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Bauer, Fredric; Ericsson, Karin; Hasselbalch, Jacob; Nielsen, Tobias; Nilsson, Lars J

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PO Box 117
221 00 Lund
+46 46-222 00 00



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Department of Technology and Society

Environmental and Energy Systems Studies

Climate innovations in the plastic industry: Prospects for decarbonisation

Fredric Bauer, Karin Ericsson, Jacob Hasselbalch, Tobias Nielsen, and
Lars J Nilsson

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Environmental and Energy Systems Studies, Department of Technology and Society, Lund University, Sweden

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Preface

This report is written as part of the REINVENT project which is funded through the European Union Horizon 2020 Research and Innovation Programme under agreement no. 730053. The work has benefited from results, discussions and insights from several colleagues and other projects, notably STEPS (Pathways to Sustainable Plastics) funded by Mistra – the Swedish Foundation for Strategic Environmental Research.

Summary

Plastics are efficient materials for many purposes, e.g. packaging and construction, but are also associated with significant problems. These span from littering in forests and oceans, toxicity of additives, to the fundamental dependence on fossil resource for the production of the plastic material. This report aims to give an overview of the challenges for decarbonisation of plastics, i.e. moving away from a dependency on fossil resources for the production. Firstly, it identifies different possible development pathways for the industry towards decarbonisation and the key arguments for and against these pathways – reduced use of plastics, recycled plastics, and bio-based plastics.

Secondly, it presents an analysis of structural characteristics of the industry that affect the potential for low-carbon innovation. This includes identifying and understanding the potential that traditional as well as new types of agents have to affect the direction of development. The report presents decarbonisation initiatives and engagement throughout the system of plastics, i.e. not only by primary production firms but also by knowledge organisations, intermediary firms, consumer groups etc. As the development pathways are contested and challenged both on technological and other grounds, the issue of power becomes pressing. The formation and use of coalitions to support and/or counteract certain developments is important, as political regulation of this highly globalised and diffuse sector has previously been difficult. The interaction between geographical particularities and scales must be given due consideration. Finally, the aspect of materiality is a key concern for the development of a system of specific materials. This relates of course to the limits of different types of feedstocks and material properties, but also to other resources and their exploitation within a system that is deeply entrenched in a system with capital invested in technologies and facilities adapted for processing fossil resources into fuels, plastics, and other products.

Despite the strong carbon lock-in that the plastics industry is in, the identified pathways show that there are possibilities for decarbonisation. New types of actors are creating pressure for the sector to move towards a future plastic sector that is both circular and independent of fossil resources.

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1 Introduction

Plastics are integral to modern and sustainable societies. For example, they protect food and help reduce food waste, are key components in modern buildings and constructions, enable the design of lighter vehicles, and facilitate efficient transmission of electricity as an insulator in cables. Plastics offer many solutions to environmental problems, not least to reduce greenhouse gas emissions in other sectors, but they also generate new ones. The problems associated with plastics are not new and include the use of limited feedstocks, greenhouse gas emissions, toxicity, littering and pollution, and low levels of collection and recycling, but awareness has increased in recent years. Especially the issue of accumulation of plastic materials in marine environments has risen on the global agenda, largely thanks to a recent report which pointed out that there could be more plastics than fish, by weight, in our oceans by 2050 if current trends continue (World Economic Forum et al. 2016). The fundamental question of resource use for the production of plastics, which is currently completely dominated by petroleum fractions as feedstock, has however hitherto largely been ignored in the public discourse.

A society that aims to become independent of petroleum for energy purposes must also address other uses of the resource, such as chemicals and plastics. The European Commission published its plastics strategy in early 2018 as part of the circular economy package in order to lay the foundation for a new and more sustainable use of plastics (European Commission 2018a). The EU Plastics Strategy does however make few claims about the problems of using fossil feedstock, e.g. carbon dioxide emissions, but is highly concerned about the sustainability of feedstock for bio-based plastics. Increased recycling will reduce the need for fossil feedstock but due to downgrading of plastics in the use and recycling phases there will be a continued need for virgin material. In addition, global production is expected to increase.

Although policies around the production and use of plastics have been rather lax until the last few years when bans on specific plastic products have been introduced, the plastics industry is under increasing pressure to change in light of the unsustainability of the current plastics system. This interest manifests itself in corporate initiatives such as the Coca-Cola PlantBottle, LEGO's ambition to switch to bio-based plastics, and IKEA's goal of using 100% recycled or bio-based plastics in their products. There are also smaller and less recognised initiatives, e.g. recycling of fishing nets, public innovation procurement for bio-based plastic aprons for health care, and multi-use food packaging systems, some of which are presented in the REINVENT Decarbonisation Innovations Database (Hansen et al. 2018).

This report thus aims to shed light on the potentials and challenges that exist within the realm of plastics to break free from its dependence on fossil petroleum resource use – decarbonising plastics – outline what pathways for such developments that exist in Europe, and analyse the capabilities that are required for these pathways to materialise. Strictly speaking “decarbonisation” is a misnomer in the context of plastics, since carbon is typically the main element in plastic materials. The term is however widely used in the meaning of production decoupled from fossil resource use or carbon dioxide emissions.

2 The system of plastics

2.1 Material flows

Although the famous synthetic resin Bakelite was introduced to the market already in the beginning of the 20th century, the large-scale production and use of plastics, or synthetic organic polymers, took off in the post-war period with the diffusion of modern petrochemistry. In 1950 the global production was about 2 Mton (Geyer et al. 2017) which increased to about 15 Mton in 1964 and around 335 Mton today (World Economic Forum et al. 2016). European industries were key actors in the early development of the sector (Freeman et al. 1963) but have since lost their leading position as producers and currently produce about 60 Mton of plastics (Plastics Europe 2018). The global production volume is equal to a demand for plastics of around 45 kg per capita, although the demand in Europe is approximately the double, around 100 kg per capita. Global demand is further expected to double in the next two decades, mainly in developing regions (World Economic Forum et al. 2016).

The production of plastics mainly uses fossil feedstock in the form of light hydrocarbons such as ethane or propane, commonly called natural gas liquids, from natural gas processing or naphtha from oil refineries. The hydrocarbons are then cracked to produce monomers such as ethylene and propylene that in subsequent process stages are polymerised. The term plastics obscures the high diversity and complexity of the range of products it describes. Five types of polymers do however constitute over 90% (by weight) of all plastics produced: polyethylene (34.4%), polypropylene (24.2%), polyvinyl chloride (16.5%), polyethylene terephthalate (7.7%), and polystyrene (7.3%). The basic polymers take different forms and are modified in different ways for different applications (e.g. high and low density PE, rigid and flexible PVC) (Plastics Europe 2018).

