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Quantifying environmentally relevant and circular plastic innovation: Historical trends, current landscape and the role of policy

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This Working Paper presents the underlying technical analysis quantifying environmentally relevant innovation in plastics. It has been authored by Damien Dussaux and Shardul Agrawala. The paper was discussed by WPIEEP at its meeting in March 2021. It was subsequently integrated as a shorter version with key findings, as Chapter 5 “Innovation in plastics” into the Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options”, which was declassified by EPOC and published in February 2022. Following the publication of the Global Plastics Outlook this full analysis is now being published as a technical working paper.

Authorised for publication by Alain de Serres, Acting Director, Environment Directorate.

Keywords: Innovation, Circular Economy, Plastics, Recycling, Waste, Environmental Policy

JEL Codes: O31, O38, Q53, Q55, Q58

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Abstract

Innovation is key to reducing the environmental impacts of plastics. However, literature is generally lacking in the field of environmentally relevant plastics innovation. This paper develops an innovative conceptual framework to document and map environmentally relevant plastics innovation. Using this framework, it develops plastics innovation metrics using patents and trademarks to quantify trends over time, across countries, and to establish preliminary empirical links between policies and innovation outcomes.

Plastic waste prevention and recycling innovation has increased slightly more rapidly than overall plastics innovation. In contrast, innovation in bioplastics have witnessed a significant slowdown in recent years. Another key finding of this analysis is that environmentally relevant plastics innovation is concentrated in OECD countries and China and that top inventor countries are not specialized in the same technologies. Finally, the patent analysis shows some empirical evidence that recycling regulations may have triggered innovative activity in plastic recycling.

Keywords: Innovation, Circular Economy, Plastics, Recycling, Waste, Environmental Policy

JEL Classification: O31, O38, Q53, Q55, Q58

Résumé

L'innovation est cruciale pour réduire les impacts environnementaux des plastiques. Cependant, la littérature sur l'innovation pertinente pour l'environnement dans le domaine des plastiques est généralement insuffisante. Ce papier développe un cadre conceptuel innovant visant à documenter et cartographier l'innovation pertinente pour l'environnement dans le domaine des plastiques. Le papier utilise ce cadre pour développer des indicateurs d'innovation basés sur les brevets et les marques déposées pour quantifier des tendances au cours du temps et pour différents pays, et établir des liens empiriques préliminaires entre les politiques publiques et la quantité d'innovation produite.

L'innovation centrée sur la prévention et le recyclage des déchets plastiques a augmenté légèrement plus rapidement que l'innovation dans le domaine des plastiques en général. Inversement, l'innovation dans les bioplastiques a connu un ralentissement significatif ces dernières années. Un autre résultat clé de cette analyse est que l'innovation pertinente pour l'environnement dans le domaine des plastiques est concentrée dans les pays de l'OCDE et en Chine et que les principaux pays inventeurs ne sont pas spécialisés dans les mêmes technologies. Enfin, l'analyse des brevets fournit quelques preuves empiriques que les réglementations en matière de recyclage ont probablement stimulé l'innovation dans le recyclage des plastiques.

Mots clés : Innovation, Économie Circulaire, Plastiques, Recyclage, Déchet, Politique Environnementale

Classification JEL : O31, O38, Q53, Q55, Q58

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Executive Summary

Innovation is increasingly recognised as key to reducing the leakage of plastics into the environment, as well as for reducing other environmental impacts of plastics such as the greenhouse gas emissions linked to their production. However, unlike environmental problems like climate change and air pollution where there is extensive evidence on green innovation, such literature is generally lacking in the field of environmentally relevant plastics innovation.

This paper develops, for the first time, a conceptual framework to document and map environmentally relevant plastics innovation, with an emphasis on innovation related to plastic waste prevention and recycling. Well-established indicators – most notably patents and trademarks – are then deployed to develop plastics innovation metrics and quantify trends over time, across countries, and to establish preliminary empirical links between policies and innovation outcomes.

While the analysis presented in this paper is built primarily around patents, the paper also highlights several types of environmentally relevant plastics innovation where trademarks have an equal or potentially more important role to play. This is, for example, the case for reusable plastic goods where there are a much larger number of registered trademarks than patents. Meanwhile, in the case of innovation for repair, both trademarks and patents are important. Trademarks can measure non-technological innovations that are not reflected by patents and contrary to traditional indicators of innovation, trademarks are used in almost every sector of the economy, including services.

Environmentally relevant patented plastics innovation increased by a factor four globally between 1990 and 2017. The growth in patented innovation for plastic circularity, that is innovation for plastic waste prevention and recycling, was slightly slower (a 3.8 times increase), while innovations related to biobased feedstock and to the conversion or disposal of plastic waste grew slightly faster than the overall average (a 4.7 times increase). However, innovation in bioplastics (both bio-feedstock and biodegradables), in particular, have witnessed a significant slowdown in recent years due to their mixed environmental impacts.

Despite the recent growth in circular plastics innovation, the number of such innovations remained only around 1% of all patented innovations in plastics between 1990 and 2017. Within circular plastics innovation, more mature technology fields like mechanical recycling and sorting of plastic waste, as well as repair, tend to dominate patenting activity. Meanwhile, innovation in plastic-to-plastic chemical recycling technologies currently constitutes a relatively small share but has grown rapidly between 2010 and 2017. Upstream innovations related to design for recycling or reuse, meanwhile, constitute a relatively small share of such innovations. This may however partially reflect the intrinsic nature of such innovations, which may not lend themselves as easily to patenting.

Another key finding of this analysis is that environmentally relevant plastics innovation is concentrated in OECD countries and China and that top inventor countries are not specialised in the same technologies. Japan, for example, leads by a significant margin patenting in circular plastic technologies and biobased plastic feedstock. The European Union, meanwhile, leads in the number of patented innovations related to the conversion or disposal of plastic waste and to leakage removal, followed closely by the United States and China.

The patent analysis in this paper also shows empirical evidence that recycling regulations may have triggered innovative activity in plastic recycling. Preliminary analyses of the 1991 German Packaging Ordinance and the 1995 Packaging Recycling Act in Japan both show an increase in plastic recycling innovation activity relative to the counterfactual. The quantification of plastics innovation, as shown in this paper, allows for further development and evaluation of the impact of other policies on innovation outcomes.

There are three major policy implications from these findings. First, considering that the share of circular plastics innovation in all plastics innovation has not changed during the last two decades, much more ambitious policies are needed to redirect plastics innovation towards circularity. These policies can take various forms. The paper finding suggests that EPR systems are effective at triggering innovation. Yet, the use of EPR system is far from being mainstream over the globe. Some EPR systems include bonus-malus eco-modulation for plastics packaging where for example the fees paid to the Producer Responsibility Organisation is lower if the packaging incorporates 50% or more secondary raw material. This further increases the demand for secondary plastics and can thus incentivise innovation in plastic recycling. In addition to circular economy policies, innovation policies might also play a critical role. For example, R&D subsidies that are attributed via competitive calls for proposal could help credit constrained firms to develop innovative solutions in areas that deliver high public benefits and are not necessarily profitable for firms.

Second, policies that aim to support innovation in plastic circularity should target innovation related to the prevention of plastic waste. The paper shows that there are more patents in technologies that are dealing with the treatment of plastic waste than patents in technologies related to the reuse, durability and repair of plastic goods. Environmental impacts of plastics can be better addressed if the latter technologies are promoted.

Third, there is a need to accelerate the international transfer of circular plastics technologies, especially towards developing countries but also between OECD countries. Innovation improving plastic circularity is highly concentrated in OECD countries and China. Yet, plastics is produced is used in all countries in the world and plastic leakage to the environment is particularly significant in many emerging and developing economies. The paper also reveals significant heterogeneity between OECD countries across the different categories of circular plastics technologies, highlighting the benefit of accelerating technology transfer within the OECD as well.

1 Introduction

Plastics are important materials that are used in a very wide range of applications in all sectors of the economy. The volume of plastic produced has been rising continuously and the world produced an equivalent of 460 million tonnes of plastic or 60 kilogrammes of plastic per capita in 2019 (OECD, 2022[1]). In the recently published Global Plastic Outlook, the OECD estimates that only 9% of plastic waste was ultimately recycled in 2019 (OECD, 2022[1]).

Almost 72% of the 353 million tonnes of plastic waste finish their life in landfills or in the natural environment and around 22 million tonnes of plastics leak into the environment every year (OECD, 2022[1]). The concerns around leakage are reinforced by the presence of chemical additives in plastic such as plasticizers, fillers and flame-retardants. Some of these additives may be hazardous to the environment and/or to human health, via direct exposure or after a certain threshold concentration (Watkins et al., 2019[2]). Furthermore, close to 99% of plastics are made from fossil fuel feedstock (European Bioplastics, 2019[3]). In addition, the carbon emissions associated with plastic production, estimated at 1.8 gigatonnes (Gt) of CO_2-equivalent (CO_2e) per year, are significant and represented 3.4% of the global annual GHG emissions in 2019 (OECD, 2022[1]). Reducing the environmental footprint of plastics is therefore an urgent global priority.

Circular business models can support the transition to a more resource efficient and circular economy but they currently represent a small share of the economy (OECD, 2019[4]). While certainly not a panacea, innovation has a central role to play in the emergence of new circular business models ad in the search for substitutes for non-essential uses of plastics; for closing and slowing plastic material flows[1]; to reduce plastic leakage into the environment; in the monitoring, capture and removal of plastic waste; and for reducing the environmental footprint of plastic feedstock. In 2018, the G7 launched an Innovation Challenge to Address Marine Plastic Litter, which seeks to promote “innovative social or technological solutions for a more sustainable management of plastics throughout their lifecycle” (G7, 2018). The deployment of such innovative solutions is similarly emphasised in the G20 Implementation Framework for Actions on Marine Litter (G20, 2019).

Despite this growing attention, there is very little analytical work to *conceptualise the scale and diversity* of plastics innovation to combat marine litter or the broader environmental impacts of plastics, let alone to *quantify* the pace of innovation, its *evolution over time and across countries*, or the *impact of policies* to drive plastics innovation in these areas. This paper is the first attempt to fill these key information gaps. In Section 2 the paper develops a framework to classify plastics innovation relevant for circularity and for the reduction of broader environmental consequences. In Section 3, the paper develops measures to quantify innovation in plastic technologies in these areas. Section 4 unpacks the different trends in environmentally relevant plastics innovation across technology fields and across time. Section 5 analyses the geography of environmentally relevant plastics innovation. Then, Section 6 uses the new plastics innovation metrics to examine empirically the extent to which policies might affect such innovation. Finally, Section 7 concludes.

[1] Closing resource loop means ensuring that plastic material does not get out of the system of re-use and recycling. Slowing down resource flows means reducing the quantity of material required for a good or equipment to provide a particular service for a given period of time. In other words, it means reducing inflows of new plastics into the economy. Improving the durability or service life of goods made of plastic is slowing down plastic resource flows.

2 Classifying plastics innovation

The central focus of this paper is on plastics innovation to reduce plastic waste generation and its leakage into the environment, which has been the primary driver for the international and domestic policy responses around the world. However, given the close interlinkages between plastics production, fossil fuel use and climate change, innovations that reduce the greenhouse gas footprint of plastic production are also examined.

Therefore, innovations environmentally relevant plastic technologies for the purposes of this paper address three main objectives:

- Prevention and recycling of plastic waste to reduce the production of new plastics and the generation of plastic waste (also called circular plastics technologies in this report);
- Conversion or disposable of plastic waste and removal of plastic leakage into the natural environment[2];
- Switching from fossil-based feedstock towards biobased feedstock to reduce greenhouse gas (GHG) emissions.

