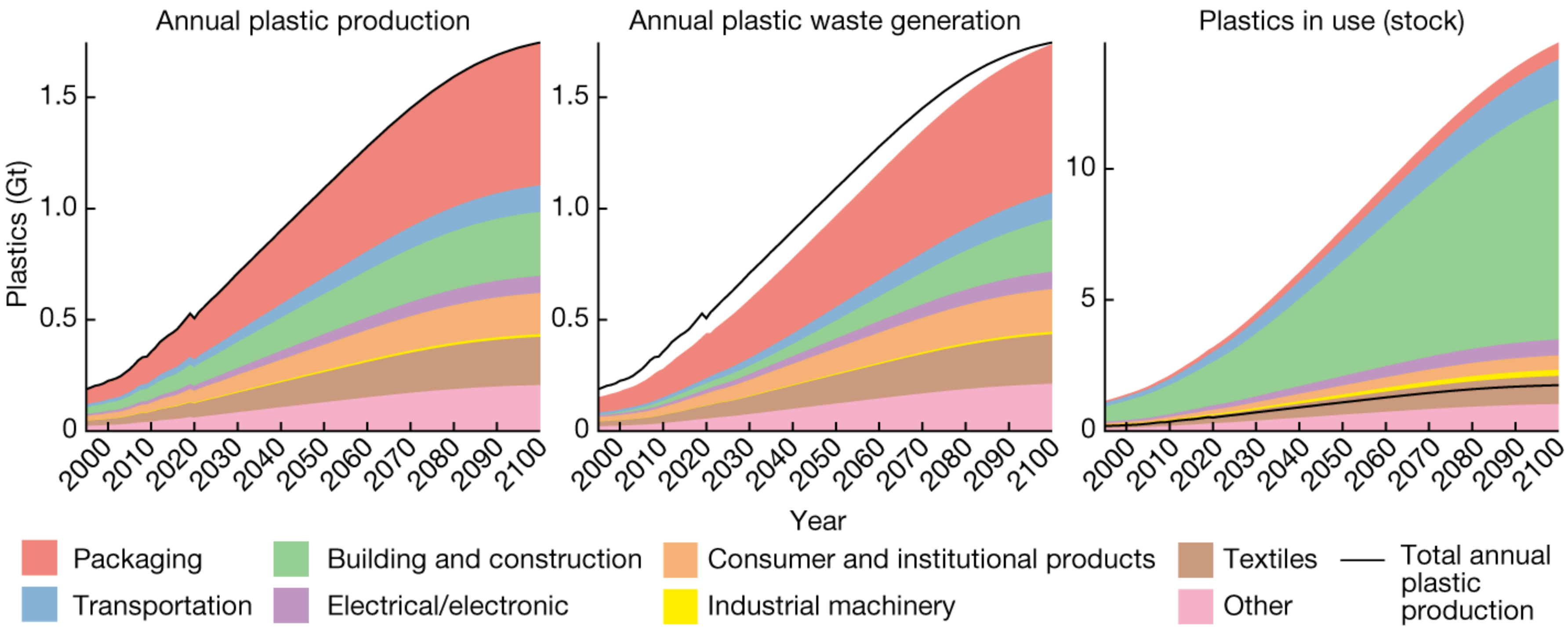


UNEP (2021). From Pollution to Solution: A global assessment of marine litter and plastic pollution. Nairobi.

Geyer, R. (2020). Production, use and fate of synthetic polymers in plastic waste and recycling. In Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions. Letcher, T.M. (ed.). Cambridge, MA: Academic Press.13-32.

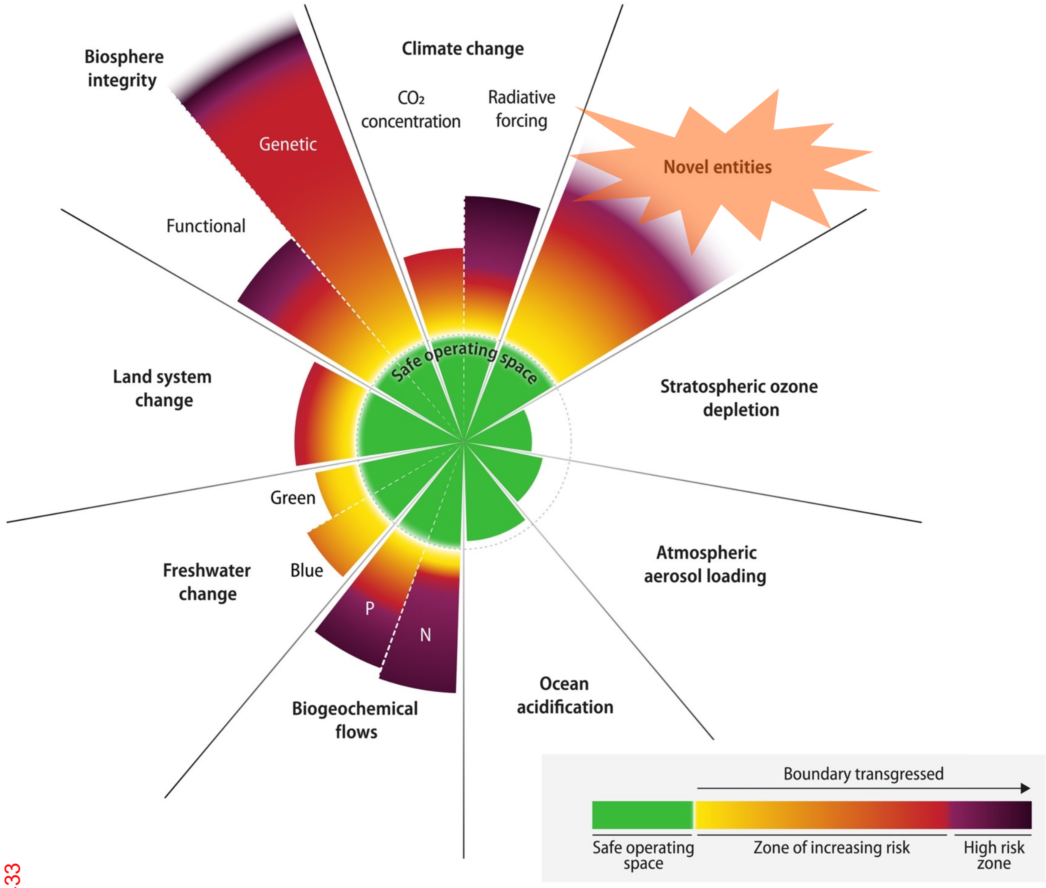
Global plastic production and accumulation

Projections of global plastic production, waste generation and plastic stocks in use, by sector (SSP2)

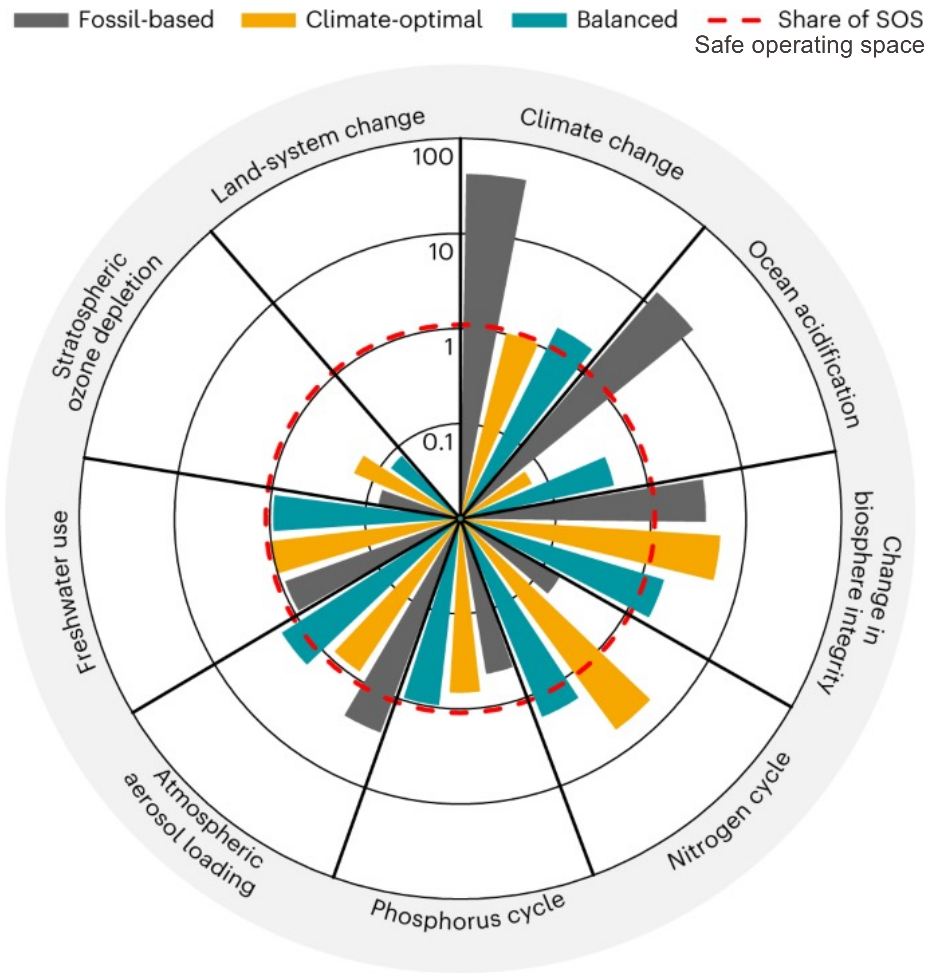


Stegmann et al., Nature, 612 (2022)

Plastics (novel entities) have a huge impact



Richardson *et al.*, *Sci. Adv.* **9**, eadh2458 (2023)



Bachman et al., Nature Sustainability volume 6, pages 599–610 (2023)

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Plastics are energy intensive materials!