The virgin polymers typically come in granulates which are then compounded, i.e. the main polymer is mixed with a number of additives to achieve the desired properties for the intended application. These additives can be fillers, heat and light stabilisers, antioxidants, flame retardants, plasticisers, blowing agents, and others (Pelzl et al. 2018). The compounding process produces a mixed plastic with the desired properties for specific applications and this is what is used in subsequent conversion processes where the plastic material is converted into a product through moulding, extrusion or blowing. The main market demand sectors for plastic materials are packaging (39.9%), building and construction (19.7%), automotive (10%), and electrical and electronic (6.2%) (Plastics Europe 2018).

A significant share of the plastics accumulates in society and constitutes the societal stock of plastics, i.e. by being used in construction materials that are being used for several decades. The rest becomes waste, but whereas glass, paper and metals are recycled at high rates plastics are far behind. Only about 30% of the plastic waste in Europe is collected for recycling and even less is actually recycled. The rest is incinerated in solid waste incineration plants, landfilled, exported – or lost. The material flows of in the European system of plastics are shown in Figure 1, together with associated carbon dioxide emissions which are further discussed in the next section.

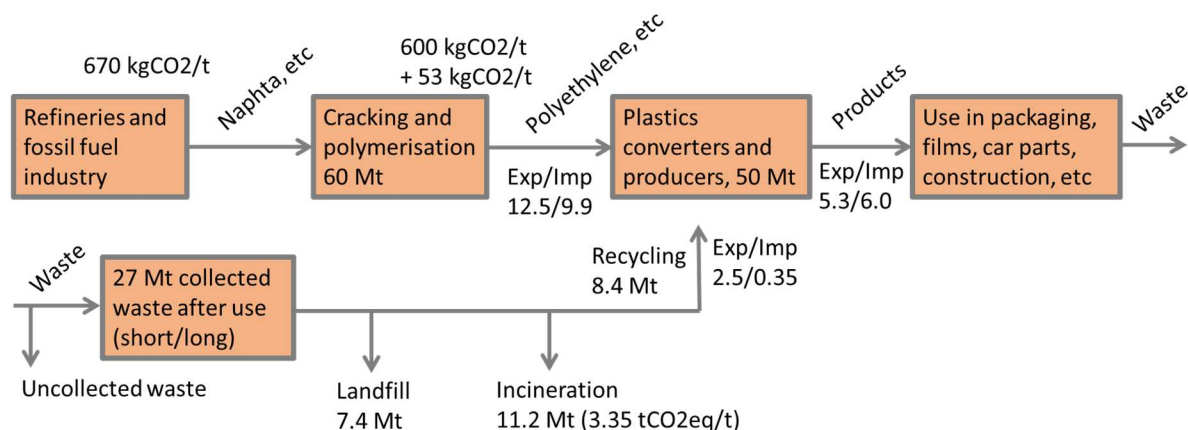


Figure 1. Flows in the EU plastics system. Due to different sources the numbers for production (Plastics Europe) and export/import (EU Market Access Database) do not balance completely. Increases/decreases in the stock of plastics are unknown. Emission factors per ton of feedstock based on (Eriksson & Ahlgren 2013), and for monomer and polymer on (Borealis 2017) for polyethylene.

2.2 Feedstock use and CO₂ emissions

The production of plastics is in a strong lock-in to petro-chemistry and fossil feedstock use after decades of co-evolution in a ‘special relationship’ of material, knowledge, and economic synergy (Bennett 2007). The primary production of virgin plastics is also typically co-located with petrochemical clusters and petroleum refineries to efficiently use the different product fractions from crackers and refineries. The share of oil, or oil and gas, that is used for producing plastics is generally placed at 4-8 %.¹ The share of oil consumption used for plastics is expected to grow rapidly in the future. Business-as-usual projections puts plastic’s share of global oil use to around 20% by 2050 as the demand for gasoline and diesel will most likely not increase similarly due to electrification and new fuels being used for vehicles (World Economic Forum et al. 2016). In the USA alone, oil used to produce petrochemicals is expected to be the largest source of growth in future oil demand, making up 44% of the increase in crude oil consumption through 2040 (International Energy Agency 2017). By 2025, global production capacity for two key plastics feedstock ethylene and propylene are expected to grow by more than 33%. Ethylene is projected to grow from 170 million metric tons to 230 million tons, while capacity for propylene could rise from 120 to 160 million tons (Center for International Environmental Law 2017b). Production routes from coal are also used, e.g. in China, but are less common, and associated with significantly higher CO₂ emissions, 5-7 times those of conventional naphtha based production (Ren & Patel 2009; Xiang et al. 2014). Biomass is another alternative and bio-based plastics existed long before large-scale petro-chemistry based production was developed. The current global production of bio-based plastics is only about 2 million tons per year, i.e. less than 1% of the total production, and around 18% of the bioplastics are produced in Europe (European Bioplastics 2017).

Although petrochemicals and plastics were originally a way for fossil fuel companies to make money from their waste streams, today plastics is a profitable business, e.g. ExxonMobil’s Chemicals segment accounted for roughly 10% of its revenues in 2015 but more than 25% of its overall profits, driving future investments in infrastructure for petro-based plastic production (Center for International Environmental Law 2017a). During years of increasing prices for petroleum in the early years of the millennium there was a growing interest in looking beyond conventional petroleum based feedstocks which increased the interest

¹ Oil accounted for about 4 326 Mtoe and gas 2 948 Mtoe of global primary energy in 2015, and 322 Mton of plastics were produced in that same year (Plastics Europe, 2017).

for renewables. However, the development of unconventional petroleum and gas resources (e.g. shale gas) introduced large volumes of alternative, easily usable feedstocks for plastics and petrochemicals (Sirola 2014). Recent investments have thus focused mainly on making use of ethane in the US and Middle East where it is extracted (Amghizar et al. 2017).