Figure 2.1 provides the detailed classification adopted in this paper.

Figure 2.1. Classification of innovation in environmentally relevant plastics technologies

PREVENTION & RECYCLING TECHNOLOGIES	CONVERSION OR DISPOSAL OF WASTE & LEAKAGE REMOVAL	BIOBASED FEEDSTOCK
Prevention Design for longer lifespans, light weighting or recycling Reuse and repair **Recycling** Sorting plastic waste Mechanical recycling Plastic-to-plastic chemical recycling Enabling digital technologies	**Conversion or disposal of waste** Biodegradable plastics Plastic-to-fuel conversion Waste to energy Sanitary landfill **Leakage removal** Mitigating release at the source Removing from wastewater Monitoring and removing from nature	**Feedstock** Crop-based feedstock Algae-based feedstock Fungi-based feedstock Other biomass

Note: *Mismanaged plastic waste are plastic waste that are landfilled, littered and leaked into the natural environment.
Source: Own elaboration of the authors.

2 In this classification, chemical recycling is split between two categories: recycling technologies and conversion or disposal of waste. The reason is that chemical recycling aggregates two innovation families that do not have the same main environmental outcome. Plastic-to-plastic chemical recycling innovation contributes to the closing of plastic loops and thus to prevention and recycling while plastic-to-fuel innovation mitigates the impact of mismanaged waste but does not close plastic loops.

The first category covers circular plastics innovations and is sub-divided into two subcategories: prevention and recycling. First, innovations that prevent the use of new plastics and the generation of plastic waste by designing goods and equipments using smaller quantities of plastics designs or that have longer service life, reusing products, improving recyclability, and repairing plastic goods. The second subcategory covers innovations that improve plastics recycling by sorting plastic waste and recycling plastic waste by mechanical or chemical means. It also includes enabling digital technologies such as artificial intelligence.

The second category contains innovations related to the conversion or disposal of plastic waste and to the removal of plastic leakage into the natural environment. This is further sub-divided into two categories. First, innovations related to biodegradable plastics and innovations that convert compostable plastics such as bio-waste treatment, plastic waste to fuel, plastic waste to energy and sanitary landfill. Second, innovations that mitigate the leakage of plastic into the natural environment including technologies for monitoring macro and micro-plastics, mitigating plastic release at the source from personal care products, textile washing and road wear, and removing plastics from wastewater and cleaning rivers and oceans.

The third category is not related to plastic waste generation or its leakage to the environment, but to greenhouse gas emissions. It covers innovations for switching away from fossil-based feedstock, including plastic synthetized from crop, algae and fungi. These biobased plastics can, in some circumstances, emit lower amount of GHG during their life cycle.

The above classification does not indicate all the environmental impacts of the different plastics innovation but rather focus on the main objective of the innovation. For example, switching towards biobased plastics decrease GHG emissions but is associated with larger land use environmental impacts.[3] Similarly, waste-to-energy plants generate significant pollution and biodegradable plastics face many environmental challenges.[4] In addition, sanitary landfill should be considered as the treatment of last resort since it is only beneficial when it substitutes for unsanitary landfill or litter.[5] Conceptually, investing in sanitary landfill remains problematic as it delays the closing of resource loops that is the most effective way to reduce the environmental impact of plastic waste. Finally, the above classification does not explicitly classify innovation according to their impact on health due for instance to chemical exposure. This would require another classification based on polymer type and additives.

[3] Generally, biobased polymers have better climate and energy performance than their fossil-based counterparts. However, the production of biobased plastics generates indirect land use impacts by pushing the transformation of forests into agricultural land. Consequently, they have larger impacts in terms of acidification, eutrophication and carbon depletion of cultivated soil due to the agricultural production of their feedstock (Groot and Borén, 2010[23]; Danish Environmental Protection Agency, 2018[24]; Edwards, C.; Fry, J. M., 2011[25]; Gironi and Piemonte, 2011[26]; Belboom and Leonard, 2016[27]; Tabone et al., 2010[28]).

[4] First, the necessary conditions for biodegradable plastics to fully degrade are not met in the natural environment (Farah, Anderson and Langer, 2016[9]; Wierckx et al., 2018[10]). Second, there is evidence that mismanaged biodegradable plastic waste remain in the environment and break into smaller debris (Napper and Thompson, 2019[11]). Third, some biodegradable plastics can be ecotoxic in the natural environment (OECD, 2013[12]; Souza et al., 2013[13]; Kershaw, 2015[14]; Adhikari et al., 2016[15]).

[5] While sanitary landfills limit leakage of hazardous leachate into the environment compared to unsanitary landfills in the short run, they accumulate leachate that contains micro-plastics and hazardous compounds such as aromatic and halogenated compounds, phenols, pesticides and several heavy metals over time (Fernandes et al., 2015[29]). The accumulated leachate requires remediation treatments such as electrochemical processes, but these are difficult or impossible to apply to large volumes and consumer energy.

3 Tools for measuring plastics innovation

Overview of innovation indicators

Several indicators exist to measure innovation, including patents, trademarks, industrial designs, R&D expenditure, scientific publications, venture capital, and research funding. Table 3.1 summarises their main advantages and drawbacks.

Table 3.1. Main advantages and drawbacks of indicators measuring innovation

	Main advantages	Main drawbacks
Patents	- organised and comprehensive information - identification of narrowly defined technological fields - capture innovation of significant value	- not always reaching commercialisation - heterogeneous value - not the only appropriation strategy - do not capture organisational innovation or low-tech
Trademarks	- capture commercialized innovation - used in all sectors including services	- focus on products rather than processes - cannot identify narrowly defined technological fields - less stringent measure of novelty
Private R&D expenditures	- capture also non-patented inventions - continuous measure proportional to the value of the invention	- difficult to collect - measure innovation effort and not output - cannot identify narrowly defined technological fields
Scientific publications	- organised and comprehensive information	- capture scientific interest rather than innovation
Deployment level indicators	- can be linked to environmental impacts (GHG abatement, material saving, etc.)	- difficult to collect

Source: Own elaboration of the authors.

Patent data

A patent is an exclusive right granted to an inventor to use and sell their invention for a certain number of years. Patent counts are a common way to measure innovation (Narin, 1995[5]). Using patent counts as a measure of innovation outcome presents the following advantages.

First, patentable technologies must be non-obvious, novel to the local context and susceptible to industrial application. Second, applying for a patent is costly so that inventors do it exclusively for innovations that have significant value. Third, patents contain important information such as the applicant and inventor country of residence, the year of the patent application, and the countries in which the technology has been patented. Most importantly, patents contain texts that provide the detailed characteristics of the innovation.

Finally, there are plenty of data available on patent. Notably via the PATSTAT database created by the European Patent Office (EPO) in 2006 that is nearly comprehensive and allows for the identification of patents in almost any country and in any technology field. PATSTAT has near global coverage, although one notable exception is India, which is not included[6]. PATSTAT is organised according to the Cooperative Patent Classification (CPC) scheme, which was jointly developed by the EPO and the U.S. Patent and Trademark Office (USPTO). However, there is currently no CPC codes for the environmentally relevant plastics innovations described above except for biobased packaging, plastic repair and plastic waste recycling (see Annex A).

Despite having many advantages, using patent data to measure innovation is not perfect. Many patented inventions are never commercialised and therefore do not reflect technological deployment. Patents are also heterogeneous in terms of value and quality. Firms may also patent for more strategic reasons, or not resort to patenting but other tools such as trade secrets. Patents are also focussed on technologies and do not capture organisational innovation.[7] Furthermore, low-technology innovations are also absent from the patent data since they are not protected by intellectual property rights.

Finally, emerging innovations such as those limiting plastic leakage into the environment are difficult to capture using patent data. For these technologies, only a handful of patents have been filed so far and the time period is too short to measure meaningful trends.

Trademarks

A trademark is any sign, or any combination of signs, capable of distinguishing the goods or services of one undertaking from those of other undertakings. Trademarks offer several advantages. First, trademarks do not have the disadvantages generally associated with the traditional innovation indicators such has R&D expenditures and patents. Contrary to those traditional indicators, trademarks correspond to the commercialisation of products as they are used to sell new products or new services on the market (Millot, 2009[6]). Second, trademarks can measure non-technological innovations that are not reflected by patents and R&D data. Third, contrary to traditional indicators of innovation, the range of trademarks used is very large. Trademarks are used in almost every sector of the economy, including services.

Using trademarks as indicator of innovation also comes with challenges. First, trademarks make it difficult to identify narrowly defined technologies, especially processes, as they cover bundles of products and services and some trademark descriptions are too vague. For instance, a description containing recycling waste does not tell us what type of recycling technologies is registered under the trademark. Another illustration is that a single trademark can cover waste-to-fuel equipment as well as mechanical recycling equipment. Second, trademarks also capture products that do not represent a technical novelty. The only criterion to register a new trademark is the novelty of the sign itself, which must not be similar to any

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[6] Indian patent office data are not available to PATSTAT.

[7] These challenges, detailed in **Error! Reference source not found.**, can be mitigated.

trademark that has already been registered (Millot, 2009[6]).Therefore, trademarks can potentially overestimate the quantity of innovations. Third, trademark systems significantly differ across countries and makes it more complicated to pool data across different offices (Millot, 2009[6]).The analysis of trademarks must take into account the specificities of the legal systems (Schmoch, 2003[7]).

Other indicators of innovation

Private R&D expenditures can capture non-patented inventions and are likely proportional (on average) to the value of the inventions. However, R&D expenditures measure innovation effort rather than innovation output. Their data availability is extremely limited and detailed data for specific technological fields are rare. Meanwhile, there is extensive data on scientific publications. However, they capture scientific interest rather than innovation. Deployment level indicators such as the number of plastic-to-plastic chemical recycling plants or the number of smart contract platform for secondary plastics offer the benefit of being directly linked to environmental impacts such as material saving as well as operating cost. However, they are difficult to collect in a systematic way.

To conclude, patent is the only indicator that is at the same time comprehensive and available. It also allows to discriminate − through text analysis of patent application − between narrow technological fields that have highly different environmental impacts. Therefore, this paper uses patent as the main indicator and provides data on trademarks, when available and relevant.

Measuring circular and environmentally relevant plastics innovations using patent data

Identification of plastic related patent and trademark using text analysis

At the time of writing, there is no systematic classification of environmentally relevant plastic technologies. The Cooperative Patent Classification (CPC) developed by the EPO and used in PATSTAT contains only a few relevant codes covering plastic recycling, plastic repair and biopackaging. However, these codes aggregate technologies that have highly different environmental impacts. For example, the plastic recycling codes of the CPC cover mechanical recycling, plastic-to-fuel chemical recycling and plastic-to-plastic chemical recycling under the same code, preventing a separate analysis for each type of innovation (see details in Annex A).

To overcome this issue and cover more environmentally relevant plastics innovations, this paper exploits the textual information contained in patent abstracts from PATSTAT. More specifically, the different plastic technologies are identified using various combinations of keywords, as detailed in Annex A. Box 3.1 provides illustrative examples of four patent abstracts that document plastics innovations closing plastic loops, mitigating the environmental impacts of mismanaged plastic waste, and switching towards biobased feedstock.