Material	Energy intensity [MJ/kg]
Steel	31.9
aluminium (primary)	189
aluminium (secondary)	18.6
Concrete	0.89
Cement	5.04
Construction wood	1.94
Synthetic rubber	109
Cardboard	15.0
Ceramics	7.15
Copper	108
Polyurethanne foam	114
Paper	20.4
PEHD	83.5
PELD	95.3
PET	119
Platinium	201'000
Polycarbonate (PC)	126
Polypropylene (PP)	101
Polystyrene (high impact)	96.2
PVC	89.9

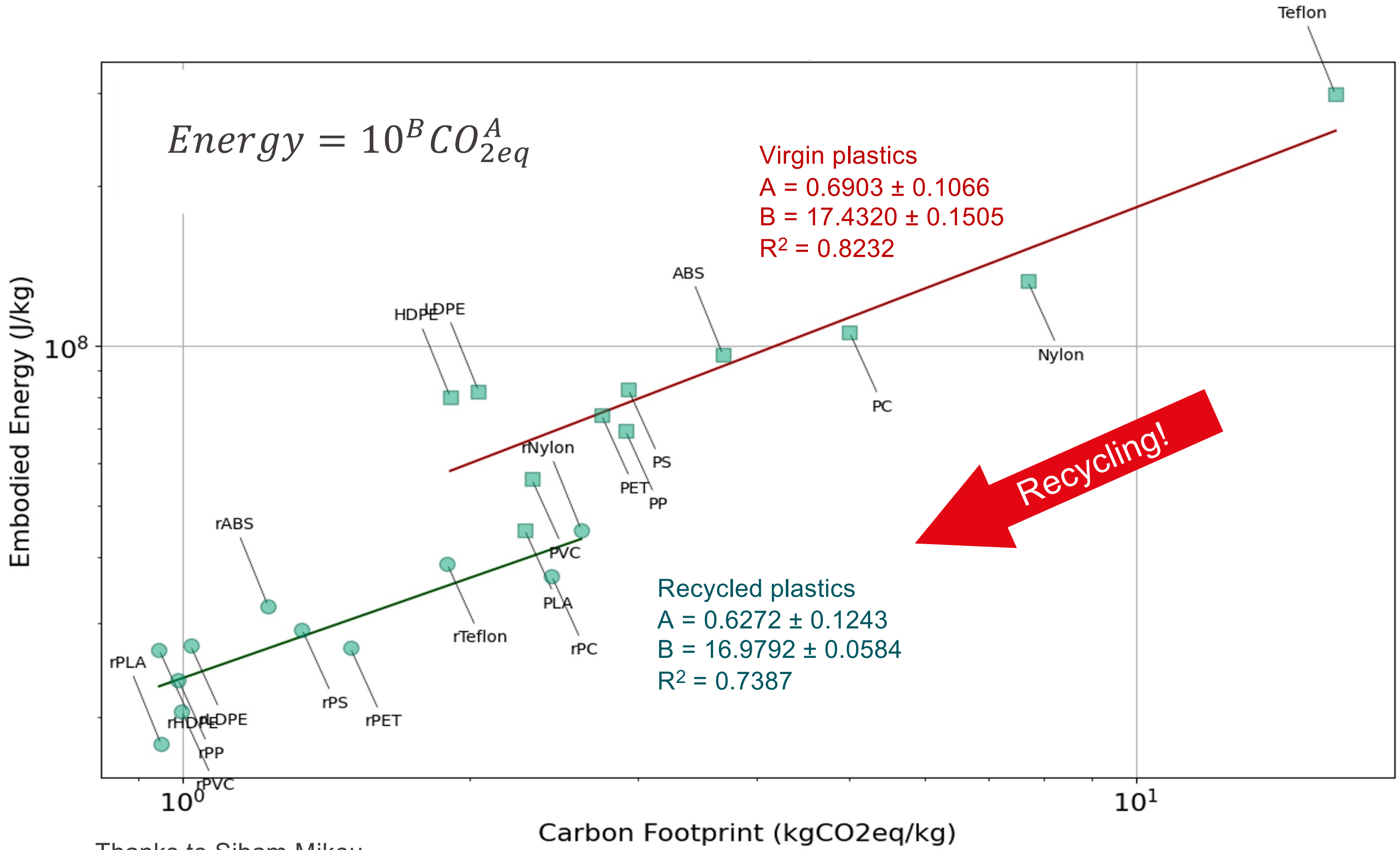
Ecoinvent

Energy intensity of plastic processing methods

Plastic processing type	Energy intensity [MJ/kg]
Injection molding	11.2
Pipe and profile extrusion	5.42
Film extrusion	4.85
Thermoforming	22.2
Rotational moulding	21.0
Compressional moulding	11.4
Fiber extrusion	3.06
Compounding	2.27

Sarswatula et al., Front. Manuf. Technol. 2022

Plastics are energy intensive materials!



Thanks to Siham Mikou

Global carbon balance of plastics during the XXI century

- The four most greenhouse gases polluting industries are iron, steel, cement and plastics.
- These industries are responsible for 66% of the total industrial CO2e emissions.
- However, due to the steeper increase of plastic consumption, the plastic sector is also expected to present the largest growth of CO_2 emissions in the forthcoming years.

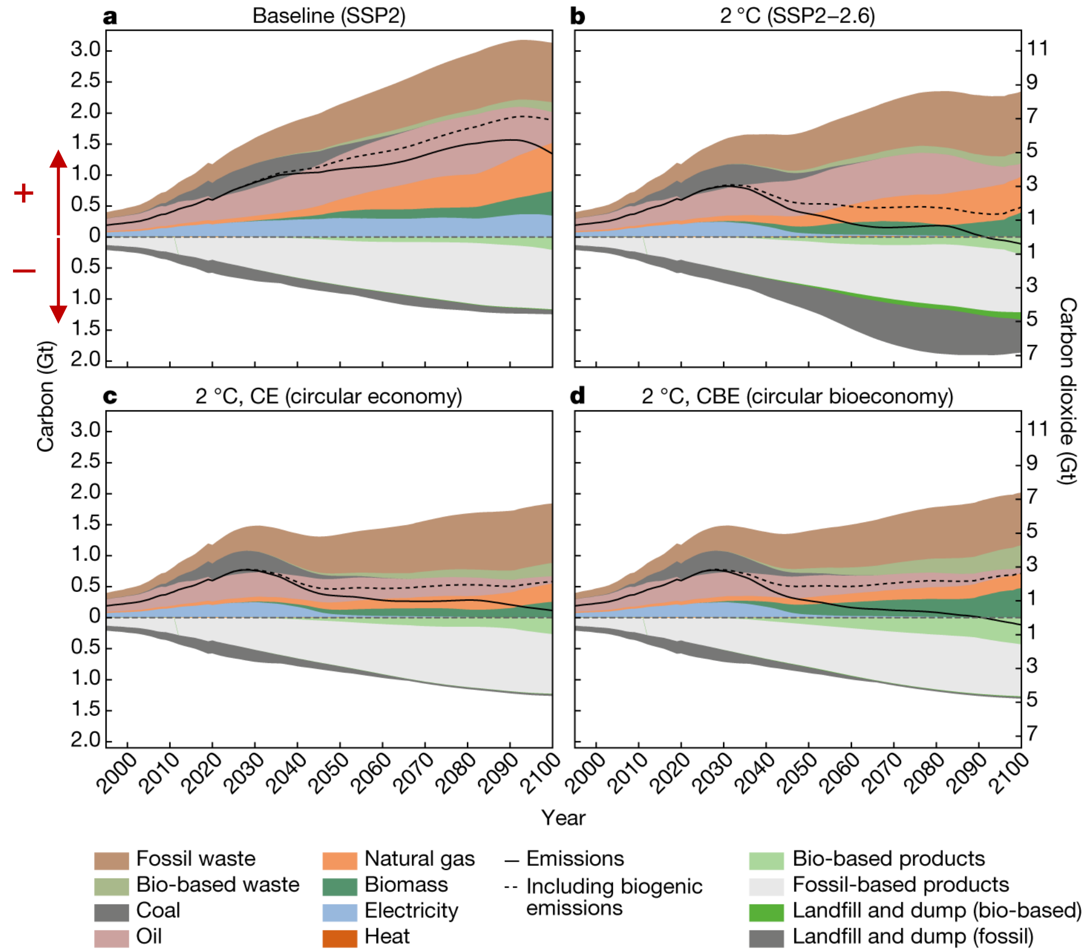
Pires da Mata Costa et al., Processes 9, 759, 2021
IEA The Future of Petrochemicals https://www.iea.org/reports/the-future-of-petrochemicals
Gutowski et al., Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 2013, 371, 20120003
Sinha, Chaturvedi, Renew. Sustain. Energy Rev. 2019, 114, 109304
North, Styring, Faraday Discuss. 2015, 183, 489–502
Griffin et al., Energy Procedia 2017, 105, 4347–4356

Global carbon balance of plastics during the XXI century

+ plastic production and waste (recycled, incinerated, landfilled, lost)