In the US alone, investments of 164 billion USD are planned for 264 new facilities or expansion projects by 2023, largely driven by the expansion of shale gas (Center for International Environmental Law 2017b). In Europe, no new plastic production facility has been built for years – due to cost disadvantage to North America and the Middle East. However, the US fracking boom is also fuelling increased plastic production capacity in Europe, e.g. INEOS announced it will expand the production of PP by 1.6 million tons. As recent large investments in production facilities in the Middle East enter production, this region will also see a considerable increase in plastic production. Another growth region is China, where coal-to-olefins output increased from 430 thousand tons to 6.48 million tons over the period 2011-2015. China is expected to invest more than 100 billion USD in coal-to-chemicals technology over the next five years. If these massive investments materialise it will perpetuate the current lock-in of cheap fossil-based plastics for decades to come. However, if the market shifts away from (fossil-based) plastics also represents a considerable risk for stranded ‘plastic’ assets.

Plastics is a sector that so far has not seen much pressure to change in terms of carbon dioxide emissions. The complexity of refineries and petrochemical clusters makes it difficult to attribute carbon dioxide emissions to plastics. Figure 1 shows three major points of emissions: 1) refineries and upstream transport/extraction that require roughly 20% of the energy in oil, 2) the cracker is energy intensive and takes another 20%, and 3) incineration of plastics lead to emissions per ton that are roughly equal to burning oil. Total direct carbon dioxide emissions from these three points of emissions are on the order of 130 Mt per year for Europe.² As in the rest of the petrochemical industry, production of plastics is highly energy intensive and energy efficiency improvements have been a prominent driver of innovation (Ren 2009), leading to significant decreases in fuel and power consumption as well as energy intensity of production over the past decades (Cefic 2012). Refineries from which much of the feedstock is sourced are under the EU Emissions Trading Scheme with partly free allocation of emission permits and relatively low carbon prices. The fossil feedstock used for production of plastics, in turn, does not have a carbon price since carbon dioxide is priced at the emissions source, e.g. a waste incineration plant.

² Assuming 75 Mton fossil feedstock at 670 kgCO₂/t, 60 Mton polymers at 653 kgCO₂/t, and about 40 MtCO₂ from incineration of plastics. The total 130 MtCO₂ is slightly more than what Belgium emitted in 2015 (122 MtCO₂eq) and about 3 % of EU total GHG emissions.

3 Decarbonisation pathways

Different pathways have been identified which propose to deal with the current unsustainability of plastics: Bio-based, Biodegradable, Recycled, Fewer types, and Reduced use. Each of these pathways have their advantages and drawbacks, as well as potentials for decarbonisation, and are summarised in Table 1. The biodegradable pathway mainly addresses the aspect of littering, and fewer types is mainly about improving recycling by reducing the complexity of the plastic system. The other three pathways, which have larger potential for decarbonisation, are presented in more detail.

Table 1. Overview of individual pathway promises and challenges as well as potential conflicts and synergies with other pathways (Nielsen et al. 2018).

Pathway	Pathway promise	Pathway challenge	Synergy with other pathways	Conflict with other pathways
Bio-based	Alternative to fossil feedstock and reduces greenhouse gas emissions	Can add complexity to recycling. Concern for future biomass scarcity and land-use competition	(Biodegradable)	(Recycling) Fewer types
Biodegradable	Better disposal of plastic waste and some claim an end to littering. Novel plastic types with new distinct properties	Collection and industrial facilities still required. Potential consumer confusion about sorting and recycling	Bio-based	Recycling
Recycling	Reduce use of virgin feedstock and thus emissions, and improved resource efficiency.	Maintaining high material quality. Low demand for recycled material and risk of down-cycling	Fewer types	(Bio-based) Biodegradable
Fewer types	Decrease plastic system complexity and improve plastic recycling and reuse	Fear of hampering innovation and increasing the use of resources.	Recycling	Bio-based Biodegradable
Reduced use	Reduced plastic littering, use of resources, and exposure to potentially harmful chemicals	Risk of unfavourable material substitution or other negative impacts of not using plastics	All pathways	-

3.1 Reduced use of plastics

The reduced use pathway promotes various ways of reducing the use of plastics, such as design options, material substitution, changing habits, or outright refusal to use. Individuals are encouraged to live a low plastics life or decrease their amount of waste by refusing plastics. Political action is called upon to tax or ban certain types of plastics applications (or additives and fillers), either through legislation or public procurement guidelines. In essence, this pathway argues that it is not enough to switch to alternative feedstocks and recycle more – to have a more sustainable plastics system the use of plastics must decrease. In particular, it questions the current ‘overconsumption’ of single use plastics, but at the same time it risks narrowing the focus to certain plastic objects, e.g. bags, micro-beads, and drinking straws, while losing sight of the larger picture.

The opportunities for reducing plastic consumption consist of material substitution, design options and changed habits. The environmental benefits of pursuing such strategies are, however, not evident for all applications since this may lead to lost functionality and undesirable material substitution. For example, paper or cotton bags can have higher carbon footprints than plastic bags, depending on use and disposal (Mattila et al. 2011). Furthermore, increased plastic consumption for insulation and in automotive applications, where it enables more lightweight vehicles, can provide energy savings.

This pathway has gained traction within the policy world. Several public authorities have regulated the consumption of certain plastic objects – often in order to reduce the risk of leakage. The reduce pathway is a key focus of the EU strategy and of the recently proposed EU legislation on single use plastics. The pathway has also gained considerable traction amongst NGOs and civil society, with a large number of campaigns on reducing the use of certain plastics. On the other hand, the pathway is challenged by in particular plastic producers (both conventional and bio-based) that argue it is the misuse of plastics that needs to be addressed, not the use.

3.2 Recycling plastics

The (material) recycling pathway is intimately linked to ideas of a more circular economy in which material loops are narrowed or closed through improved end-of-life processes and better product design. Recycling and reuse is one of the key gaps of plastics when comparing to other basic materials. In the EU ca. 30% of plastic waste is collected for recycling (Plastics Europe 2017). However, not all of the 30% was actually recycled. On a global scale of the 8.3 billion tons of plastics ever produced, only 9% has been recycled (Geyer et al. 2017).

In terms of its decarbonisation potential, the main promise is to reduce the use of virgin feedstocks and increase overall resource efficiency of the plastics system. Recycling is emphasised in the EU strategy and has received broad support across the value chain and from NGOs. However, it does not challenge the dominance of petro-based plastic production. Moreover, there are technical (e.g. collecting and sorting), market (e.g. low market demand for recycled plastics), and material challenges (e.g. risks of down-cycling to this pathway). Critics have also argued that it risks maintaining the current petro-based plastics systems, and essentially allows for the current plastics system to continue with some modifications. Some critics also point to the limitation of relying on recycling as many types of plastics are not recyclable with the best available technology today.