From patent and trademark applications to meaningful innovation indicators

In this paper, only data on patents that have been granted by patent offices are used to ensure that they fill the requirement of an innovation being non-obvious, novel to the local context and susceptible to industrial application. Similarly, we only count trademarks that have been granted by the EUIPO or registered under the USPTO.[8]

[8] Unfortunately, we are not able to use our text analysis tools on JPO trademarks because it would require translation of a massive amount of text from Japanese to English.

The main indicator of innovation used in this paper is the count of patent families. A patent family is a group of patent applications covering the same invention. Counting patent families prevent double counting the same innovation relying on several patents.

In this paper, we only count patent families that are international when performing cross-country comparison. An international patent family is a patent family that includes at least two patents that has been filed in different countries. We do that because patent offices do not have the same standard across countries. Merely counting the number of granted patents could lead to an overestimation of innovation in countries with laxer rules that typically have a high number of low value patents. International patent families solve this issue since they are generally considered to be high-value patent families (Dechezleprêtre, Ménière and Mohnen, 2017[8]).

Environmentally relevant plastics innovations covered by patent and trademark data

The text analysis of patent abstracts allows recovering the vast majority of environmentally relevant plastics innovations except innovations mitigating plastic leakage from mismanaged plastic waste. Table 3.2 shows the list of the plastics innovations for which patent data can be extracted. Patent data are available for sixteen plastics technologies: biobased, biodegradable, plastic waste composting, plastic-to-fuel, plastic-to-power, re-use, repair, design easing recycling, sorting, other plastic waste pre-treatments, mechanical recycling, plastic-to-plastic chemical recycling, designs using smaller quantities and designs increasing the service life. The quality of the text analysis is high since the share of patent applications that are effectively related to the targeted technologies varies from 86% to 100% and is equal to 95% on average.

The text analysis of trademark description allows recovering only four categories of innovation: reuse of plastics, repair of plastics, biodegradable plastics and biobased plastics. Trademarks data are not available for other plastics technologies for two main reasons. First, trademarks cover families of products that mix several technological fields together. For example, a mechanical recycling innovation and a thermal conversion innovation might be cover by the same trademark. Second, the terms used in trademark description are often more generic such as “recycling equipment” that prevents the classification to either mechanical or chemical recycling.

Box 3.1. Examples of excerpts of patent abstracts

Improving sorting of plastic waste

Patent International Publication Number: WO 2005/024854 A1 filed in 2004 by Korea Institute Of Geoscience And Mineral Resources

…An electrostatic separation system for separating fine metal and plastics is disclosed. An electrostatic separation system according to the present invention comprises a negative electrostatic induction plate and positive metal net made of special materials, which have appropriate dimensions and an appropriate space between them to improve separation efficiency, and a separating plate, which is appropriately positioned to improve separation efficiency. The electrostatic separation system has processing capacity more than 5 times in comparison to conventional electrostatic selection systems and is able to separate fine particles of 0.1 mm in size. In addition, the electrostatic separation system has wide application in recycling other useful recourses as well as separating the mixture of fine particle metal and non-metal materials…

Plastic-to-plastic chemical recycling

Patent Number: US 7462649 B2 filed in 2002 by Teijin Ltd

...A through process comprising depolymerisation reaction of used PET bottles with EG, recovering DMT by ester interchange reaction with MeOH, obtaining terephthalic acid by hydrolysis of the recovered DMT, and manufacturing a PET polymer which can be used for manufacturing PET bottles again by using the terephthalic acid…

Biodegradable plastics

Patent International Publication Number: WO/2020/079202 filed in 2019 by CDL and LEYGATECH

...The invention relates to a biodegradable plastic film that can be used in flow pack type packaging methods, having at least two layers, formed of at least two different polymer materials having a difference in deflection temperature under load, and also to a method for manufacturing such a film…

Switching towards biobased feedstock

Patent International Publication Number: WO 2015/102831 Al filed in 2014 by Avery Dennison Corporation

…A multilayer film comprising: a first layer including polylactic acid (PLA) resin and at least one bio-based plasticizer; a second layer including polylactic acid (PLA) resin and at least one bio-based plasticizer. Wherein the bio-based plasticizer is derived from biological renewable sources. The multilayer film is optically clear and flexible...

Source: Authors' selection from the OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Table 3.2. Patent data on environmentally relevant plastics innovations

Innovation category	Captured in patent data†	Examples of excerpts of patent abstract
Prevention and recycling technologies (circular plastic)		
Prevention		
Designs using smaller quantities	Yes – 91%	- The invention relates to a method that allows both increasing the strength of the bottle and using less plastic raw material by applying vertical column structure.
Designs increasing the service life	Yes – 88%	- The utility model provides a durable PVC pipe and relates to PVC pipe technical field.
Re-using products	Yes – 100%	- A reusable plastic container that can be used for the storage and transportation of products.
Repairing plastic intensive goods	Yes (CPC)	- A self-healing pneumatic tire, which uses stored sealant in the tire to fix the leak. - A silicone composition having a unique particle size distribution useful as a self-sealing agent for silicone fluid applications.
Recycling		
Sorting plastic waste	Yes – 86%	- A near-infrared intelligent plastic garbage sorting system having front image processing and a reflecting type spectrum unit. Progressive self-adaptive learning based on the statistical machine-learning mode is conducted continuously.
Other pre-treatments of plastic waste	Yes – 100%	- the utility model relates to polystyrene waste plastic recycling equipment, which comprises a washing kettle that can effectively remove impurities and carbides on the surface of materials
Mechanical recycling	Yes – 96%	- A system including a press designed to compact products in expanded polystyrene and similar material thereby permitting ecological recovery and regeneration for re-utilisation after crushing the polystyrene scrap
Plastic-to-plastic chemical recycling	Yes – 92%	- A method for the chemical depolymerisation of waste polyethylene terephthalate by application of microwave radiation and solvolysis in the presence of a catalyst.
Design easing recycling	Yes – 96%	- The present invention relates to polyethylene tarpaulin which exhibits high strength greater than or equal to 1,000 n/cm and can be easily recycled
Enabling digital technologies (smart contracts using blockchain)	No – emerging technologies*	
Conversion or disposal of waste and leakage removal		
Conversion or disposal of waste		
Biodegradable plastics	Yes – 98%	- The invention discloses a degradable plastic with good mechanical properties and a preparation method of the degradable plastic.
Composting plastic waste	Yes – 87%	- The invention belongs to the technical field of microbial fermentation and biodegradation and particularly provides a method of degrading polyethylene by extracellular laccase of bacillus
Thermal conversion (plastic-to-fuel)	Yes – 98%	- The residual hydrocarbon is produced by the pyrolysis of plastic waste such as of one or more of polyethylene polystyrene or polypropylene.
Waste to energy (plastic-to-power)	Yes – 91%	- A boiler burning refuse derived fuels waste plastics and waste wood mainly comprising a hearth and a combustion chamber a superheater chamber.
Sanitary landfill	Yes – 100%	- landfill barrier system that comprises a leachate collection and removal layer and a hdpe (high-density polyethylene) geomembrane infiltration proof layer
Leakage removal		
Mitigating plastic release at the source	No - emerging technologies**	

Removing plastics from wastewater	No - not plastic specific	
Monitoring and removing plastics from the natural environment	Yes – 100%	- a sediment micro-plastic extraction method capable of preventing a sample from being polluted by microfibers in the environment - a mobile marine micro-plastic recovery vessel and a marine micro-plastic recovery method thereof
Switching from fossil-based feedstock to biobased feedstock (crop, algae, fungi, etc.)	Yes – 100%	- A polylactic acid polymer safe for using in food packaging and medical materials

Note: † The share of valid patents, i.e. effectively related to the targeted technology, after reading 100 randomly selected abstracts is provided. * Several digital technologies are captured in other innovation categories e.g. machine learning in plastic waste sorting. ** The number of filed patents is too low and too recent to develop meaningful indicators
Source: Patent abstract from OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

4 Unpacking trends in environmentally relevant plastics innovation

Environmentally relevant plastics innovation is growing but is still a very small share of total plastics innovation

Plastics innovation grew at various speeds across environmental objectives

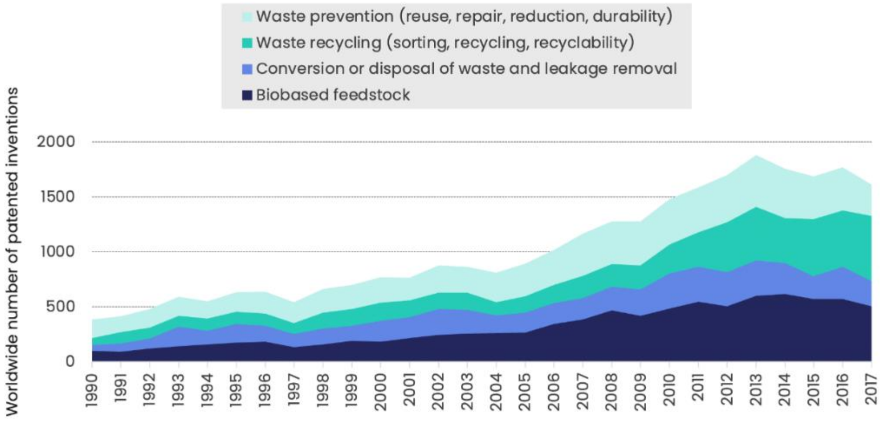
Environmentally relevant plastics innovation increased rapidly over the last 30 years (see Figure 4.1). The number of patented inventions in environmentally relevant plastic technologies were multiplied by a factor of 3.4 between 1990 and 2017.[9] However, the growth in innovation varies across environmental outcomes. Innovations to switch from fossil-based feedstock to biobased feedstock (dark blue) and innovations for the conversion or disposal of waste and for leakage removal (light blue) increased by a factor of three. In comparison, the number of patented inventions in technologies for waste prevention and recycling were multiplied by a factor of 4 during the same period of time.

In the most recent years, innovation in biobased feedstock and in innovation for the conversion or disposal of waste and for leakage removal has been slowing down while innovation in circular plastics technologies has remained constant. Considering that biodegradable plastics make up for a large share of the innovation in plastic waste conversion or disposal technologies, these trends are not surprising. One possible interpretation is that recent concerns of both biobased and biodegradable plastics regarding their mixed environmental impacts have discouraged further investment in the development of these technologies.

[9] The data stops at 2017 because it the latest year with comprehensive patent data.

Figure 4.1. Innovation in plastics prevention and recycling have grown the most

Worldwide patented inventions in environmentally relevant plastics technologies, 1990-2017



Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Circular plastics innovation grew slightly faster than plastics in general

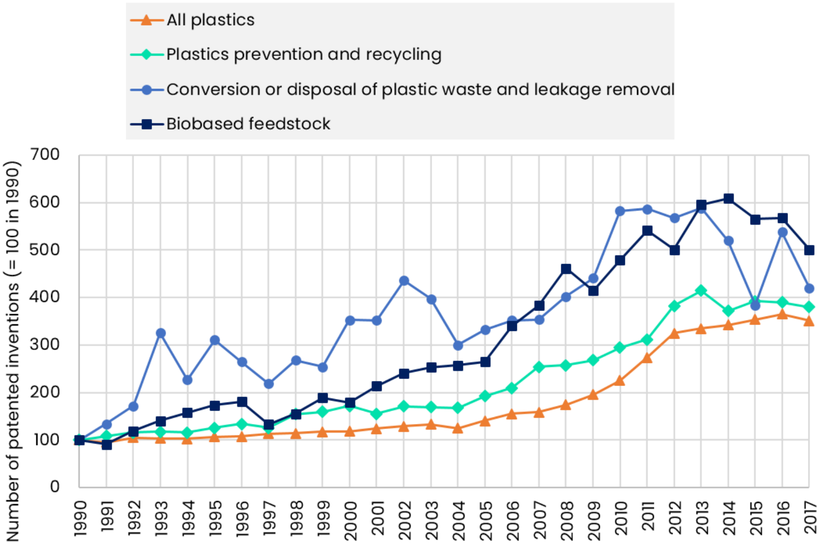
Environmentally relevant plastics innovation increased slightly more rapidly than innovation in all plastics. Figure 4.2 shows the number of patented inventions normalised at 100 for the year 1990. This normalisation allows the comparison of trends across innovation categories that differs in terms of size. Environmentally relevant plastics innovation grew more rapidly than innovation in all plastics in general, suggesting that the plastic sector became greener over time.