– all carbon additions to plastic product stocks, landfills and dumps

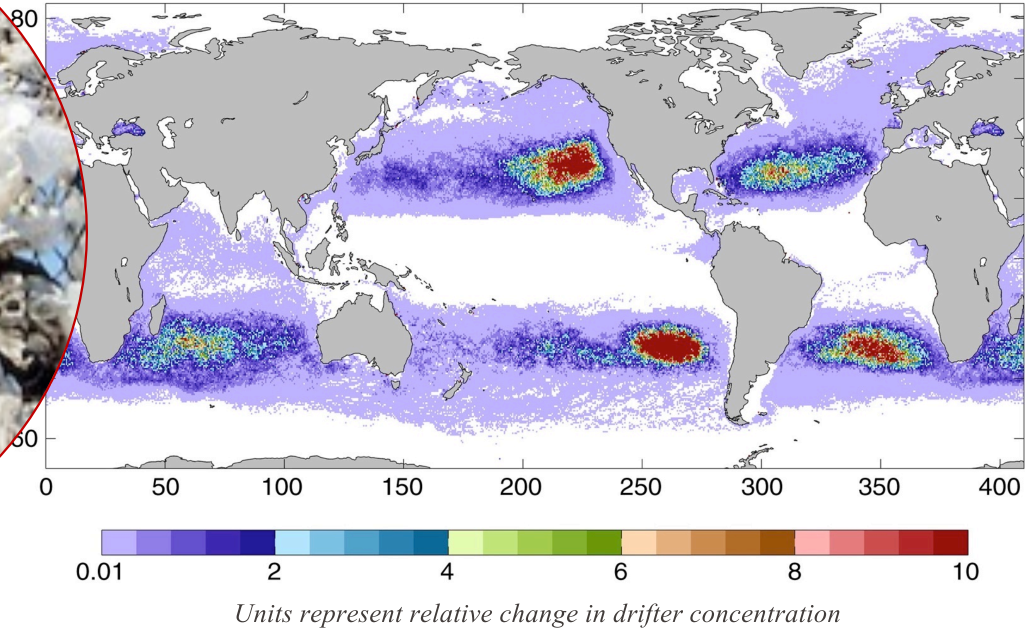
Black solid lines represent net emission balance, with and without biogenic emissions



Stegmann et al., Nature, 612 (2022)

Plastics are a disaster

Xavier Delaporte



Dohan and Maximenko, *Oceanography* (2010)
http://oceanmotion.org/html/impact/garbagepatch.htm

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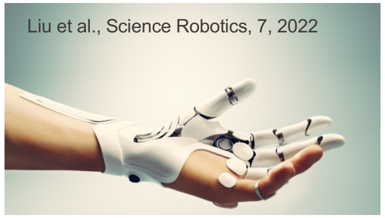
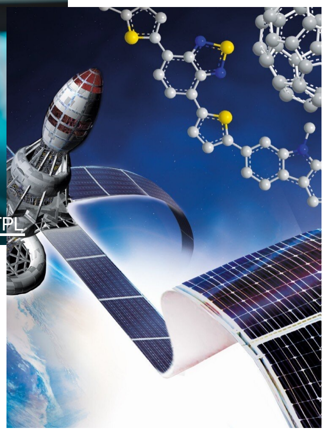
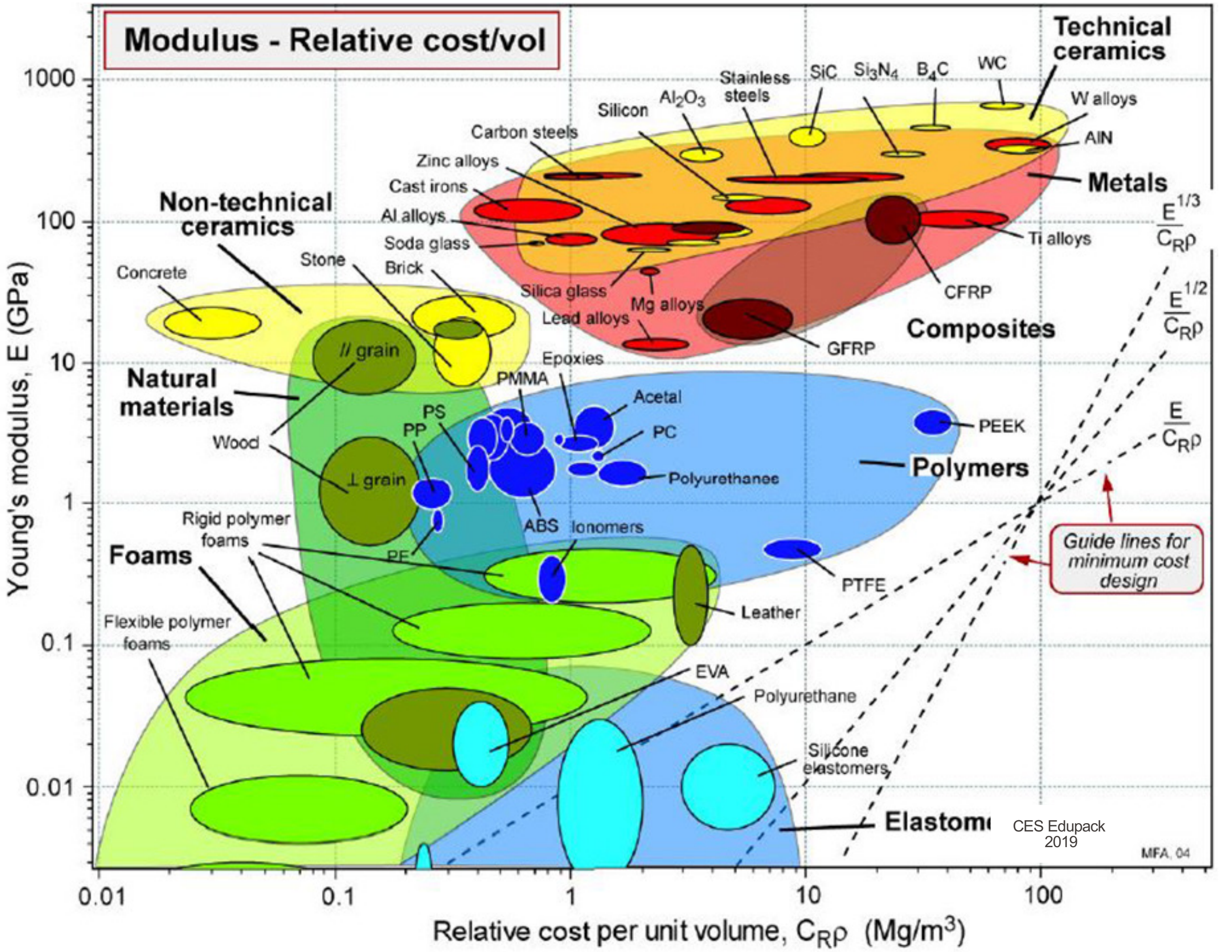
Plastics are cost-effective high-tech materials





https://phys.org/news/2019-07-solar-cells-years-space.html

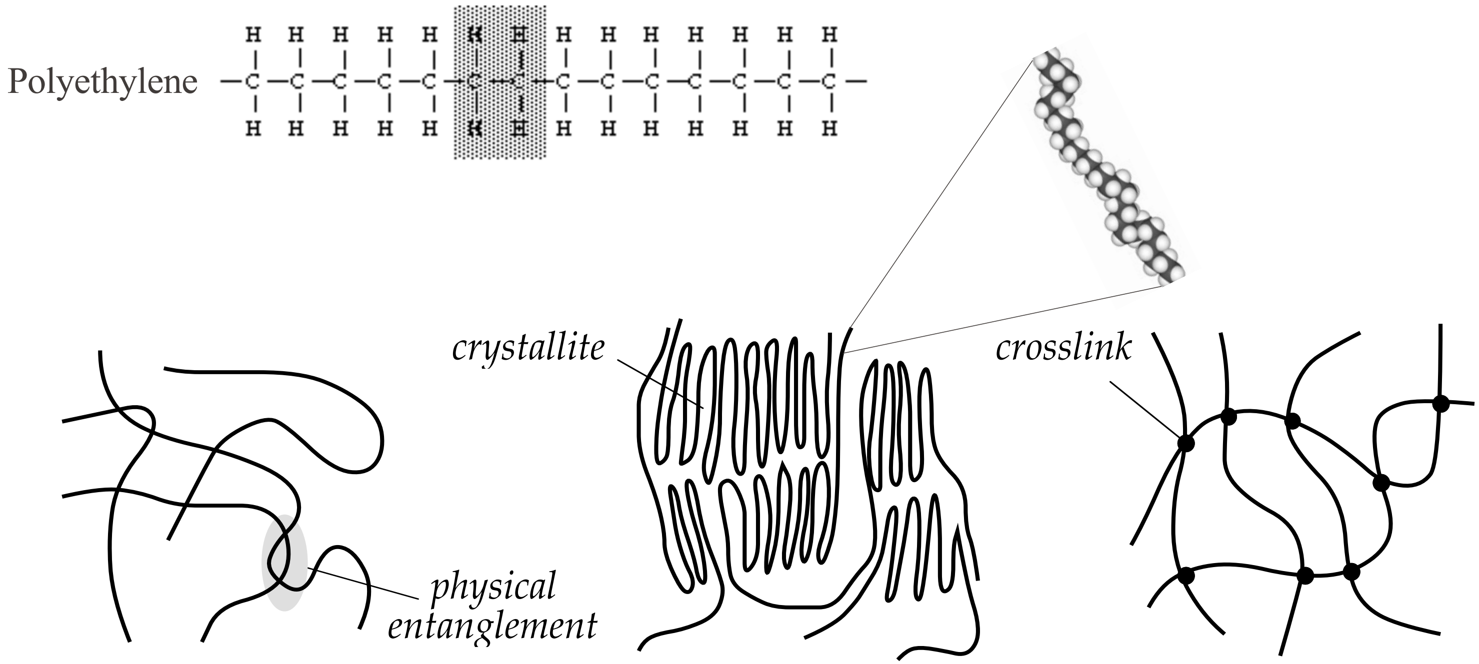


$C_R\rho$ = (cost/kg x density of material) / (cost/kg* x density of mild steel rod) (*) 0.3 USD/kg