Plastics recycling reduces the need for virgin feedstock but is hampered by the durability and diversity of plastics. In theory, around 75% of the current plastics mix could be mechanically recycled while the remaining 25% would require chemical recycling which is not deployed commercially yet (Hestin et al. 2015). The recycling of plastics in the EU amounts to only 10% if measured as the production of secondary plastics in relation to the use of plastics. The production of high-quality secondary plastics is inhibited by a number of technical barriers including mixed streams of plastics (various polymers) which contain various additives and that may be contaminated with other materials and substances. These barriers lead to considerable losses in the recycling system, including downcycling (the production of less valuable products). The diversity of plastics also makes it difficult to achieve economies of scale in recycling. If major technical barriers can be overcome, plastic recycling, including reuse, could increase to 50% by 2050 (Material Economics 2018). Hence, a future plastics system with considerably higher recycling rates than today will still have important input of virgin feedstock of some sort.

3.3 Bio-based plastics

Bio-based plastics are mainly based on agricultural feedstocks, typically starches and sugars from crops, such as sugar cane and corn. However, feedstock can also be cellulose, bio-waste, and even carbon dioxide. Some bio-based plastics are distinctly different from conventional plastics (e.g. PLA, PBS, TPS), whereas others are drop-in plastics that are identical to conventional plastics (e.g. bio-PE, bio-PET). Some bio-based plastics are also biodegradable, e.g. PLA, PBS and PHA, yet bio-based and biodegradable plastics are not synonymous, although both groups are commonly denominated bio-plastics. Most of the currently produced 2 Mton bio-based plastics (almost 60%) are used in packaging (European Bioplastics 2017). Packaging is an application that is close to consumers, and one in which bio-based adds value. Although the interest for this pathway is increasing – several large brand owners are showing an interest for bio-based plastics (see section 5. Current initiatives) – thus far no significant increases in the projected growth path of bioplastics have been seen (European Bioplastics 2017).

The main opportunity in terms of decarbonisation is that bio-based (or alternative) feedstocks have the potential to reduce GHG emissions and to disconnect the plastics system from fossil fuels. For policy-makers the prospect of reducing dependency on foreign fossil resources and supporting rural development through biorefineries, also resonates. However, the pathway has been criticised for potentially adding complexity to the systems, for not fundamentally changing the way we use plastics, nor dealing with leakage. Its emissions reduction potential has also been questioned. A recent environmental impact assessment shows a great variation in greenhouse gas reduction from starch-based plastics versus their conventional counterparts, from an 85% reduction to an 80% increase depending on the plastics composition (Broeren et al. 2017). The EU Strategy addresses bioplastics through more funding to R&D and improving understanding the lifecycle impacts of alternative feedstocks, while individual countries (e.g. Italy) have introduced policies supporting bioplastics by including exemptions from plastic bag bans.

Finally, this pathway is challenged for its use of biomass, a resource for which there will most likely be increased competition as more sectors decarbonise. Biomass, including biogenic CO₂, is the only renewable source of carbon feedstock for production of plastics, liquid fuels, and other materials, e.g. paper and construction materials. Current bio-based plastics are almost entirely sourced from sugar-, starch- and oil-rich crops. A considerable scale-up of production of bio-based plastics in the EU would require that the sourcing is broadened to lignocellulosic biomass such as forest biomass, agricultural residues and lignocellulosic biomass crops. These biomass feedstocks compete less with food production, but have other competing uses and face ecological constraints (residues). Lignocellulosic biomass can be converted via thermochemical or biochemical routes to platform chemicals such as ethanol and methanol. These chemicals can then be converted to olefins (such as ethylene) or other monomers for production of plastics, or be used as transportation fuels which is an application competing for this resource.

Scaling up to replace the global production of plastics could require well over 100 million hectares of land for biomass production.³ Figure 2 shows the biomass resources that could be available for production of chemicals, plastics and fuels (expressed as Mt of biogenic carbon) in the EU and the potential demand for biogenic carbon for production of plastics and transportation fuels in this region. The potential biomass

³ The energy content of 300 Mt plastics assuming it is the same as for oil is equivalent to 12,5 EJ. Assuming that cellulosic feedstock can be gasified into syngas and then converted to polymers at an efficiency of 50 % it would require 25 EJ biomass feedstock. This is somewhat less than half of the current use of biomass for energy (62 EJ according to REN21 (2017)). Assuming yields of short rotation forestry at 10 tonDS/ha-yr and an energy content of 20 GJ/ton then 25 EJ biomass feedstock would require 125 million hectares of land.

supply includes estimates from (Wiesenthal et al. 2006) EEA of forestry and agricultural residues, various by-products, biowaste and complementary fellings.⁴ It also includes an estimate of the potential supply of biomass crops which is based on the assumption that 10% of the cropland area in the EU is dedicated to production of biomass feedstock.⁵ The potential demand for biogenic carbon for plastics production is illustrated first by the demand for virgin feedstock for the current use of plastics and second by a future scenario where demand for plastics has increased to 62 Mt and plastics recycling has increased to 50% (Material Economics 2018). The figure also illustrates the potential demand for biogenic carbon from the transportation sector, first based on the current use of fuels in this sector (including aviation and shipping) and second for a scenario where two thirds of the fuel use in road transportation has been phased out while fuel use in shipping and aviation remains the same as today. In 2016 liquid biofuels accounted for about 5% of the fuel use in the EU road transportation sector and less for the transportation sector as a whole, which is heavily dominated by fossil fuels (European Commission 2018b).