Nevertheless, the difference in pace between environmentally relevant plastics innovation and all plastics innovation has been reduced since 2013. From 1990 to 2017, only the growth in circular plastics innovation equal to 380% was larger than the growth in all plastics innovation equal to 350%. The gap in the growth rates remains small and the number of patented inventions in all plastics is 86 times larger in absolute terms than in circular plastic technologies in 2017. Innovation in circular plastics accounted for 1.1% of all plastics innovation in 1991 and 1.2% in 2017.[10] This suggests that much stronger policies are needed to redirect innovation towards circular plastic technologies considering the massive environmental issues associated with plastics innovation.

[10] This magnitude is consistent with the small, 5 to 10%, market penetration of circular business models in economic terms (OECD, 2019[4]).

Figure 4.2. Environmentally relevant innovation grew faster than all plastics innovation

Worldwide patented inventions (index = 100 in 1990), 1990-2017



Note: The index is equal to 100 in the baseline year that is 1990. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

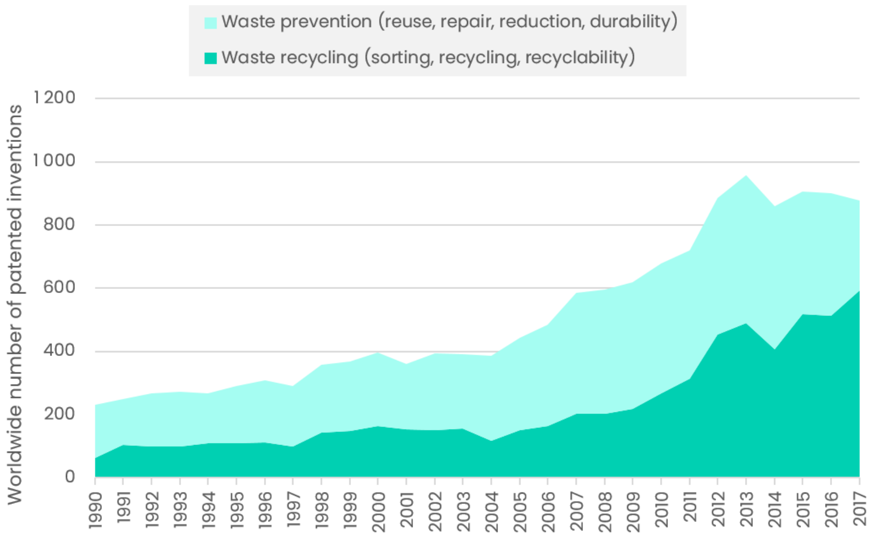
Unpacking trends in circular plastics innovation

Waste recycling innovation became more important than waste prevention innovation recently

Most of the growth in circular plastics innovation is driven by innovation in technologies that improve plastic waste recycling, which has grown by more than a factor of 9 from 1990 to 2017 (see Figure 4.3). In comparison, innovation in plastic waste prevention evolved much less rapidly with a growth increasing only by a factor of 1.7 over the same period of time.

Figure 4.3. Waste recycling innovation became more important than waste prevention innovation recently

Worldwide patented inventions in circular plastics technologies, 1990-2017



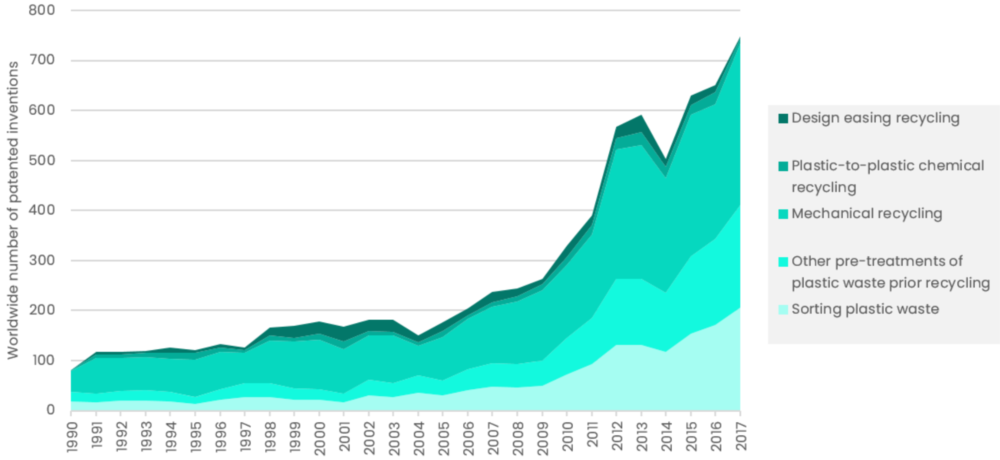
Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Mechanical recycling and plastic waste sorting alone account for 89% of waste recycling innovation (see Figure 4.4). The rest is dominated by designs increasing the service life of plastics and repair of plastics. In contrast, innovation for plastic-to-plastic chemical recycling, pre-treatment of plastic waste, design easing recycling, reuse of plastic and design reducing the amount of plastic is small. It is not clear what exactly drives these differences. For example, the low level of innovation in design easing recycling may partly reflect the intrinsic nature of such innovations that may not easily lend themselves to patenting. Furthermore, the comparison of innovation across technologies based on patent counts has limitations and can only provide orders of magnitude.[11]

[11] For example, the propensity to patent is not the same across the value chain. Technologies that are more codifiable and high tech will tend to be patented more on average. Therefore, two technology fields having equal amount of innovation could have different number of patented inventions. Nevertheless, the number of patents can give an order of magnitude.

Figure 4.4. Innovation in mechanical recycling and waste pre-treatments have grown the most

Worldwide patented inventions in plastics recycling technologies, 1990-2017



Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

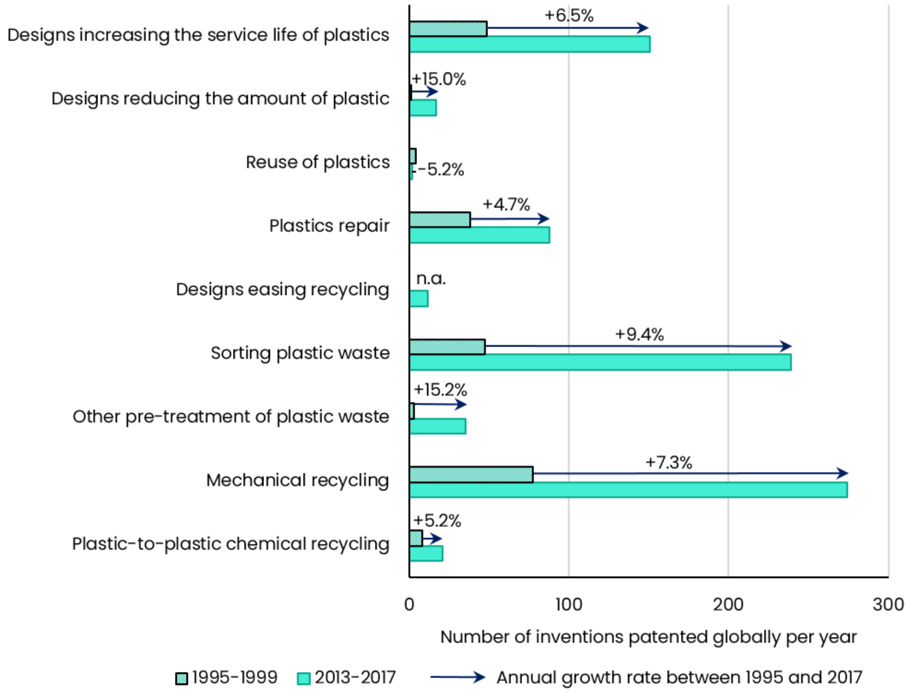
Design reducing the amount of plastic use and innovations contributing to better plastic recycling are growing faster

The different kinds of circular plastic innovations do not only vary in relative size but also in terms of growth rates that can are more comparable across technologies (see Figure 4.5). Pre-treatment of plastic waste prior recycling and design reducing the amount of plastic use grew the most rapidly by 15% per year on average between 1995-1999 and 2013-2017. Plastic waste sorting and mechanical recycling, which were already dominant among circular plastic technologies, grew also quickly by 9.4% and 7.3% per year respectively. Design increasing the service life of plastics, plastic-to-plastic chemical recycling and plastics repair grew relatively less rapidly but still at a significant rate of 6.5%, 5.2% and 4.7% per year respectively.

The development of some technologies has even accelerated in recent years. For example, innovation in plastic-to-plastic chemical recycling grew by 11% per year between 2008 and 2017. Development in plastic-to-plastic chemical recycling is also expected to grow faster as mechanical recycling cannot keep the desirable properties of some plastics, especially contaminated one, over repeated life cycles.

In contrast, innovation technologies allowing the reuse of plastics appears to be small and even decreasing. However, this only reflects that patents were less and less used to appropriate those inventions.

Figure 4.5. Global innovation in plastics prevention and recycling technologies



Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Average annual growth rate between 1995 and 2017 is displayed. n.a. stands for non-available because no patent could be recovered for 1995-1999.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Trademarks capture increasing innovation trend in plastics reuse and repair

Innovation in some technologies is not necessarily well captured by patent data. This is the case of plastics reuse, which contains low-tech innovation that are generally not patented and plastics repair that has higher degree of commercialisation. The number of registered trademarks is more appropriate to capture innovation trends in these technologies.12 For example, trademarks are used to protect reusable plastic transport containers, cups; reusable plastic water bottles sold empty and distribution service for reusable plastic dunnage. Box 4.1 contains one example of such trademark. If the reusable products may seem relatively low-tech, the logistics behind shared transport systems and containers signal innovation. During 2013-2017, there were 65 new registered trademarks every year related to reuse of plastics and 2 700 related to the repair of plastics.

[12] Trademarks data are not available for the other circular plastics technologies as trademarks cover families of products that mix several technological fields together.