Plastic = polymer(s) + additives

Adhesion promoters
Antifogging agents
Antimicrobial agents
Antioxidants
Antistatic agents
Carbon blacks and graphite
Catalysts, peroxide
Catalysts, urethane
Chelating agents
Chemical and physical blowing agents
Colorants and coloring aids
Coupling agents and compatibilizers
Crosslinking agents
Emulsifiers
Flame retardants
Heat stabilizers
Impact modifiers
Lubricants, mold release agents and processing aids
Metallizing agents
Nucleating agents
Optical brighteners
Pigments and masterbatch dispersing agents
Plasticizers
Reactive additives
Slip agents
Smoke suppressants
Specialty monomers
Surface active agents
Tack, antiblock and flatting additives
Thixotropic thickeners
UV light stabilizers
Viscosity suppressants

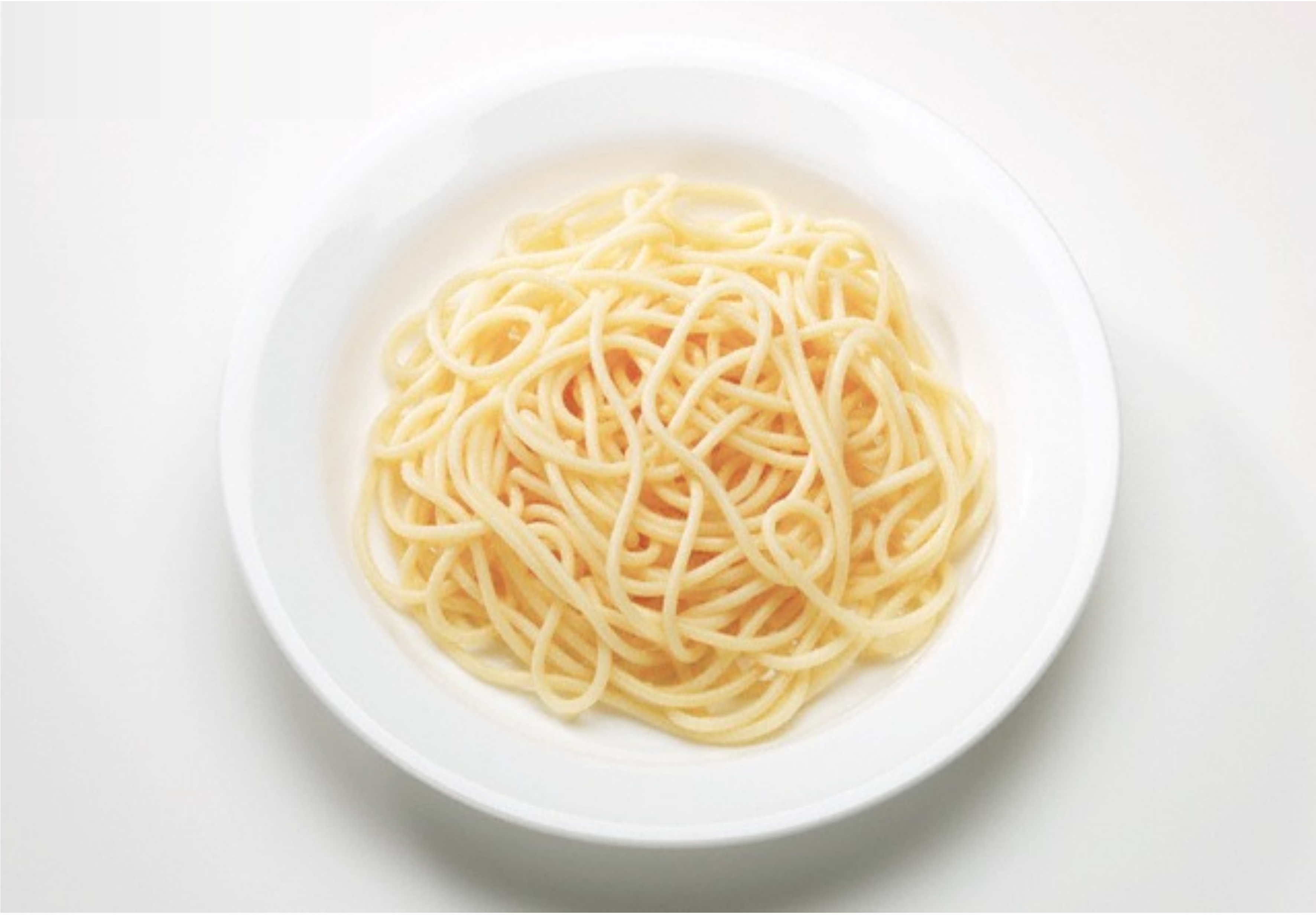
Polymer configuration



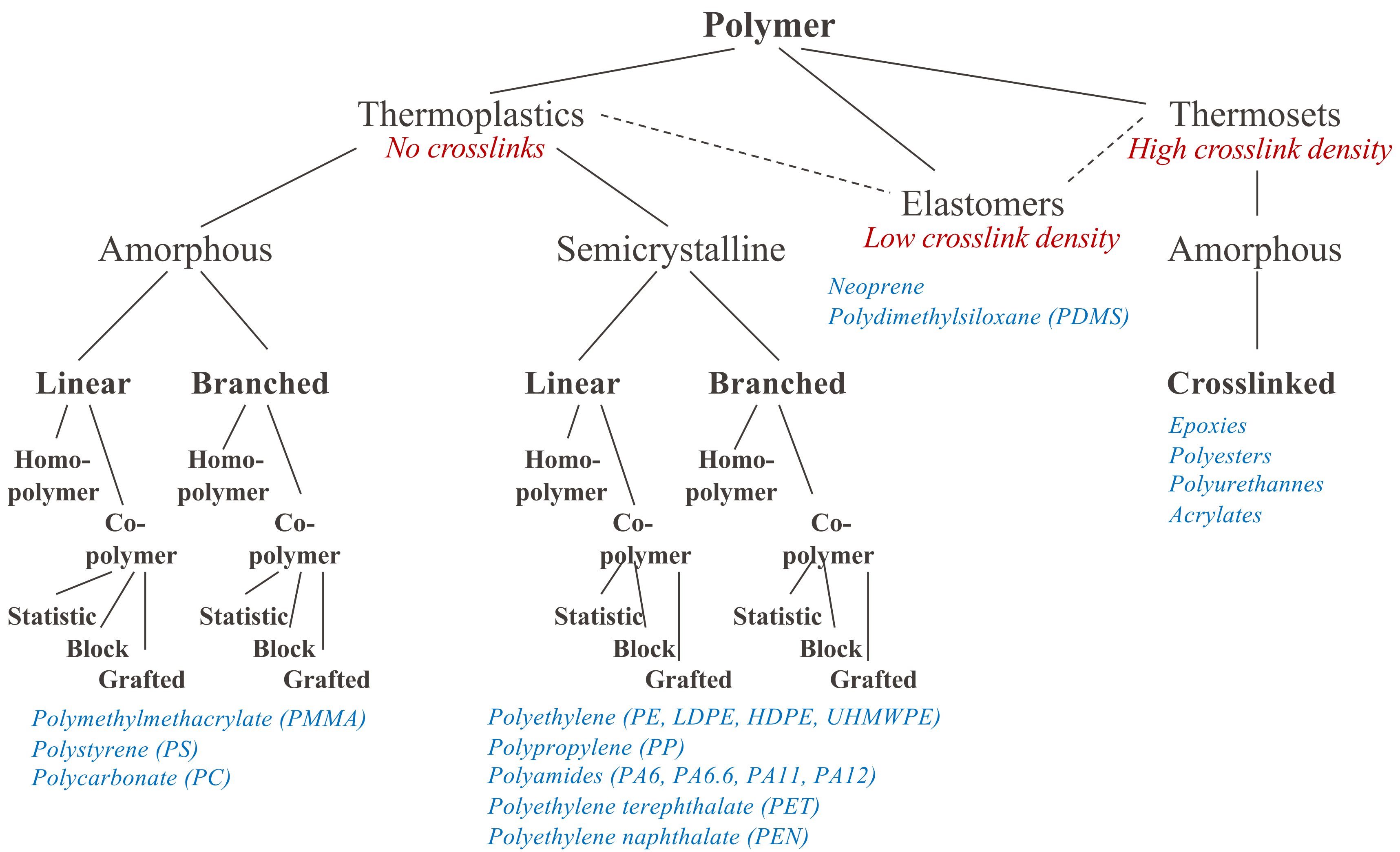
Amorphous thermoplastic

Semi-crystalline thermoplastic

Thermoset network

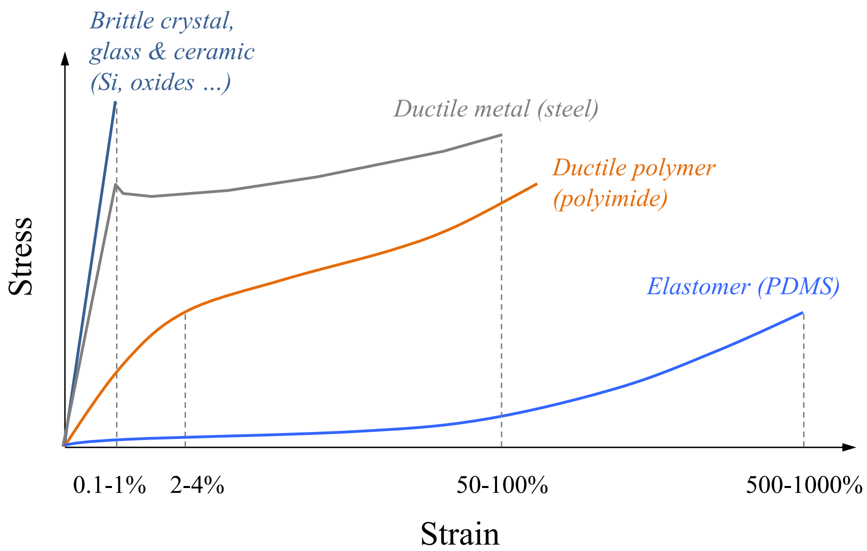


Polymer configuration

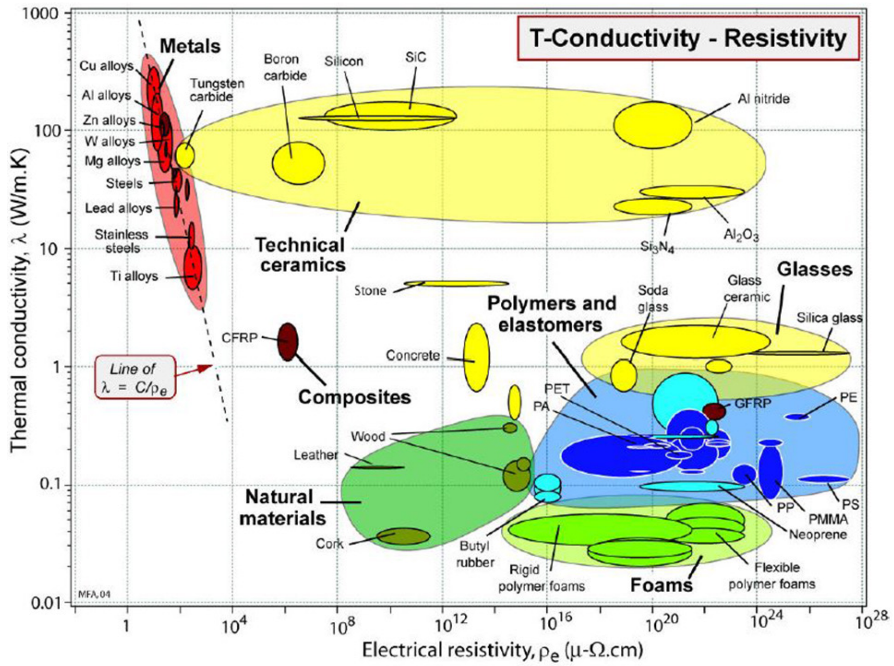


Plastics have unique sets of properties

Plastics are soft and strong



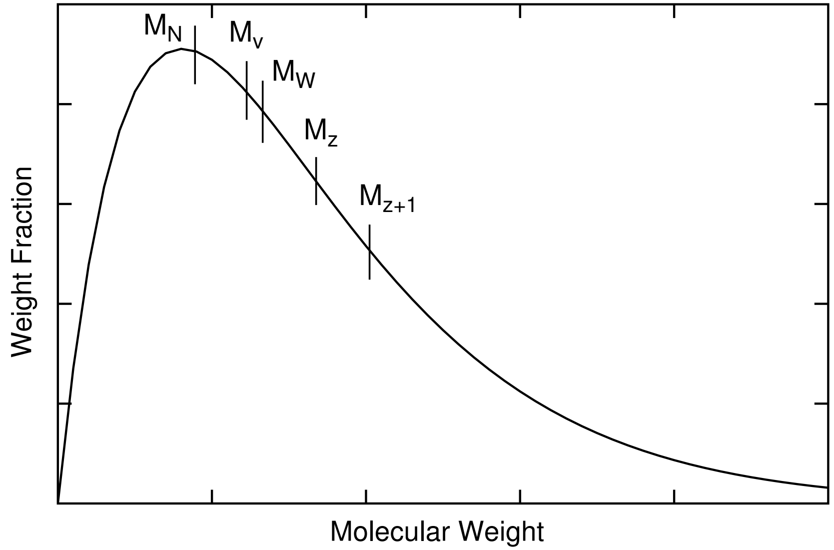