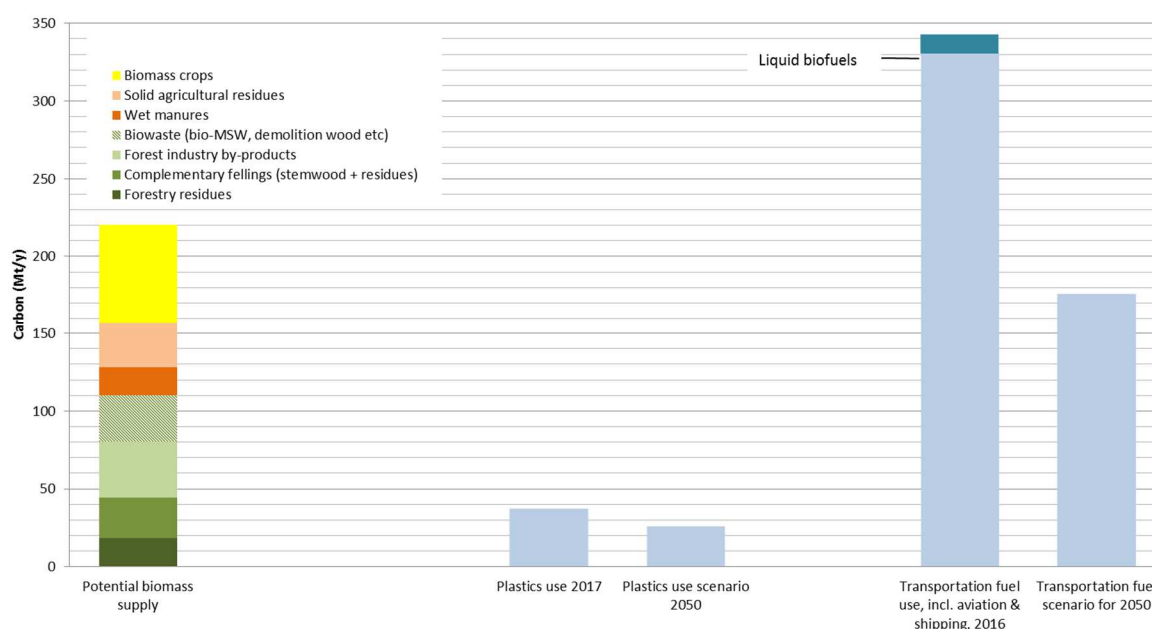


Figure 2: The potential supply of biomass in the EU (expressed as biogenic carbon)⁶ and the potential demand for biogenic carbon for production of plastics⁷ and transportation fuels⁸ based on the current consumption and two scenarios for 2050.

⁴ Complementary fellings is the difference between maximum sustainable harvest level and actual harvest. It includes stem wood and forest residues.

⁵ The cropland area in the EU includes arable land (107 Mha) and land with permanent crops (12 Mha) (Eurostat 2016).

⁶ The potential biomass supply is based on estimates from (Wiesenthal *et al.* 2006) and the assumption that 10% of the cropland area is dedicated to biomass crops (such as short rotation forestry) with a yield of 10 tonDS/ha/y and energy content of 20 GJ/t. The carbon content was calculated based on a CO₂ emission factor for biomass of 100 kg CO₂/GJ (~27 kg C/GJ)

⁷ The demand for virgin carbon for plastics use in 2017 was calculated based on statistics from (Plastics Europe 2018) and the assumptions of 10% recycling and 85% carbon content in plastics. The plastics use scenario for 2050 assumes a plastics consumption of 62 Mt/y and 50% recycling.

⁸ The carbon content in transportation fuels was calculated based on the reported CO₂ emissions from the sector (EC, 2018). The transportation fuel scenario assumes that two thirds of the fuel use in road transportation has been phased out while fuel use in shipping and aviation remains the same

When comparing the potential supply and demand in Figure 2 it should be noted that the conversion of biomass into chemicals, biofuels and plastics generally involve considerable carbon losses, in particular carbon that ends up as CO₂. This CO₂ can be used for production of platform chemicals by applying CCU technologies (Ericsson 2017). Such concepts provide a means to economise with the biogenic carbon but require potentially large inputs of electricity. One Mt of CO₂ converted to methanol would require 136 kt hydrogen, which in turn requires 6.5 TWh electricity.⁹ CCU is thus only relevant in a low-carbon electricity system. From an economic point of view, electricity must be less expensive than the bio-based chemicals/fuels produced. It is a situation opposite from today where hydrocarbons are used to produce electricity. The estimates presented in Figure 2 clearly illustrate the scarcity of biomass and point to the size and importance of the transport sector as a potential competitor for biogenic carbon and CO₂. The figure does not include the energy sector which used about 5.2 EJ of biomass (~140 Mt C) for production of power and heat in 2016 (Eurostat 2017). The CO₂ emitted from large-scale biomass combustion could be used by applying CCU technologies.

⁹ Assuming hydrogen has an energy density of 120 MJ/kg and that the electrolyser has a conversion efficiency of 70%. Assuming a 95% conversion of the CO₂ would yield 14.3 MJ (725 kt) of methanol.

4 Capabilities for change

When considering the capabilities and capacities of actors to drive and sustain change towards a decarbonised plastic system, it is crucial to consider the highly different nature of these actors as well as the many different types of plastic and uses to which they are put. To provide an overview of the sector and assess capabilities for change, we consider industry structure, networks, government policy, and markets, largely following the approach outlined by Wesseling et al. (2017).

4.1 Industry structure

The plastics industry lies on the intersection of the petroleum industry and the chemical industry. To gain an overview, it is useful to distinguish between the production of plastics materials, the conversion of plastics materials, and the production of plastics products as three distinct stages in the value chain.

The plastics manufacturers are the ones which are closest to the petroleum and energy sectors. They are generally large, international corporations with significant resources for research, development and innovation. In many cases plastics manufacturers are simply the chemicals divisions of global energy companies such as ExxonMobil or Shell. In other cases, the energy companies may choose to retain ownership or joint ownership of more independent chemicals companies, such as in the case of Chevron Phillips. But the world's largest plastics manufacturers are the giants of the petrochemical industry, such as Dow Chemical, BASF, Braskem, Sinopec, or SABIC, to name a few (Tullo 2017).

According to the business association Plastics Europe the industry gives direct employment to 1.5 million people, in close to 60 000 companies (mostly small and medium sized enterprises) with a total turnover of 350 billion EUR. Plastics manufacturers provide the feedstock for plastic production by turning mineral oil into polymers. Next in the value chain, plastic converters and compounders use polymers as inputs to produce new plastics materials. Compounders generally mix polymers with other polymers or additives (such as colouring, stabilising, or strengthening components) to produce blended plastic materials with desirable properties for different kinds of products. Converters use these blends or just basic polymers to produce other intermediate forms or end products in various processing machines such as extruders, moulders, printing presses or laminating, coating, and slitting machines. Compounders and converters make up the bulk of the plastics industry, even if manufacturers remain the most profitable in relative terms. Recyclers make up the smallest part of both employees, companies, and turnover, as can be seen in Table 2.

Table 2. Turnover and employment in the European plastic industry. Numbers from European Plastics Converters.