Box 4.1. Examples of excerpts of trademark description

Reusing plastics

Trademark serial number: USPTO #88158205 filed in 2019 by Schoeller Allibert GmbH

…The COMBO LIFE trademark is used in the following business: Goods of plastic, namely, packaging containers of plastic, stacking and nesting plastic packaging containers, modular container systems comprised of plastic containers for packaging and transport, plastic containers for transport, small load carriers in the nature of plastic bins, large load carriers in the nature of plastic bins, plastic boxes, plastic cases, plastic pallet boxes, plastic handling pallets, plastic loading pallets, plastic transport pallets, modular pallet systems comprised of plastic pallets for handling, loading and transport, plastic trays for foodstuff packaging, and plastic fittings for the aforesaid goods, namely, lids, covering plates, pallet runners and container closures of plastic , Logistics management of shared transport systems and transport containers in the nature of business management of the pooling and sharing of transport containers and transport systems among various users…

Repairing plastics

Trademark serial number: EUIPO # 012056123 filed in 2013 by PLASTIC REPAIR SYSTEM 2011, S.L. SOCIEDAD LIMITADA

… The PRS PLASTIC REPAIR SYSTEM trademark is used in the following business: Welding wire of plastics; plastic materials in the form of strip; plastic injection mouldings; articles of plastics (semi-manufactures); Wholesale and retail sales in shops and via worldwide data networks of plastic welding wire, plastic materials in the form of strips, plastics for injection moulding and plastic good; Repair and maintenance of plastic goods…

Plastic Repair System (PRS) claims to have developed a patented welding method that guarantees 100% recovery of the object's functionality and at least 98% of its original strength. Repairable items include containers used for shipping or storage, such as jumbos, pallets, containers, tanks, industrial boxes, pliable boxes, etc. PRS allows to extend the service life of plastic equipment and according to the company is 70% less costly than the purchase of new items.

Source: Authors' selection from the OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

When measuring innovation with trademarks, innovation in reusing plastic increased by 23% every year while innovation in plastics repair rose by 12% every year between 1995 and 2017.

Unpacking trends in other environmentally relevant plastics innovation

Innovation for conversion or disposal of waste and for leakage removal is dominated by biodegradable plastics and sanitary landfill technologies

While it is possible to measure innovation on the monitoring and removal of plastics from the natural environment and innovation related to sanitary landfill, it is not currently possible to measure some of the innovation that mitigates the leakage of plastics into the natural environment. For example, innovation mitigating plastic release at the source such as textile with lower microfiber shedding cannot currently be measured because these technologies are emerging and data on patent and trademark are scarce. Another example includes innovation related to the removal of microplastics from wastewater because the current technologies are not targeting microplastics specifically and that technologies to remove microplastics from sewage sludge are scarce. In contrast, there is more data on the conversion of unsorted plastic waste, such as plastic-to-fuel technologies as defined in Section 2.

Most innovation to convert unsorted plastic waste relates to the design of biodegradable plastics (see Figure 4.6). Between 2013 and 2017, 228 patent families on biodegradable plastics were granted every year. Innovation in biodegradable plastics, measured by the number of patented inventions, doubled between 1995 and 2017. Over the same period, the number of trademarks in biodegradable plastics rose by 15.5% every year.

Conversely, innovation in waste management of compostable plastics has been very low. This stark difference can be explained by different factors. First, there are many more varieties of biodegradable designs that can be patented than varieties of composting systems. Second, innovators underinvested in composting technologies assuming that biodegradable plastics would fully degrade in natural environments. This is problematic for several reasons. First, the necessary conditions for biodegradable plastics to fully degrade are not met in the natural environment (Farah, Anderson and Langer, 2016[9]; Wierckx et al., 2018[10]). Second, there is evidence that mismanaged biodegradable plastic waste remains in the environment and breaks into smaller debris (Napper and Thompson, 2019[11]). Third, some biodegradable plastics can be ecotoxic in the natural environment (OECD, 2013[12]; Souza et al., 2013[13]; Kershaw, 2015[14]; Adhikari et al., 2016[15]).

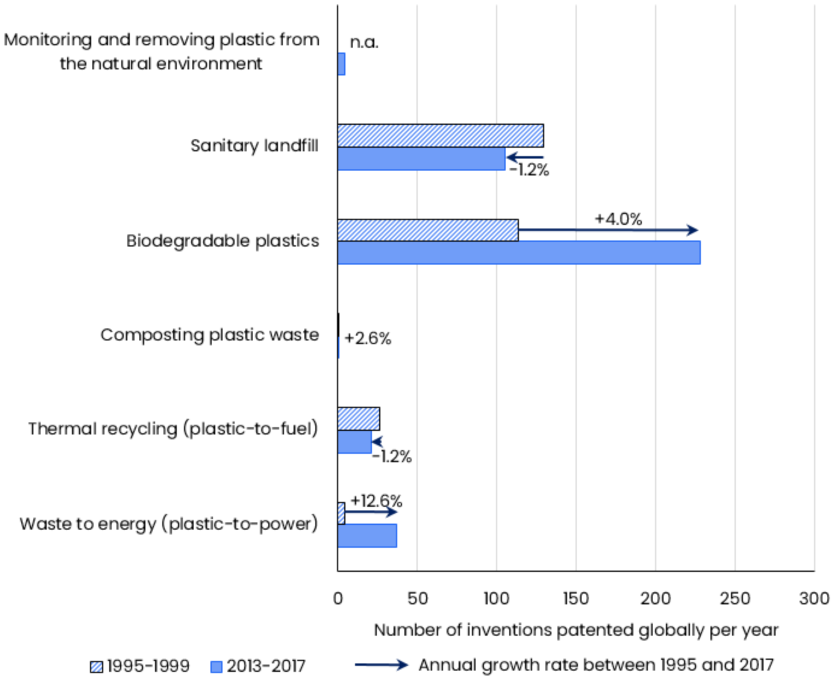
Innovation in plastic-to-fuel, in plastic-to-power and in sanitary landfill technologies have similar orders of magnitude but are much smaller than innovation in biodegradable plastics. Between 1995 and 2017, innovation in plastic-to-fuel and sanitary landfill technologies slightly decreased while innovation in plastic-to-power and biodegradable plastics respectively increased by 12.6% and 4% every year.

Before 2016, there was no patented invention related to the monitoring of plastics and their removal from the natural environment. From 2016 to 2018, there were 22 inventions patented in this field. Recent numbers indicate that innovation in related to the monitoring of plastics and their removal from the natural environment doubles every year.

Innovation in biobased feedstock increased rapidly during the last decade

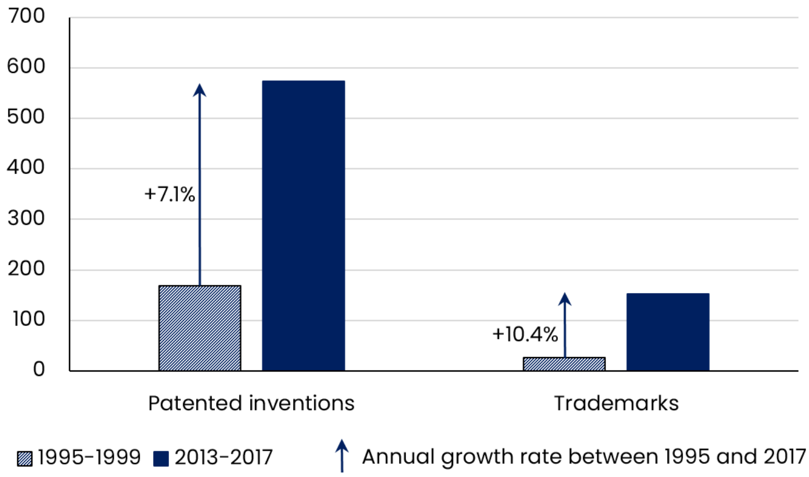
Innovation in technologies switching from fossil-based to biobased feedstock is significant both in terms of patented inventions and registered trademarks (see Figure 4.6). Between 2013 and 2017, 573 inventions in biobased plastics were patented every year while 152 trademarks were registered every year. There has been a spectacular growth in biobased plastics innovation. Since 1995, the number of patented inventions in biobased plastic has increased by 7.1% every year while the number of registered trademarks has risen by 10.4%.

Figure 4.6. Global innovation in conversion or disposal of waste and leakage removal technologies



Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Average annual growth rate between 1995 and 2017 is displayed on the right. Technologies that mitigate plastic release into the environment at the source and that removes plastic debris from wastewater are not displayed because of insufficient data points (see Table 3.2). n.a. stands for non-available because no patent could be recovered for 1995-1999.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Figure 4.7. Global innovation in technologies switching towards biobased feedstock



Note: Author's calculation based on PATSTAT, UPSTO and EUIPO. The number of trademarks is equal to the sum of trademarks registered at the USPTO and at the EUIPO. One patented invention corresponds to one patent family. An internationally patented invention is a patent family for which at least one patent has been filed in a country, which is different from the priority country. Only granted patents are measured. Average annual growth rate between 1995 and 2017 is displayed on the top.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020, Scopus, July 2020.

5 The geography of environmentally relevant plastics innovation

Most innovation in environmentally relevant plastics occurs in OECD countries and China

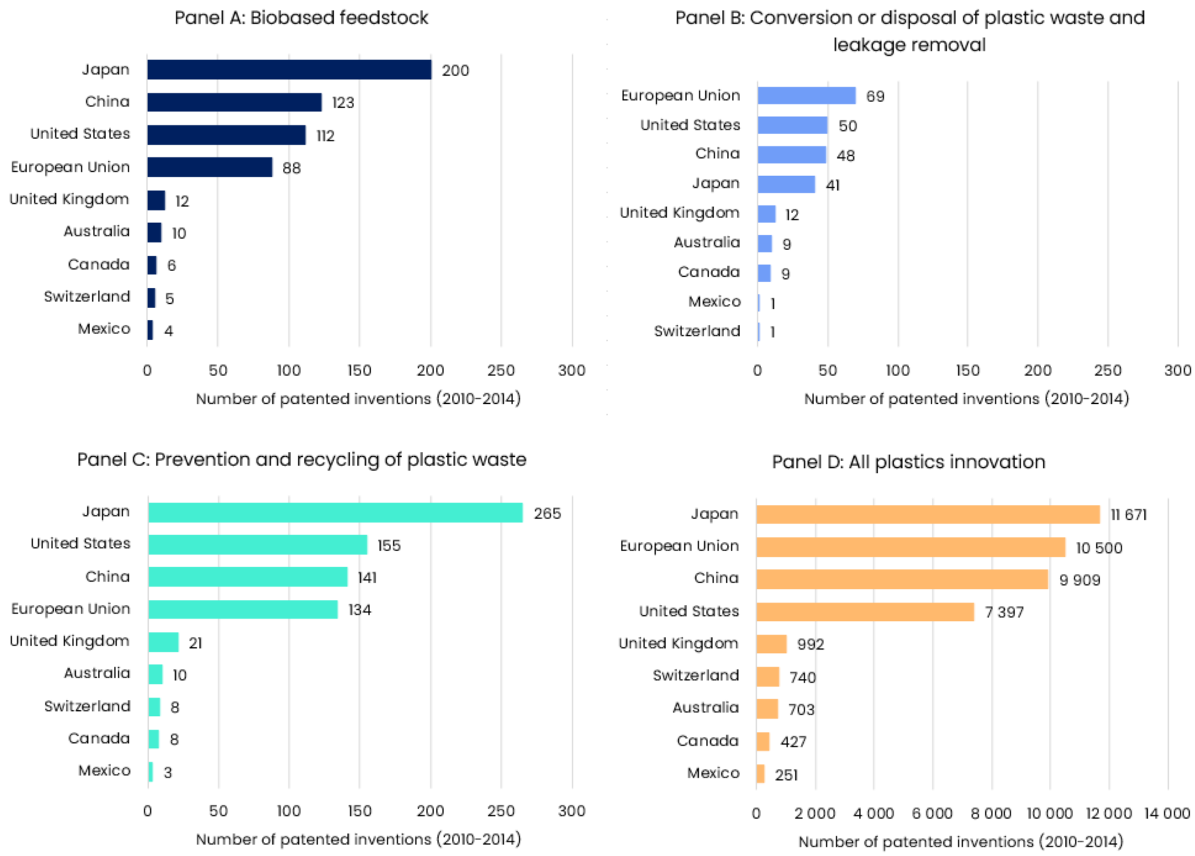
Innovation in environmentally relevant plastic technologies has not been evenly distributed around the globe over the last decade (see Figure 5.1).[13] This skewed distribution can be observed for innovation in biobased feedstock, innovation for the conversion or disposal of waste and for leakage removal and innovation improving plastic circularity. OECD countries and China concentrate the vast majority of environmentally relevant plastics innovation. For instance, only 10 countries account for 92% of circular plastic patenting with Japan, the United States, China and the European Union accounting for 82%.