Plastics are good insulators



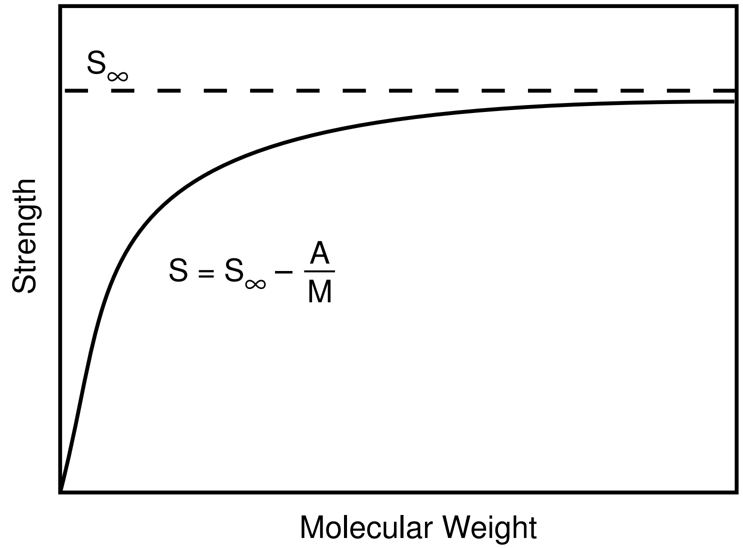
https://proxom.net/material-selection/

Molecular weight

Molecular weight distribution



Mechanical strength



Molecular weight

number average

$$M_n = \frac{\sum_{i=1}^{\infty} n_i M_{wi}}{\sum_{i=1}^{\infty} n_i}$$

weight average

$$M_w = \frac{\sum_{i=1}^{\infty} n_i M_{wi}^2}{\sum_{i=1}^{\infty} n_i M_{wi}}$$

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Paris treaty for plastics

In March 2022, 175 countries agreed to work on a global treaty to combat plastic pollution

Climate activists march to demand stronger global commitments to fight plastic waste in Busan, South Korea, November 23, 2024. REUTERS/Minwoo Park

WORLD ECONOMIC FORUM

Feb. 11, 2025

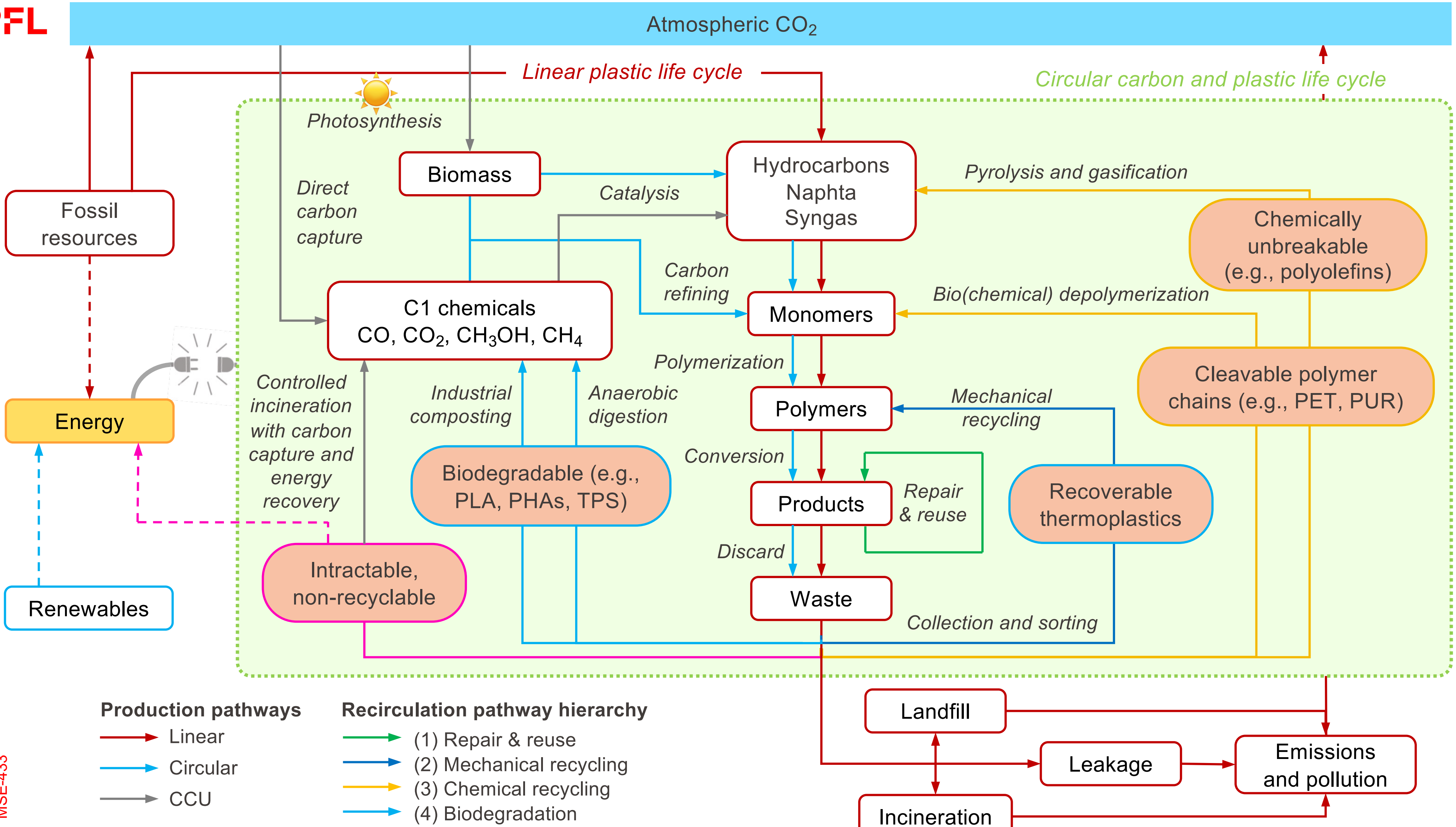
A Paris Agreement for plastics

Do we need a global treaty to tackle plastics pollution, similar to the one on climate change. Campaigners and a growing number of governments and businesses say we do. Ahead of a United Nations Environment Assembly whi could launch talks on a plastics pact, the World Economic Forum heard from a range of experts on why we need a treaty and what it might contain.