	Companies		Turnover		Employees	
Manufacturers	2 000	3.8 %	100 BEUR	27.6 %	140 000	7.9 %
Converters	50 000	94.3 %	260 BEUR	71.8 %	1 600 000	90.4 %
Recyclers	1 000	1.9 %	2 BEUR	0.5 %	30 000	1.7 %
Total	53 000	100 %	362 BEUR	100 %	1 770 000	100 %

Converters and compounders are commonly smaller actors with less direct dependency on the petroleum sector. As these firms are commonly smaller and have less insight into the technologies concerning the original manufacture of the plastic materials, these actors have few incentives to push a transformative agenda from within the industry. The processes, routines, and technologies used by these actors are

however part of the carbon lock-in of the plastic system as they have all been developed in the era of petro-chemistry, and these actors are thus likely to resist innovation for plastic decarbonisation that would require significant investments, i.e. to this group any type of drop-in solution is probably the most acceptable, even though they do not have a direct stake in or relation to the petroleum sector.

The geography of the plastic sector is complex, as the different types of actors have diverging incentives to locate in particular settings. Manufacturing of the basic monomers and polymers is most often an integral part of petro-chemical clusters, and many times also physically connected to petroleum refineries, due to integrated flows of intermediates, products, and utilities. As the knowledge base of these industries is similar these regions are likely to have strong competence in these areas to draw upon. Compounders and converters are however less likely to be located in the same type of setting, as their needs in terms of material and immaterial resources differ significantly from those of plastic manufacturers. These firms, which are also smaller, are instead more likely to be found in regions with other manufacturing industry. Users of plastics on the other hand are ubiquitous and everywhere. There is thus not one geography of the plastic sector but several, layered geographies at play.

4.2 Networks

As described in the previous section, there is a ‘special relationship’ between the chemical and (fossil) energy industries, that still remains intact (Bennett 2007). This relationship is evident both in terms of organisational and material structures, such as the integration of fuels and chemicals production within multinational corporations, e.g. ExxonMobil and BP, and the flows of feedstocks and products between petroleum refineries and chemical production plants, e.g. in large petrochemical clusters such as Rotterdam (NL) and Baton Rouge (USA). The relationship between the chemical and energy sectors is also institutionalised in the knowledge base of chemical engineering, which has become the foundation for operations in petroleum and natural gas processing as well as chemical production since its emergence in the early 20th century (Rosenberg 2000).

These networks may also take the form of corporate interlocks through governance and share-holding arrangements. For example, Petrobras is a majority shareholder in Braskem. Executives from the energy and chemical industries also frequently sit on multiple boards of directors for companies in the other sector – a practice which is referred to as ‘interlocking directorates’ (Buch-Hansen 2014).

4.3 Government policy and regulation

The globalised and complex nature of the plastic system, involving different types of actors (large manufacturers, smaller converters, compounders, and recyclers) at different points in the value chain, makes it difficult to regulate through national policies, which is most likely the reason that regulation has been lagging, with the exception of specific issues, e.g. toxicity of plastic components. Flows of feedstocks, intermediates, and products are international, as are many of the firms that make up the powerful segment of plastic manufacturers, albeit that downstream actors such as compounders and converters are less international. At the same time, all facilities are indeed located in specific places, and affected by local regulations, rules, and norms. This multi-scalarity necessitates coordination between different types of policy on different political scales.

Indeed, the plastics sector is characterised in global governance terms as ‘having no one in the cockpit’ (Hajer et al. 2015) – in other words, no one is doing any steering of the sector as a whole. There is no globally recognised political or scientific body tasked with defining and addressing the problems and potentials of plastics. Instead, developments in the plastic sector are shaped in large measure by the

investment decisions of the largest plastics producers as well as patterns of consumption and demand rather than by government policy. The plastics industry has been largely successful in framing themselves as a sector that lies beyond the immediate considerations of the climate change debate. Sustainability issues in the chemical industry and its subsectors have mainly been connected to toxicity of specific products and emissions, and issues related to the safety of production (Johnson 2012). Additionally, the petrochemical industry has actively shielded themselves from regulation in the past by resisting the initiatives of different governments, instead offering up internal systems of self-regulation. These have however largely been criticised as being ineffective (Hoffman 1999; Rees 1997).

Having said that the politics of plastics is dispersed and piecemeal, targeting individual links of the value chain in geographically circumscribed settings, it is also important to note the recent arrival of larger and more ambitious political strategies addressing global and regional plastics concerns. All of these, however, address plastic only as marine litter: the G7 and G20 recently laid out action plans on the matter (G20 2017; G7 2015), the United Nations has formed a Global Partnership on Marine Litter and passed a resolution on marine litter and microplastics in its Environment Assembly (UN Environment Assembly 2017), and the EU highlighted plastic marine pollution when it hosted the 'Our Ocean Conference' in Malta in 2017. High-level political attention is converging on plastics as an environmental problem facing mainly the health of our oceans. A directive regulating certain types of single-use plastics and fishing gear has also been presented by the European Commission (2018b) to reduce the most common types of plastic marine litter.

Much of this has certainly been influenced by NGO and media attention to this exact aspect of plastic pollution. Influential NGOs and alliances, such as Break Free From Plastics, the Plastic Pollution Coalition, and Five Gyres have done much to make the impact of plastics on marine ecosystems tangible and salient. Images of wildlife entangled in plastics, the plastic contents of their stomachs, and artificial plastic garbage islands (such as the 'Great Pacific Garbage Patch') have brought these issues to the forefront of the public discourse. NGOs have also tended to organise environmental campaigns centred on specific plastic objects, such as the plastic bag, microbeads, water bottles, cotton buds, straws, disposable cups, and so on. The combination of these things has galvanised public opinion in recent years, but it is still unclear which forms eventual solutions will take. Although many different countries have responded especially to campaigns on plastic objects by banning or regulating bags, bottles, and microbeads, treating the environmental problems of the plastic sector as pertaining mainly to marine pollution is not likely to induce the type of large-scale, globally relevant transition that decarbonisation requires (see also section 3.1 Reduced use of plastics).