However, analysing the three different categories of environmentally relevant plastics innovation reveals clear differences across countries:

- Japan patented the highest number of inventions in biobased feedstock and circular plastic technologies by a large margin. In these two fields, the United States and China patented a similar number of inventions.
- The European Union has the highest number of patented innovations related to conversion or disposal of plastic waste and leakage removal, followed closely by the United States and China.
- The European Union patented more inventions in circular plastics than inventions in biobased feedstock.
- Most countries have more patented inventions in circular plastics than in the other two categories with the exception of Australia that innovated more equally across the three categories.
- Canada, Switzerland and Mexico have filed a lower number of patents but it is still significant relative to the rest of the world.

[13] For cross-country comparison, we restrict the analysis to international patent families defined as patent families that contains at least one patent filed in more than a single country. This restriction is standard in the literature and allows capturing high value innovations and preventing patent inflation due to different practices across countries.

Figure 5.1. Internationally patented inventions in environmentally relevant plastic technologies, 2010-2014



Note: An invention corresponds to an international patent family defined as a patent family that contains one or more patents filed in more than a single country. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Grey indicates that data are not available.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

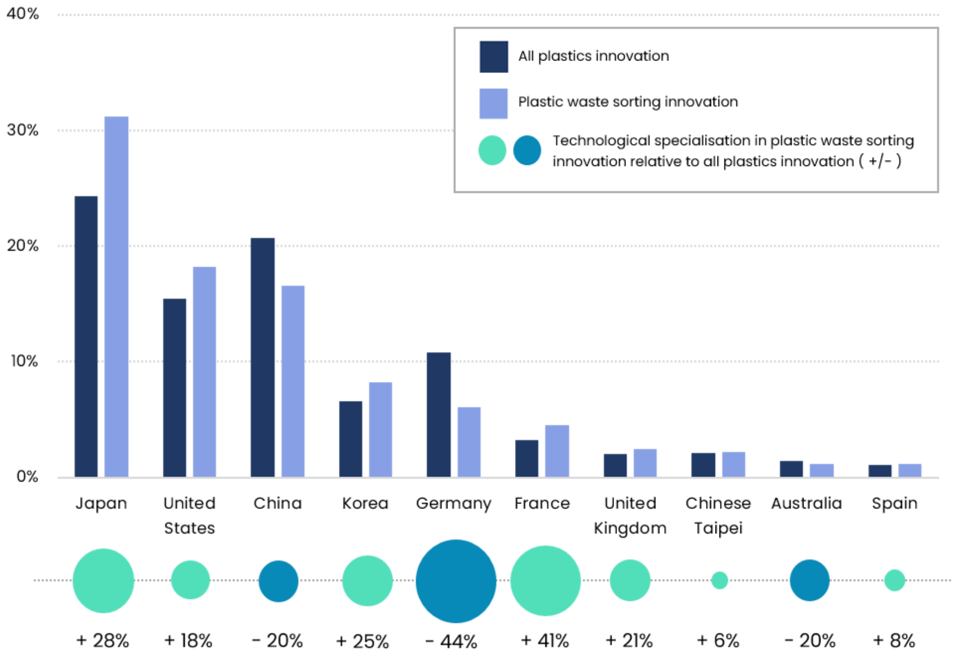
The direction of innovation differs across countries

Simply looking at the level of patenting across countries also captures not only differences in actual level of innovation across countries but also differences in patenting behaviour, which are notoriously significant and illustrated in Panel D of Figure 5.1. Therefore, we use all plastics innovation as a benchmark to assess the specialisation of countries in plastic circularity. More specifically, we compare the global share of patented invention in circular plastics innovation of a country with its global share of patented inventions in all plastics innovation (see Figure 5.2). We focus on 2010-2014 since it covers the more recent year for which international patent data are comprehensive.[14]

[14] Note that focusing on *international* patent families reduced the number of years available from 2017 to 2014 because there is a time lag between the first patent application in a given country and the subsequent patent applications in other countries. The aim is not to provide a ranking of countries in terms of historical circular plastics innovations but rather focus on innovation that occurred in 2010-2014.

Figure 5.2. Some countries specialise in circular plastics innovation

Top ten inventing countries in plastics prevention and recycling innovations, global share 2010-14



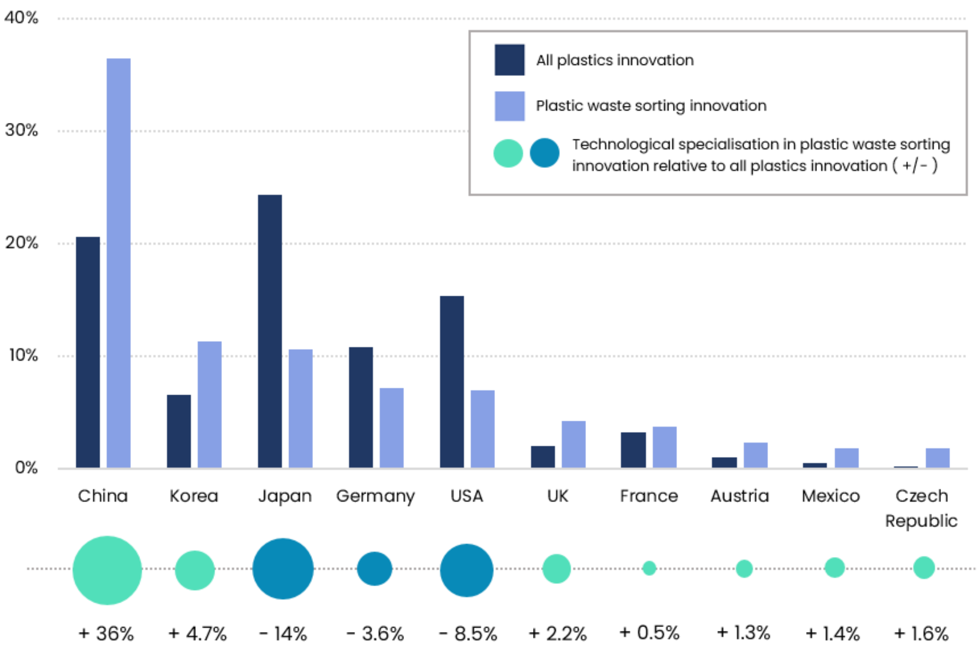
Note: All plastics innovation includes plastics innovation that is environmentally relevant and not environmentally relevant. An invention corresponds to an international patent family defined as a patent family that contains one or more patents filed in more than a single country. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Unsurprisingly, countries that innovate in plastics in general also tend to innovate in plastics circularity technologies. Nevertheless, some countries invest relatively greater effort in plastics prevention and recycling technologies. For instance, France, Japan, Korea, the United Kingdom and United States invested a relatively large share of their innovation efforts in plastics circularity between 2010 and 2014. In contrast, Germany, China and Australia were relatively less focused on plastics circularity during the same period. Nonetheless, due to their high number of plastic-related innovations, these three countries are leaders when considering the absolute number of circular plastics patents filed. In addition, the focus on circular plastics technologies is likely to increase in several countries. For example, a full waste export ban will come into effect in Australia by mid-2024 and will significantly increase the domestic demand for plastic recycling. The growing Australian market, also supported by a public investment of AUD 190 million in recycling modernisation, will likely spur innovation in plastic waste recycling.

This overall picture hides important heterogeneity across types of circular plastics innovation. For example, between 2010 and 2014 China innovated relatively more in plastic waste sorting than the United States, Japan and Germany as illustrated by Figure 5.3. This result is consistent with the fact that during the same period, China has been a massive net importer of plastic waste from these countries and therefore had a relatively larger market and therefore demand-pull to develop plastic waste sorting technologies. This heterogeneity also makes sense at the country level. For example, the Japanese recycling act compels municipalities to collect and sort plastic packaging waste. However, municipalities largely rely on manual sorting because their technological capabilities are limited. Recyclers in the private sectors rely on advanced sorting systems imported from other countries. That is why Japan has a rather low relative technological advantage in plastic waste sorting compared to its large technological advantage in circular plastic activities.

Figure 5.3. Some countries specialise more in plastic waste sorting innovation

Top ten inventing countries in plastic waste sorting innovation, global share 2010-14



Note: All plastics innovation includes plastics innovation that is environmentally relevant and not environmentally relevant. An invention corresponds to an international patent family defined as a patent family that contains one or more patents filed in more than a single country. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

6 The impact of circular economy policies on circular plastics innovation

Previous sections show that there are significant differences across countries in terms of circular plastics innovation. The present sections explore circular economy policies as one determinant that contributes to these differences with two case studies.

The Japanese Packaging Recycling Act

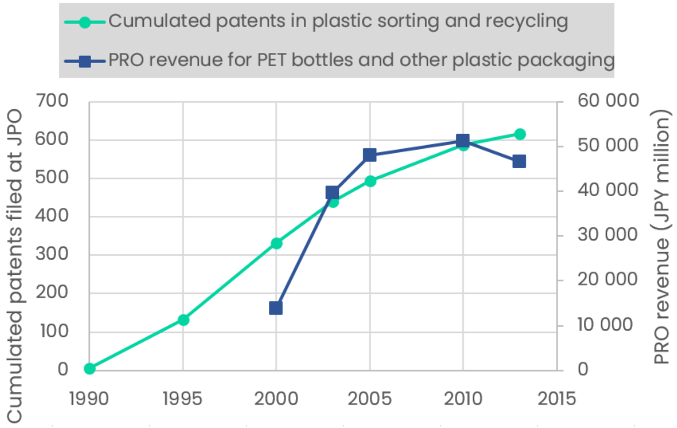
In 1991, Japan introduced a law for the promotion of effective utilisation of resources concerning all materials. The objective of the law was to promote the use of recycled resources, establish structures to simplify recycling, introduce displays explaining sorted waste collection and encourage the effective use of by-products (Yamakawa, 2016[16]). Subsequently in 1995, Japan promulgated the “Packaging Recycling Act” directly targeting plastic packaging materials. The packaging recycling act that entered into force in 1997 is an extended producer responsibility (EPR) scheme where producers are financially responsible for recycling packaging waste collected and sorted by municipalities.[15] In this system, producers pay a fee to their producer responsibility organisation (PRO) that is proportional to the quantity of waste they generate and the recycling cost of the product sold. Plastic packaging waste, PET bottles and other plastic packaging, accounted for 95% of the PRO revenue in 2010 (Yamakawa, 2016[16]).