Speakers:
Kristin Hughes, Director, Global Plastic Action Partnership, World Economic Forum; Espen Barth Eide, Minister o climate and environment of Norway and President of the UN Environment Assembly (UNEA); Marco Lambertini, Director-General, WWF International; Rebecca Marmot, Chief Sustainability Officer, Unilever; Luis Vayas Valdivie Vice-Minister, Ministry of Foreign Affairs of Ecuador; Sheila Aggarwal-Khan, Director, Economy Division, United Nations Environment Programme (UNEP); Inés Yábar, Communications Coordinator, Co-Founder, Life Out Of Plas L.O.O.P.; Gim Huay Neo, Managing Director, Centre for Nature and Climate, World Economic Forum.

Paris treaty for plastics

https://www.youtube.com/watch?v=jcGBGrkdnlI



After Vidal et al., Nature, 626, 2024

A roadmap towards sustainable plastics

A NetZero plastic economy requires a bold set of actions!

- Action 1: Reduce plastics demand
- Action 2: Switch to renewable plastics
- Action 3: Maximize recycling
- Action 4: Minimize broader environmental impacts

This roadmap follows the publication '*Designing a circular carbon and plastics economy for a sustainable future*', Nature, 626, 2024 by Vidal, van der Mare, Kerr, McElroy, Schroeder, Mitchell, Rosetto, Chen, Bailey, Hepburn, Redgwell & Williams from the University of Oxford, the University of the Basque Country and The Arctic University of Norway

Action 1: Reduce plastics demand

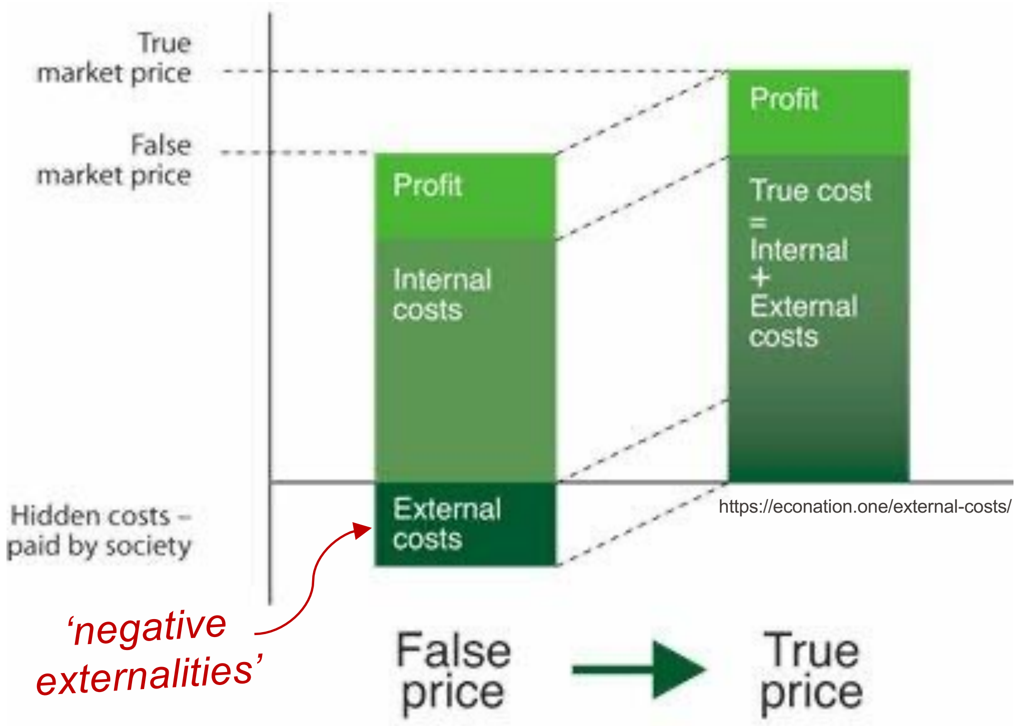
- You can choose!
- Ban or tax ‘unnecessary’ and ‘harmful’ plastics. Examples:
  - Prohibition of plastic bags (Meghalaya (India), South Africa, Eritrea, Bangladesh …),
  - EU Single-Use Plastics (SUP) Directive
  - US prohibition of microbeads in cosmetics
  - EU ban on intentionally added microplastics and ban on oxo-degradable plastics
- In the packaging sector alone, the elimination of unnecessary plastics combined with innovative design is estimated to reduce ~ 38% packaging demand in Europe by 2050.

Consumer behavior is key!

https://biobagworld.com.au/reduce-plastic-pollution/how-to-reduce-your-plastic-use/

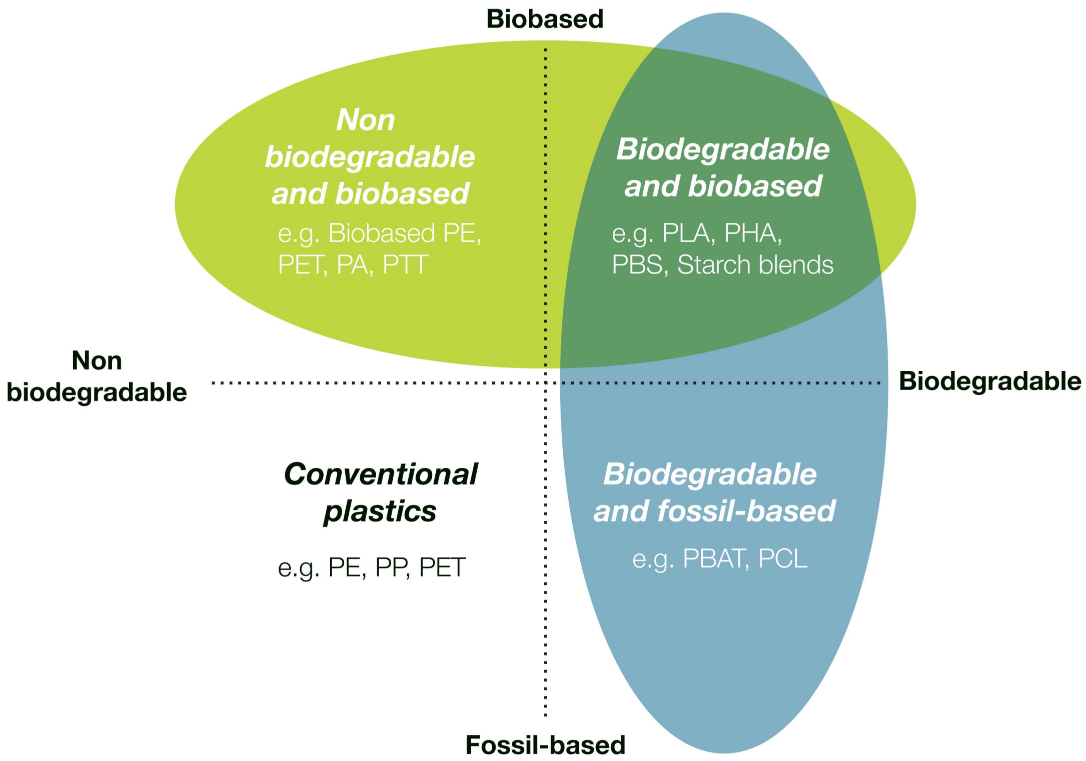
Action 1: Reduce plastics demand

- Cost internalization, through a fee on plastic products to reflect their social and environmental costs would also help to reduce demand.
- An added benefit is to generate revenue to subsidize recycling and/or composting infrastructure, helping to make recycled materials more competitive.



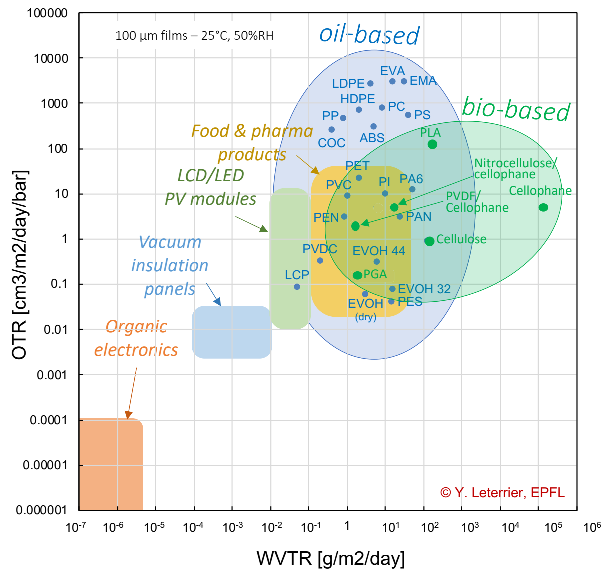
https://econation.one/external-costs/

Action 2: Switch to renewable plastics



+ Low carbon footprint (40-60 MJ/kg)
+ Energy efficiency
+ based on agriculture wastes
+ Societal acceptance?
+ Biodegradability?