One set of policy responses that are taking a more holistic and integrated approach to the plastic sector by addressing the entire value chain from production to waste and recycling are those emphasising circular economy principles. These initiatives were put on the map by several influential reports (Ellen MacArthur Foundation & McKinsey Center for Business and Environment 2015; World Economic Forum et al. 2016; World Economic Forum & Ellen MacArthur Foundation 2017). The organisations behind these reports are also leading a new global collaboration around a circular use of plastic packaging together with consumer product brand owners, packaging producers and plastic manufacturers (UN Environment 2018). This commitment clearly works along the pathways of reducing use and recycling plastics, although the motivation here is more about reducing marine littering than decarbonising plastics. Recently, the EU launched its new strategy for plastics in a circular economy, which takes aim at the European plastics sector in total (European Commission 2018a). At this point in time, the purpose of the strategy is to provide a vision and possible roadmap for the decades ahead. Some of the proposed targets include: (1) by

2030, all plastics packaging placed on the EU market is either reusable or recyclable; (2) to increase recycling capacity fourfold from 2015-2030, leading to the creation of 200,000 new jobs; (3) to establish a market for recycled and innovative plastics, in part by increasing demand for recycled plastics fourfold; and (4) to incentivise consumers towards more sustainable consumption and recycling patterns. By emphasising circular economy principles, the EU may be favouring decarbonisation transitions towards more recycling and fewer types of plastics, potentially to the detriment of bio-based plastics, biodegradability, or decreased use and consumption of plastics. Critics have also pointed out that the plastics strategy may clash with chemicals safety rules (Hervey 2018).

4.4 Markets

Figures from Plastics Europe show that global production of plastics is increasing year on year, reaching 335 million tons in 2016 worldwide, with 60 million of those tons produced in Europe. The great majority of this production (50 million tons) is used by plastic converters in Europe, whose main applications are packaging (40%), building and construction (20%), automotive (10%), electrical and electronic (6%), household, leisure, and sports (4%), agriculture (3%), and others (appliances, furniture, medical, etc. – 16%) (Plastics Europe 2018).

Packaging, which as shown above is the main application for plastics, is a type of application in which both qualities and margins are lower than more specialised applications, thus making the opportunities for significant innovation efforts lower. As this is the application with the most visibility among consumers and in the general discourse about plastics, there is a growing notion that the problems associated with these products have to be handled. These problems are however not mainly connected to the fossil content but rather to the littering aspects, as discussed earlier. Increasing pressure on plastics used for packaging and disposable products close to end consumers to not add to these problems may push the development along the pathway of biodegradable plastics which may also involve a large degree of bio-based ones. Industrial packaging on the other hand may well follow different logics and pathways, and increased recycling back through the value chain might be closer at hand than a transition towards biodegradable plastics. The needed capabilities for either of these pathways do however not lie with the converters, although these have a potential to act as intermediaries for such developments.

Energy efficient and sustainable construction is another change that may increase demand for decarbonised plastics. It is also possible that automotive manufacturers will want to meet demand or profile themselves by producing bio-based parts for cars. In general, consumers exercise a high degree of power to demand more sustainable types of plastic products given that packaging has become so visible and politicised and remains the largest use of plastics. But the vastly different requirements and driving forces in different markets for plastics (from stable material for construction and long-term applications with very high quality requirements to packaging and disposables with high visibility for consumers, high turnover and high risk of littering) may constitute a barrier to a concerted market pull towards decarbonisation.

5 Current initiatives

The space of current initiatives in the plastic sector is as varied as the sector itself. As it will not be feasible to provide a comprehensive overview of current initiatives towards decarbonisation of the sector, this report can present only a few examples that showcase initiatives along different parts of the value chain and comprising different kinds of actors. More examples can be found in the REINVENT Decarbonisation Innovations Database (Hansen et al. 2018) that covers 33 cases related to the whole plastic value chain (11 for production, 8 for consumption, 3 for recycling, and 11 for finance). Simultaneously, there are initiatives and projects aimed at exploiting current fossil based plastics further, which further entrench the system in its carbon lock-in.

From the consumer end of the value chain, the plastic sourcing strategies of firms are increasingly becoming politicised as demand for more sustainable and environmentally friendly solutions increases among consumers. Global brand owners have presented plans to change parts of their production to bioplastics and/or recycled plastics. These actors have both been praised for their ambitious targets, and criticised for symbolic gestures that will not provide significant structural changes for plastics. Two high-profile firms which are making moves to accommodate this pressure are the Coca-Cola Company and Lego. Since 2009 Coca-Cola has been working to scale up their PlantBottle technology, which was the first fully recyclable PET plastic beverage bottle made partially from plants. Their goal is to convert all new PET plastic bottles in their production to up to 30% plant-based PlantBottle packaging by 2020. As of 2015, PlantBottle packaging accounts for 30% of the company's packaging volume in North America and 7% globally, which is the equivalent of 6 billion bottles per year (Coca-Cola Company 2015). According to company figures, this has eliminated 315,000 metric tons of carbon dioxide emissions. Through licensing agreements and strategic partnerships with, among others, Heinz, Ford, Nike, and Procter & Gamble, Coca-Cola is working to accelerate the development of plant-based PET materials.

In 2018, LEGO launched their first bricks made from bio-based plastic (LEGO 2018). The botanical elements that they offer in play boxes, such as leaves, bushes, and trees, will be made from plant-based plastic (PE) sourced from sugarcane. Although they are bio-based, the new bricks are technically identical to fossil-based bricks and live up to the same high standards for quality and safety. To ensure that the required raw materials are responsibly sourced, and to build demand in general for sustainably sourced bioplastic, LEGO has partnered with the World Wide Fund for Nature (WWF) and joined their initiative called the Bioplastic Feedstock Alliance. PE elements, however, only account for a small minority of the approximately 60 billion plastic elements produced by LEGO each year. But LEGO is expanding their search for sustainable alternatives to other materials, including packaging, in line with their strategy of achieving fully sustainable materials by 2030. In 2015, LEGO invested 1 billion DKK towards this strategy, including the establishment of a new Sustainable Materials Center with more than 100 employees. There is also a large number of small companies that seek to provide solutions. Some are already demonstrating that transitioning towards a low-carbon plastic system is possible. For example, BiOBUDDi are already making bioplastic toy bricks, something which LEGO hopes to achieve by 2030. In this way, smaller brands show the feasibility of low-carbon plastics.