The development of the packaging EPR system that can be measured with the PRO revenue occurred simultaneously with the increase in patent filing in recycling technologies (see Figure 6.1). This may imply that the packaging recycling act triggered innovation in recycling in Japan. To verify that this relationship is not spurious, we examine the number of patents in plastic recycling and all plastics over time (see Figure 6.2). Innovation in plastic waste recycling jumped when the two regulations were promulgated while innovation in all plastics technologies remained constant over time. Innovation was particularly important between 1995 and 2002. This is consistent with the fact that in 1995 there were many technological barriers to overcome to achieve the recycling of plastic packaging other than PET bottles. The last peak in recycling patent in 2002 could be attributed to laggard firms that needed to comply with the mandatory plastic recycling that started in 2002.

After 2002, there is a declining trend in plastic recycling innovation in Japan. The last peak in 2005 could be attributed to the expectation of more stringent measures to be introduced in 2006. In 2006, the Japanese recycling act was actually revised with the objective to strengthen waste prevention and the possibility to convert residue from mechanical plastic recycling processes into fuel or energy. The continuous decline in recycling patent from 2006 is thus consistent with the relaxation of the severity of the mechanical recycling policies. Overall, our result suggests that there is a clear correlation between the stringency of the EPR system and patenting activity.

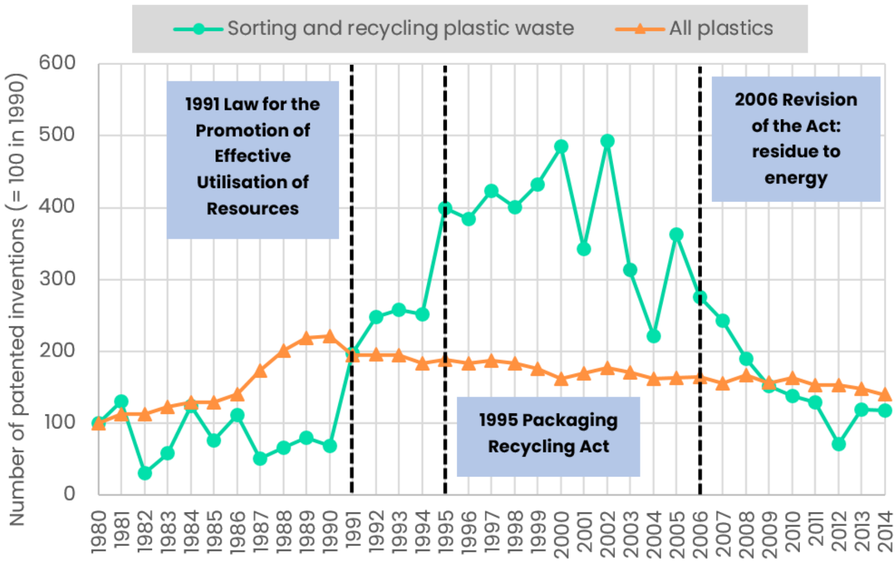
[15] The EPR system was put into force in April 1997 for PET bottles and in April 2000 for other plastic packaging.

Figure 6.1. Cumulated patented inventions in recycling and PRO revenue in Japan



Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020. PRO revenue come from Yamakawa (2016[16]).

Figure 6.2. Patented inventions in plastic waste recycling and in all plastics in Japan



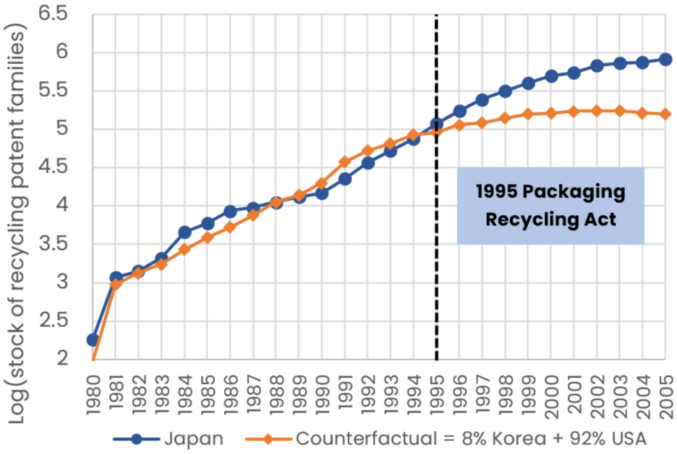
Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

The relationship between the plastic recycling law and recycling innovation could be a simple correlation. To highlight the effects of the plastic packaging law further, we employ a synthetic control method where we build a counterfactual for Japan that serves as a control group.[16] This control group is composed of countries such as Korea and the United States that are similar to Japan in terms of recycling patents but

[16] See 7Annex B for more details. See Abadie (2019[22]) for a recent review on this econometric method.

that have not introduced a similar recycling policy during the observation period.[17] Using several predictors, we are able to replicate patent filing in recycling technologies in Japan before the regulation is introduced (see Figure 6.3).[18] We find that the packaging recycling act increased the stock of recycling innovation by 105% 10 years after its introduction compared to the counterfactual for Japan in which the regulation is not introduced.[19]

Figure 6.3. The effect of the packaging recycling act on recycling innovation in Japan



Note: The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

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[17] Korea introduced its EPR system for packaging in 2003. Nine American states introduced a deposit and refund scheme for beverage containers before 1988: Oregon in 1972, Vermont in 1973, Maine and Michigan in 1978, Iowa in 1979, Connecticut in 1980, Massachusetts and New York in 1983 and California in 1987. Hawaii introduced a similar scheme in 2005 that corresponds to the end of the observation period (Kaffine and O'Reilly, 2015[30]).

[18] The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988.

[19] The predictors are well balanced between Japan and its counterfactual (see Table B.1**Error! Reference source not found.**). This result is robust to backdating the regulation five years in advance (see Figure B.1**Error! Reference source not found.**). Given the small number of countries composing the counterfactual of Japan, it is not possible to perform leave-one-out robustness checks nor inference using permutation distribution of placebo. A placebo test using the patented innovation for all plastics is not feasible since the counterfactual failed to replicate innovation trends before the regulation due to the small number of countries in the counterfactual Japan.

The German Packaging Ordinance

Germany introduced the first EPR system for the recycling and recovery of sales packaging in 1991. The Packaging Ordinance, replaced by the German Packaging Act (*Verpackungsgesetz*) in 2019, required retailers and producers to take back and recycle a fixed and yearly increasing percentage of packaging materials. The take back system was deemed to be effective as the volume of packaging materials declined by 500 000 tonnes between 1992 and 1993. Three years after the introduction of the Packaging Ordinance, plastic recycling capacities had increased by a factor of four (OECD, 1998[17]).

Qualitative evidence suggests that this significant increase in plastic recycling capacity is due to the sizeable positive impact of the German EPR for packaging waste on plastic recycling innovation. To meet the quotas set by the take back system, producers had to find new processes to convert plastic waste and create new markets for secondary materials. Among the new technologies developed at the time were new recycling processes such as technologies using hydrocyclones and centrifuges to separate individual plastics (OECD, 1998[17]).

To provide some quantitative evidence about the effect of the German packaging ordinance on plastic recycling innovation and go further than correlation, we employ a synthetic control method where we build a counterfactual for Germany that serves as a control group.[20] This control group is composed of Canada, Japan, the Netherlands, Korea and the United States that are similar to Germany in terms of recycling patents but that have not introduced a similar recycling policy before or just after 1991.[21] Using several predictors, we are able to replicate patent filing in recycling technologies in Germany before the regulation is introduced (see Figure 6.4).[22] We find that the packaging ordinance increased the stock of recycling innovation by 190% five years after its introduction compared to the counterfactual for Germany in which the regulation is not introduced.[23] There was already a difference in terms of plastic recycling innovation between 1989 and 1991. This difference cannot be fully explained by strategic patenting since the packaging ordinance was introduced within a very short timeframe making it difficult to anticipate for most stakeholders. In fact, the first German ministry of the environment initiated a regulation on take back of plastic package for beverages as soon as 1988 in reaction to the massive use of single use PET bottles.

Overall, these two case studies provide some quantitative evidence that EPR schemes triggered innovation in circular plastics technologies, especially mechanical recycling. However, to fully close plastics loops, policies also need to encourage progress in product design. In most EPR scheme, the fee schedule set by PROs is typically quite simple and provides weak incentives for design change by producers (Laubinger et al., 2021[18]). Scaling up EPR with fee modulation that is changing fees paid by producers in a collective EPR scheme based on product design, could increase innovation even more by providing producers with stronger design incentives.

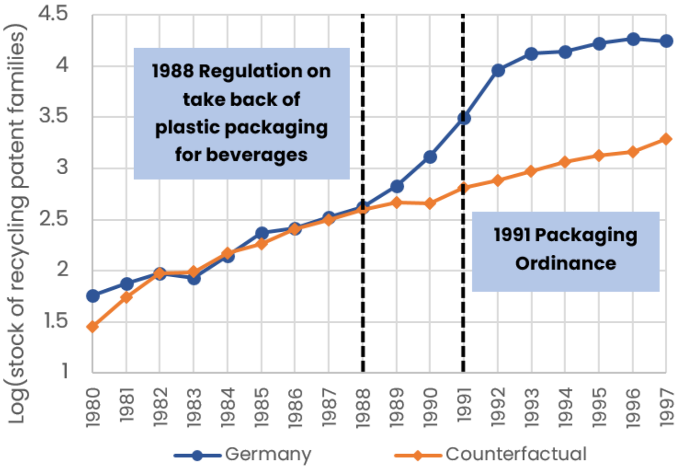
[20] See Annex B for more details. See Abadie (2019[22]) for a recent review on this econometric method.

[21] We exclude Austria and France because they introduced an EPR for packaging in 1993 and we exclude Sweden that introduced it in 1994.

[22] The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988.

[23] The predictors are well balanced between Germany and its counterfactual (see Table B.2). Our result is robust to backdating the treatment five years in advance (see Figure B.2). Permutation distribution of placebo indicates that the increase is significantly different from zero (see Figure B.3). Our result is robust to the exclusion of all donor countries separately (leave-one-out) except Canada (see Figure B.4). A similar analysis shows that the packaging ordinance had no statistically significant effect on all plastics innovation (see Figure B.5**Error! Reference source not found.**).

Figure 6.4. The effect of the German Packaging Ordinance on plastic recycling innovation



Note: The counterfactual Germany is composed of 28% Canada, 12% Japan, 24% Netherlands, 13% Korea and 23% United States. The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments. Data before 1990 includes only the Federal Republic of Germany (FRG).
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

7 Conclusion

Innovation is key to reducing the environmental impacts of plastics. However, literature is generally lacking in the field of environmentally relevant plastics innovation. For the first time, this paper develops a conceptual framework to document and map environmentally relevant plastics innovation. The paper also develops plastics innovation metrics using patents and trademarks to quantify trends over time, across countries, and to establish preliminary empirical links between policies and innovation outcomes.

Plastic waste prevention and recycling innovation has increased slightly more rapidly than overall plastics innovation. In contrast, innovation in bioplastics have witnessed a significant slowdown in recent years. Another key finding of this analysis is that environmentally relevant plastics innovation is concentrated in OECD countries and China and that top inventor countries are not specialized in the same technologies. Finally, the patent analysis shows some empirical evidence that recycling regulations may have triggered innovative activity in plastic recycling.

It is also important to highlight some data limitation. First, we are only able to go as far as 2017 because we restrict the analysis to granted patents. Given the recent and vigorous policy actions to address the environmental impacts of plastic, data on environmentally relevant plastics innovation will probably become even more interesting and revealing in a few years. Second, the comparison of patent counts between different categories of innovation should be taken with precautions. Difference can also be attributed to the difference in difficulty in identifying the relevant patents based on abstract in some areas compared to others and to the difference of intellectual property tools used to appropriate inventions across sectors. Third, patents and trademarks mostly cover technological innovations and does not necessarily capture well organisational innovations that are also key for scaling up circular business models.