– More expensive
– Compete with food supply chains
– Limited thermal resistance
– Limited UV resistance
– Moisture sensitive
– Confusion e.g., PET and bio-PET

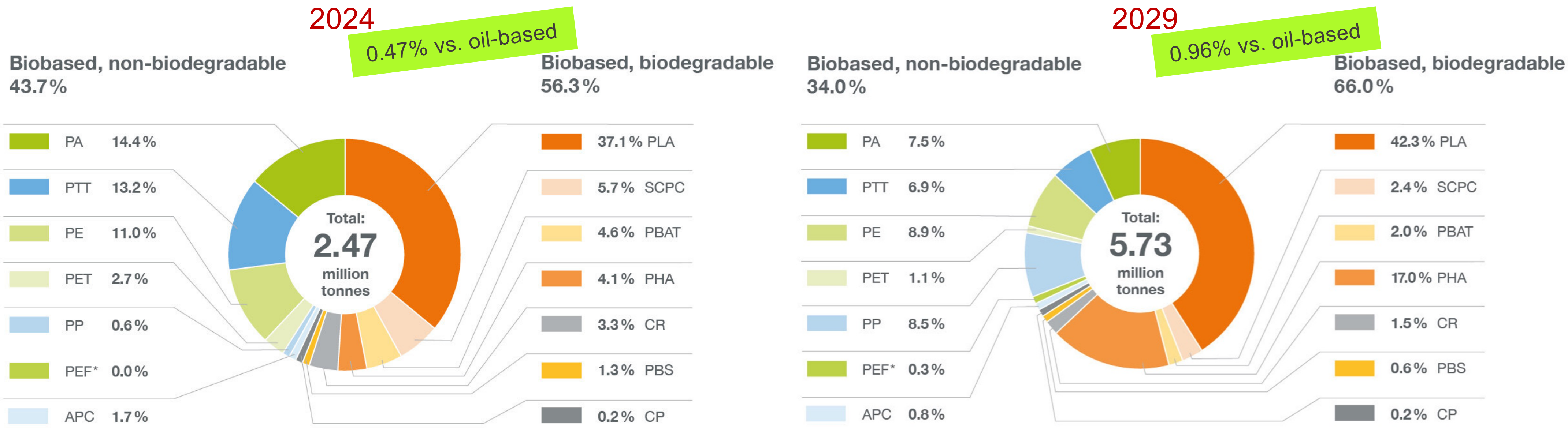


Endres H-J, Fachhochschule Hannover
https://www.european-bioplastics.org/bioplastics/materials/
Nanda et al., Environmental Chemistry Letters (2022) 20:379–395
Yu et al., Environ. Sci. Technol. 2008, 42, 6961–6966

Crank & Park, 'Diffusion in polymers' Academic Press (1968)
Chatam, Surf. Coat. Technol. (1996)
Pauly, in 'Polymer Handbook' Wiley (1999)
Leterrier, Prog. Mater. Sci. (2003)
Charton *et al.* 2006, Dennler *et al.* 2006

Action 2: Switch to renewable plastics

Global production capacities of bioplastics: CAGR 18.3% (5X vs. oil-based 3-4%)

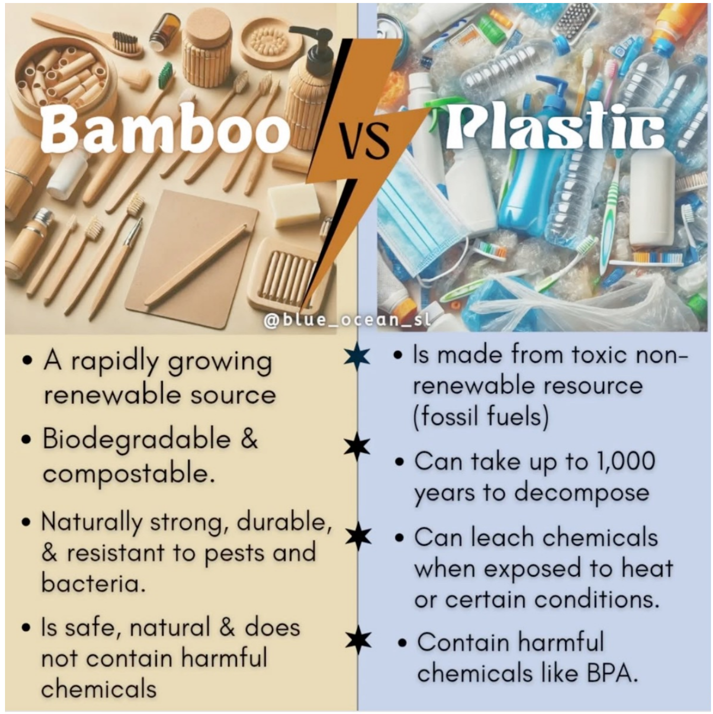


APC	Aliphatic Polycarbonates
CP	Casein Polymers
CR	Cellulose Regenerates
PA	Polyamides
PBAT	Poly(Butylene Adipate-co-Terephthalate)
PBS	Polybutylene Succinate and Copolymers
PE	Polyethylene
PEF	Polyethylene Furanoate
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
PP	Polypropylene
PTT	Polytrimethylene Terephthalate
SCPC	Starch Containing Polymer Compounds

https://www.european-bioplastics.org/bioplastics-market-development-update-2024/#

Action 2: Switch to renewable plastics

- Innovative design thinking!
- Public–private partnerships
  - e.g., the Circular Bio-based Europe Joint Undertaking, CBEJU, a 2 billion € program 2021-2031
- Economic and legal measures! Examples:
  - in the EU, > 20% of the carbon used in chemical and plastic products should be from renewable sources by 2030
  - The USA aims in 2040 to develop cost-effective and sustainable routes to convert bio-based feedstocks into recyclable polymers that can displace more than 90% of today's plastics
  - Green public procurement criteria for large-scale purchasing power
  - Financial subsidies to sell bioplastics at lower cost
  - Phasing out fossil-fuel subsidies[1]



https://www.blueoceansl.com/

(1) the petrochemical industry continues to invest in new fossil-carbon plants, which risks petrochemical lock-in

Action 2: Switch to renewable plastics

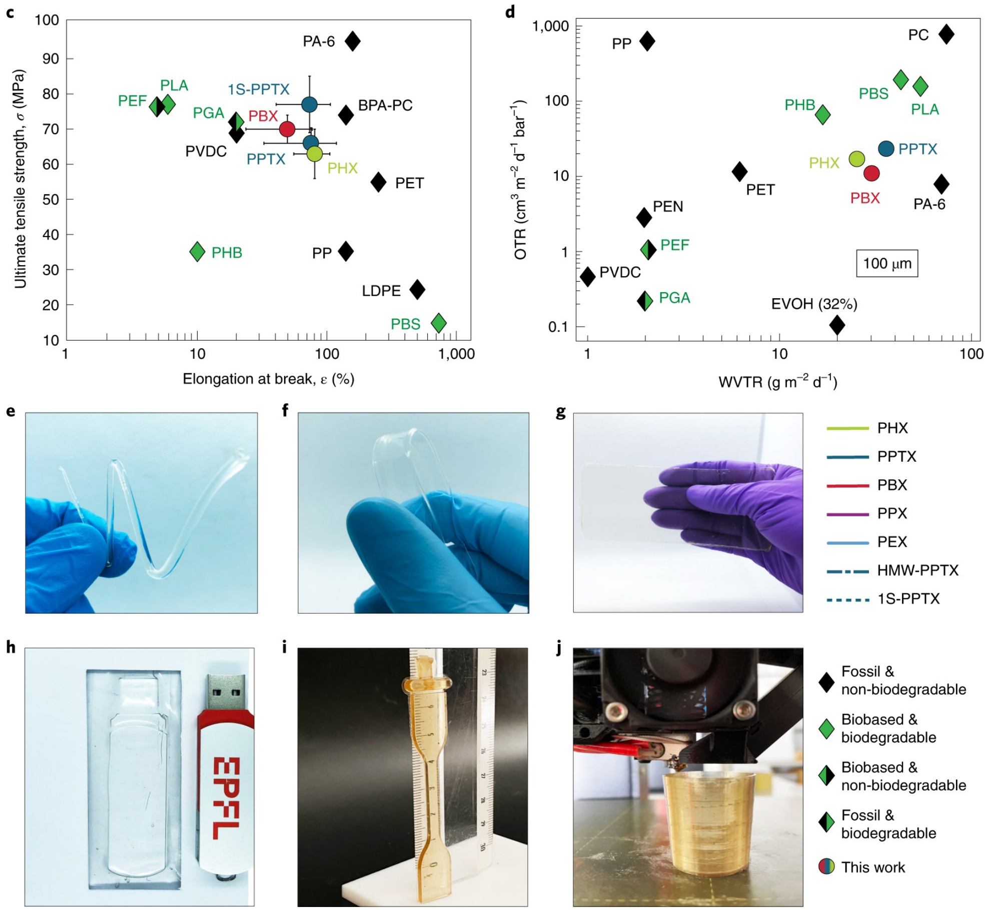
Sustainable polyesters from lignin (Collaboration with Prof. Luterbacher, EPFL)

ARTICLES
https://doi.org/10.1038/s41557-022-00974-5
nature chemistry
Check for updates