With mounting pressure on the plastic sourcing strategies of firms (particularly in the area of packaging), pulp and paper manufacturers have seized the opportunity to move into the space by offering new bio-based alternatives to plastics. There is a fast-growing market for plastic substitutes, which is reconfiguring patterns of competition in both the plastic sector and adjoining ones. The Finnish pulp and paper manufacturer Stora Enso recently unveiled a new material, called DuraSense, which is a composite made

of wood fibers (30-60% depending on product grade), polymers (bio-based or fossil-based), and additives (Stora Enso 2018). The material can mimic the mouldability of plastic and can be used to make a wide variety of goods, including car parts, kitchen utensils, and bottle caps. A similar material, called Durapulp, is also marketed by Swedish forestry cooperative Södra (Södra 2018). Durapulp is a composite of wood fibre and the bio-polymer PLA (polylactic acid). The Finnish innovation Paptic is claimed to be a new wood fibre based material that can replace plastic and paper in uses such as shopping bags and decorated/designed packaging. It is renewable, biodegradable, and recyclable like paper but has material characteristics of plastics as well (Paptic n.d.). To the extent that these new wood fiber and plastic composites are produced from sustainably sourced biomass, they can potentially have a positive impact on the global carbon balance. Questions remain as to the scalability of such new materials, given the massive extent of fossil-based plastic production they are looking to replace (see also section 3.3 Bio-based plastics). Plastics based on carbon capture is exemplified by AirCarbon, developed by Newlights Technologies. AirCarbon uses carbon in unconventional methane sources (from a farm, water treatment plants, landfills, and energy facilities) to make plastic materials and is claimed to be a carbon negative plastic (Newlight Technologies 2018).

The world of retail is also beginning to feel the pressure of consumer dissatisfaction with plastic packaging. Retail is important to consider, because 40% of plastic production goes towards packaging. There are a variety of initiatives within the sector. At one end of the spectrum, entirely plastic-free, zero-waste stores have multiplied across Europe in recent years, especially in Germany and France. Such initiatives present a potential for inducing consumers and suppliers towards more sustainable practices and habits (Beitzen-Heineke et al. 2017). At the other end of the spectrum, several large, existing retailers have committed to various initiatives towards reducing or eliminating their plastic use. Examples include the British frozen foods retailer Iceland, which was the first major retailer to pledge to eliminate plastic packaging for its own label products within five years (Slawson 2018), and Waitrose, another British retailer, which has announced that it will remove all black plastic (which has lower recyclability) used in its meat, fish, fruit, and vegetable products (Carrara 2018). There are also retailers introducing plastic-free aisles within conventional supermarkets, such as Ekoplaza in the Netherlands, largely responding to awareness-raising campaigns of NGOs such as A Plastic Planet (Taylor 2018a). This NGO is also behind a recent plastic-free eco-label or 'trust mark' that allows shoppers to see at a glance whether retail products use plastic in their packaging (Taylor 2018b). The Chilean company Algramo has launched a reusable packaging system with dispensers and multiple-use containers instead of single-use sachets. Their customers buy multiple-use plastic containers that they can then give back to the store once they cannot be used any more, aiming for a solution that both reduces the use of plastic packaging and cost for consumers. Its existing system is claimed to reach more than 220,000 customers through 1,600 stores (Algramo 2018).

Large multinationals from the petroleum industry have invested heavily to keep the current system with cheap petro-based plastic in place (see also section 2.2 Feedstock use and CO₂ emissions). As detailed in previous sections, there is a strong infrastructural lock-in, which has been built up over several decades and is growing stronger with the availability of (cheap) shale gas. The influence of the petrochemical actors extends beyond the production sector. Through subsidiaries, buy-ups and supply chains, petrochemical actors have influence over the downstream parts of the plastic system. For example, Koch Industry owns Cordura, which produces synthetic fibres for a range of especially 'green' outdoor textile companies including Patagonia. Borealis has acquired plastic recyclers MTM and Ecoplast, which on the one hand signals a commitment to a circular economy thinking, while on the other extends the influence of (petro-based) producers on what a circular plastic economy will look like. In the USA, the plastic producers have spent millions on fighting legislation in particular plastic bag regulations seeing this as a "tipping point"

for the whole industry (Romer & Foley 2012). Some petrochemical companies are active in the bioplastic sector, e.g. Total Corbion, DuPont, BASF, and Petrobras. Moreover, there is not a strong focus from these actors on reducing the use of plastic (packaging), and in the case of biodegradable plastics it can potentially complicate plastic recycling systems.

6 Conclusions and outlook

The system of production and consumption of plastics is a complex one. Value chains are often long and intertwined with those of multiple types of products, as plastics many times constitute but a part of other products such as food, vehicles, or buildings. Just as plastics are designed by manufacturers and compounders to have different properties for these different applications, consumers have very different relations to the different types of plastics – evident in the public discourse around the sustainability of plastics which has become focused on plastic packaging and single-use items, while ignoring other large categories of plastic products. At the same time, the challenge of decarbonisation is shared across these categories, as they are currently all produced from fossil resources such as petroleum naphtha or natural gas liquids.

The structure of the industry, with manufacturers of the basic polymers being integrated with, or closely connected to, the petroleum industry, is a significant barrier for decarbonisation. Although there are new actors aiming to enter the market with different types of sustainable plastics, the power of incumbent actors and their vested interests should not be underestimated. Leveraging their resources towards decarbonisation is thus most likely a key for decarbonisation to gain any momentum.

Three different pathways for decarbonising pathways have been identified: reducing the use of plastics applications where it can be removed or substituted, while at the same time ensuring that substitutes do not increase the environmental impact in other aspects; increasing recycling to close the loop of plastics, which most likely also requires new ways of designing, standardising, and tracking plastic materials for maximised recyclability; producing plastics from biogenic carbon although this increases the competition for resources between different utilisation pathways of biomass resources. These pathways are in many ways complementary and can be developed together, but that will require coordination and most likely different types of trade-offs which may be resisted by some actors.

This type of coordination for development towards a specific direction has hitherto been lacking and is a key area for the governance of a decarbonised plastic system. Despite a reluctance by traditional key actors to tackle the challenge that decarbonisation is – shown by continued investments in petro-based production – other types of actors are pressuring for a new direction. As consumers are far removed from the manufacturers and compounders and more interested in the properties of the products that they are buying (quality of food or performance of a car etc.) than those of the associated plastic materials, consumer pressure has traditionally been absent in the sector. However, global brands closer to consumers have the possibility to introduce a new type of dynamic and power over the future development of the sector. Opening up the debate and politics around plastics to not focus on plastic materials themselves could thus be a way of indirectly creating increasing pressure on the sector to decarbonise.

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