Sustainable polyesters via direct functionalization of lignocellulosic sugars

Lorenz P. Manker[1], Graham R. Dick[1], Adrien Demongeot[2], Maxime A. Hedou[1], Christèle Rayroud[1], Thibault Rambert[1], Marie J. Jones[1,3], Irina Sulaeva[4,5], Mariella Vieli[1], Yves Leterrier[2], Antje Potthast[4], François Maréchal[3], Véronique Michaud[2], Harm-Anton Klok[6] and Jeremy S. Luterbacher[1]✉

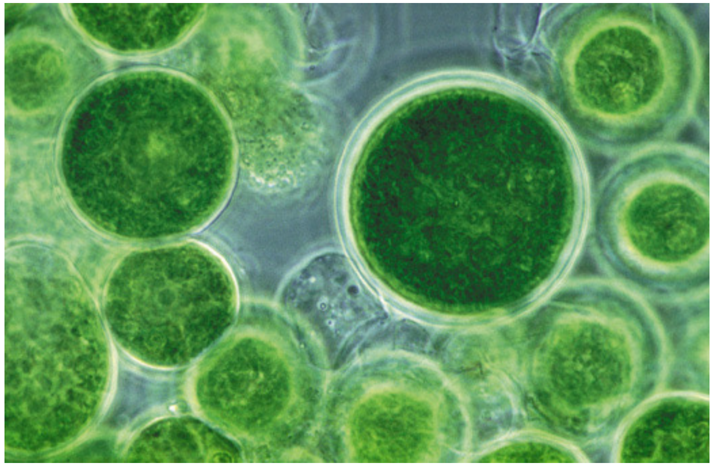
Nature Chemistry 14, 976–984 (2022)



Action 2: Switch to renewable plastics

- ⚠️ Increasing use of biomass and CO_2 might result in transfer of ecological burdens from climate change to other Earth-system processes (e.g., deforestation)

- Solution in (micro)algae? These greatly reduce greenhouse gas emissions! (67– 116% compared to oil-based plastics)



https://bioplasticsnews.com/2014/02/24/bioplastic-made-from-algae/

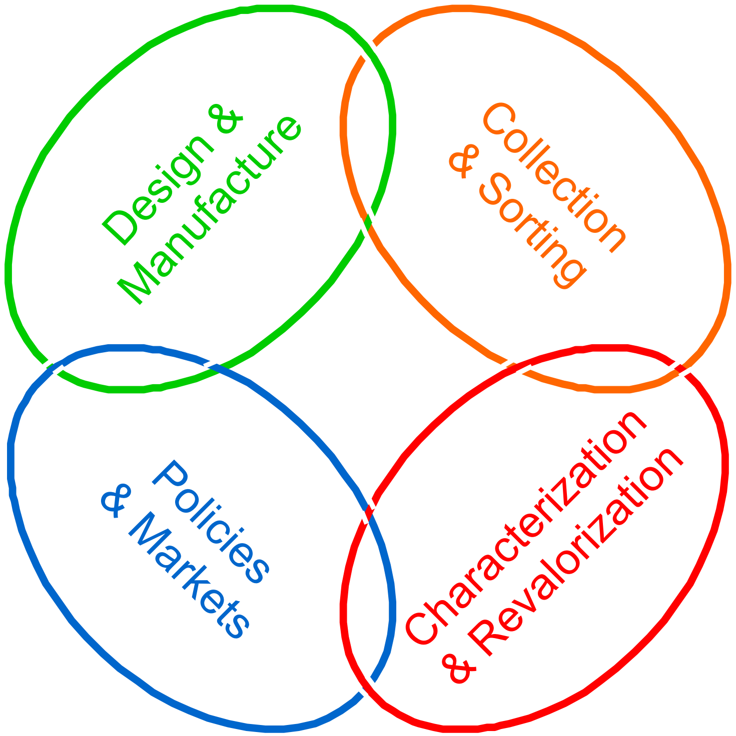
- This increase should comply with SDGs and the circular economy principles:
  1. Can biobased products be recycled? How? And how many times?
  2. Can biobased products be composted? Or biodegrade to regenerate natural systems?

Gursel et al., Sustainability 2022, 14, 12780
Beckstrom et al., Algal Research 46 (2020) 101769

Action 3: Maximize recycling

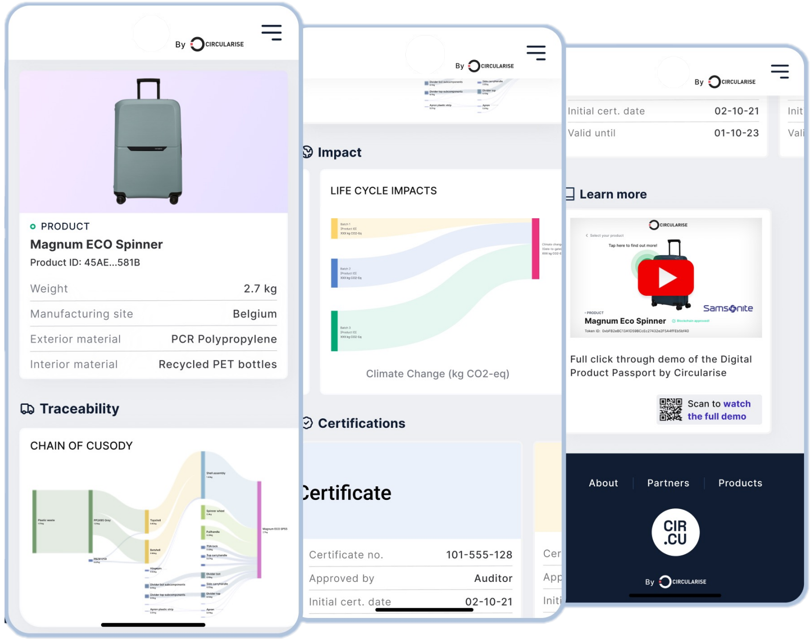
- Achieve 95% recycling rates of plastics in 2050 (EU target to recycle 55% of plastic packaging waste by 2030)
- Improvements in infrastructure (costly and inefficient logistics) and recycling technologies (heterogeneity of waste streams)
- Implement specific tools. Examples:
  - Extended producer responsibility (EPR) schemes
  - Fiscal incentives such as tax credits
  - Deposit-return schemes to incentivize consumer behaviour
  - Digital trading platforms for recycled plastics
  - Policy coordination including subsidies for recycling and removal of fossil-fuel subsidies

The Vital Recycling Chain



Action 4: Minimize broader environmental impacts

- Only use renewable energy to access the lowest CO_2 emissions.
- Eliminate pollutants, using legal measures such as the EU chemicals law (REACH).
- Develop digital product passports, i.e., making market access for products that contain plastics conditional on documenting environmental information.
- Consumer education is key!



https://www.circularise.com/blogs/digital-product-passports-dpp-what-how-and-why

Outline

Summary

- Plastics are incredible materials and WILL continue to grow at 3-4%/yr.
- A systemic, 4-action plan is required to create sustainable plastics:
    1. Reduce plastic demand: **eliminate 50%** of all plastic materials and products.
    2. Switch to renewable plastics: **replace all fossil-fuel-based plastics** with those sourced from alternative feedstocks, accelerating carbon recirculation through use of biomass and CO_2.
    3. Maximize recycling: design plastic materials and products for circularity and ensure that **95% of plastics are recycled**.
    4. Minimize broader environmental impacts: **remove all sources of hazards** to organisms and pollution to the environment, as well as decrease the carbon footprint throughout the plastics life cycle.
- The challenge is substantial but re-engineering the plastics economy is achievable.
- A future sustainable plastics economy requires a multidisciplinary and holistic vision of the entire life cycle, as well as an economic and legal perspective on what stimulates (or hampers) change.

Appendix: Design principles for sustainable plastics

1. **Net-zero feedstocks**. Maximize carbon recirculation by disengaging plastics feedstocks from fossil sources and using renewable carbon, such as biomass, industrial by-products, waste CO_2 or recycled plastics.
2. **Efficient production.** Minimize energy input by optimization of production and conversion (manufacturing), the use of catalytic processes, the balance of conditions and reduction of the number of intermediates and stages.
3. **By-product rejection.** Preserve the value of carbon, and other elements, by applying atom-economical transformations, maximizing process selectivity and recycling or repurposing by-products, offcuts and scraps.
4. **Essential purpose.** Deliver the necessary performance (for example, flexibility, density, toughness, durability, gas permeability, optical clarity) without overengineering plastic materials and products.
5. **Extended use.** Increase product lifetimes by allowing the repair of damaged materials and giving priority to reuse models (for example, return and refill for packaging).
6. **Competitive properties.** Implement bio-based plastics with properties that match or exceed those of current fossil plastics, while minimizing manufacturing costs.
7. **Preserved value.** Preserve energy and raw material value for the long term, which requires the conservation of polymer and monomer structures, if possible, during physical and chemical recycling.
8. **Easy separation.** Minimize the use of additives and other contaminants, design products for separation, sorting, disassembly and purification in recycling and replace multimaterials with homo-composites.
9. **Optimized recycling.** Maximize yield, value and quality of properties in recyclates; chemical recycling and upcycling should minimize energy inputs and preserve value.
10. **Synergistic biocompatibility.** Design materials for optimal compatibility with biological recycling plants (aerobic composting and anaerobic digestion) wherever recycling is unsuitable (for example, contaminated agricultural and food wastes).
11. **Harmless biodegradation.** Provide materials with embedded strategies for full degradation to non-toxic metabolites wherever polymers are environmentally distributed or dispersed (for example, water formulations).
12. **Minimal hazards.** Assess ecotoxicity and human toxicity of all plastics, additives and degradation products and analyse negative environmental impacts throughout the life cycle.

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