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Annex

Annex A. Detailed methodology for the identification of patents related to environmentally relevant plastics innovation

The challenges of patent as indicator of innovation

Patent data are highly useful to build innovation metrics. However, they still have some drawbacks. First, firms do not systematically patent all their innovations. Instead, firms may rely on industrial secrets to protect their intellectual property from imitators (Cohen, Nelson and & Walsh, 2000[19]). However, there are evidence that trade secrecy and patent are appropriation strategies that are complementary (Crass et al., 2019[20]). Therefore, patent counts are positively correlated with innovation output even if trade secret cannot be measured.

The second challenge in using patent as a measure of innovation is that patents can significantly differ in terms of quality and value especially across countries that have different standards and intellectual property laws. The propensity to patent also differs across sectors (Cohen, Nelson and & Walsh, 2000[19]). These differences make comparisons between countries and sectors informative but challenging. A particularly common problem is the high number of low-value patents. Nevertheless, there exist several ways to build meaningful statistical indicators of innovation using patent data such as international patent families and 5 years forward citations (Dechezleprêtre, Ménière and Mohnen, 2017[8]).

Finally, firms can use patents in a purely strategic way to prevent the use of certain technologies by competitors even if the patent holding firms do not actually exploit its patented technology (Pénin, 2012[21]). The inclusion of strategic patents in the dataset could overestimate the amount of innovation actually occurring. Yet, the significant administrative and financial costs involved in the patent application process reduce this risk.

Patent identification using keywords

At the time of writing, there is no systematic way to identify patents related to environmentally relevant plastic technologies. There are existing codes in the Cooperative Patent Classification (CPC) developed by the EPO regarding bio-packaging, plastic recycling and repair but these codes do not cover all the environmentally relevant plastic technologies identified in Table 3.2. Moreover, these CPC codes aggregate technologies such plastic-to-plastic chemical recycling and plastic-to-fuel chemical recycling that differ significantly. To overcome this gap, this paper exploits the textual information contain in the abstract of patents from PATSTAT to select patents for nearly all environmentally relevant plastic technologies. More specifically, the patents related to each plastics innovation are identified using specific combinations of keywords.

Existing CPC codes are insufficient to identify environmentally relevant plastics innovations

number of plastics technologies: biobased feedstock, repair, recovery, and wastewater treatment. Biobased plastics are classified as a climate mitigation technology under “Y02W90/10 - Bio-packaging, e.g. packing containers made from renewable resources or bio-plastics”. Repair of objects made of plastic are classified under “B29C73/00 - Repairing of articles made from plastics or substances in a plastic state”. Recovery of plastics are classified under code “B29B 17/00 - Recovery of plastics or other constituents of waste material containing plastics” and code “C08J 11/00-28 - Recovery or working-up of waste materials”. Finally, patents on wastewater treatment are classified under code “C02F - Treatment of water, wastewater, sewage, or sludge”.

Nevertheless, these codes do not always correspond to the categories defined in Table 3.2 except for repair. Code Y02W90/10 does contain patents related to biobased packaging but does not cover all biobased plastic technologies. For example, patent applications related to cellulose ester, cellulose acetate, nitrocellulose and specific biobased polymers are not captured by the EPO code. For example, code Y02W90/10 does not capture the following patent which abstract is “this invention relates to blends containing two or more polyhydroxyalkanoates (PHAs), and related methods and articles.” Code Y02W90 also captures unrelated patent applications such as “insecticidal compositions and insecticidal unit comprising” or “a water dispersible organic gel comprising a hazardous product” and does not distinguish biobased plastics from biodegradable plastics.

Existing EPO codes regarding recycling aggregate very different technologies and do not cover all of them. Code B29B 17/00 and C08J 11/00-28 do not distinguish between material and energy recovery of plastics. They can also include several recyclability innovations as well other design innovations unrelated to recovery. Most importantly, they do not cover all plastic recovery patents as only 30% of patent applications recovered using the text analysis described above have either code B29B 17/00 or C08J 11/00-28.

Methodology to identify environmentally relevant plastics innovation based on patent abstract analysis

The objective of this paper is to find the patents are that are related to environmentally relevant innovation that are specific to plastics. To cover plastics related technologies only, the data are restricted to patents which abstract contains one of the plastic terms that are listed in Table A.1. The list of plastic polymers is the own elaboration of the authors based on desk research. This filter is particularly useful for identifying the plastic specific innovations in field that concern more materials such as mechanical recycling. The filter also considerably reduces the computational requirement to perform the text analysis given the very large number of patents.

For each innovation, the patent selection process is an iterative procedure that consists in four steps that use additive keywords and subtractive keywords (see Figure A.1). Additive keywords are keywords that identify a valid patent application. In contrast, subtractive keywords indicate an invalid patent application. The four steps are the following:

1. Establishing a list of additive combinations of keywords e.g. “shred plastic waste”, “recover polymer scrap” in the case of mechanical recycling and “hydrolysis” and “glycolysis” in the case of plastic-to-plastic chemical recycling,
2. Establishing a list of subtractive combinations of keywords e.g. “recycling wastepaper” for mechanical recycling and “electricity generation” for plastic-to-plastic chemical recycling,
3. Extracting only the plastics related patent which abstract contains at least one additive combination but no subtractive combination.

4. Reading 100 randomly selected from the extracted list to assess the quality of the combinations of keywords. A percentage of valid patent applications is computed.

The four steps are repeated until the percentage of valid patent applications cannot be increased further. At each iteration, the abstracts of the valid and invalid patents help to improve the list of additive and subtractive combinations of keywords.

The functioning of the patent selection algorithm based on text analysis of the abstract is illustrated in

for a fictional case where eight patent abstracts are analysed. For clarity, the example only requires two iterations. In the first iteration, the process starts at the upper left of the figure with the eight patent abstracts to be analysed. If an abstract contains at least one additive combination such as " 'separate' and 'polyethylene terephthalate' " or " 'sorting' and 'polystyrene' ", it can go through the next step. In the illustration, 6 abstracts are selected in the first step: abstract 1, abstract 2, abstract 4, abstract 5, and abstract 6. In the second step, the algorithm verifies if the abstracts contain at least one subtractive keyword such as "self-cleaning composite" or "without a separate sorting". Only patents without subtractive combination can go through the last step of the process. In the illustration, abstract 2 contains "self-cleaning composite" and consequently does not pass this step. In the last step, the analyst reads a maximum of 100 abstracts randomly drawn from the list of abstracts that went through the first two steps. The analyst verifies that the content of the abstracts corresponds to the target innovation. Abstract 1, 2, and 6 are valid because they describe patented inventions that are related to plastic waste sorting. However, abstract 5 is not valid because it contains "without a separate sorting operation". In the end, 3 out of 4 patents are valid so that the percentage of valid patents equals 75%. This percentage is too low to use the selected patents to compute innovation statistics. Another iteration is necessary.

The second iteration is similar to the first one but differs in several aspects. The last step of the first iteration, the reading of 100 randomly drawn abstracts, provided new information or feedbacks to the analyst. In the example, two information can be used to improve the selection algorithm. First, abstract 4 suggests that the verb "classify" can also be used in the list of additive combinations. Second, the term "without a separate sorting operation" should be part of the list of subtractive combinations of keywords. Running the algorithm with these improved lists of combinations of keywords, we obtain four abstracts that are all valid. The iterative process stops because the percentage of valid patents equals 100% and cannot be further improved. In the actual algorithm, the number of iterations is much greater and depends on different factors: the complexity of the innovation, the variety of technologies in the innovation and the initial list of additive and subtractive keywords obtained via desk research. The percentage of valid patents obtained in the last iteration is not always 100% (see Table 3.2). When computing patent statistics, the percentage of valid patents is multiplied to patent counts to avoid overestimating innovation.

Even after numerous iterations, the text analysis described above may have trouble distinguishing different plastics innovations. For instance, the additive keyword combinations "eases recycling" can recover a design for recyclability innovation and a sorting technology for recycling. Another example is "depolymerisation of plastics" that can recover both plastic-to-plastic chemical recycling technologies that depolymerise plastics to produce new monomers or polymers and energy recovery technologies that depolymerise plastics to produce fossil fuels. To avoid the overlapping of patent applications between the different plastics innovation, thermal conversion patent applications are excluded from the extracted list of plastic-to-plastic chemical recycling patent applications. Patent application recovered for recyclability that are also recovered for recycling are excluded from the former but not from the latter.

Table A.1. List of keywords to identify plastics related patents

Substance	Acronym	Substance	Acronym
Generic terms		**Thermoplastics**	
plastic		polyformaldehyde	POM
thermoplastic		polyglycolic acid	PGA
thermoset		polyhydroxyalkanoates	PHA
biobased plastic		polyhydroxyalkanoates	PHA
biobased plastic		polyhydroxyhexanoate	PHH
bioderived plastic		polyhydroxyurethanes	
bio-derived plastic		polyhydroxyvalerate	PHV
bioplastic		polylactic acid	PLA
bio-plastic		polylactide	
cellophane		polymethyl methacrylate	PMMA
plastic from soy		polyolefin	
plastic from starch		polyoxymethylene	POM
plastics from soy		polyphenylene ether	PPO, PPE
plastics from starch		polyphenylene oxide	PPO, PPE
soybased plastic		polyphenylene sulfide	PPS
soy-based plastic		polypropylene	PP
starchbased plastic		polystyrene	PS
starch-based plastic		polysulfone	PES
Thermoplastics		polytetrafluoroethylene	PTFE
acetal	POM	polyvinyl acetal	PVA, PVOH, PVAI
acrylic glass	PMMA	polyvinyl alcohol	PVA, PVOH, PVAI
acrylic polymer		polyvinyl-chloride	PVC
acrylic resin		polyvinylidene fluoride	PVDF
acrylonitrile butadiene styrene	ABS	styrene acrylonitrile resin	SAN
celluloid		teflon	
celluloids		thermoplastic elastomers	TPE
cellulose acetate		**Thermoset**	
cellulose ester		bakelite	
expended polystyrene	EPS	benzoxazine	
fluoropolymers		bismaleimide	
nitrocellulose		cyanate ester	
nylon		duroplast	
perspex	PMMA	ecoflex	
plexiglas	PMMA	epoxy novolac resin	
poly methyl methacrylate	PMMA	epoxy resin	
poly-3-hydroxybutyrate	PHB	furan	
polyacetal	POM	melamine resin	
polyamide 11		phenol-formaldehyde	
polyaryletherketone	PAEK	polybenzoxazine	
polyarylsulfone	PSU	polycyanurate	
polybenzimidazole		polyester resin	
polybutylene adipate	PBAT	polyimide	

terephthalate			
polybutylene adipate-co-terephthalate	PBAT	polyurea	
polybutylene succinate	PBS	polyurethane	PUR
polybutylene terephthalate	PBT	rubber	
polycaprolactone	PCL	silicone	
polycarbonate	PC	thermoset	
polyester		thermosets	
polyether ether ketone	PEEK	thermosetting	
polyether sulfone	PES	thiolyte	
polyetherimide	PEI	unsaturated polyester	
polyethylene	PE	urea-formaldehyde	UF
polyethylene terephthalate	PET	vinyl ester	

Source: Own elaboration of the authors.

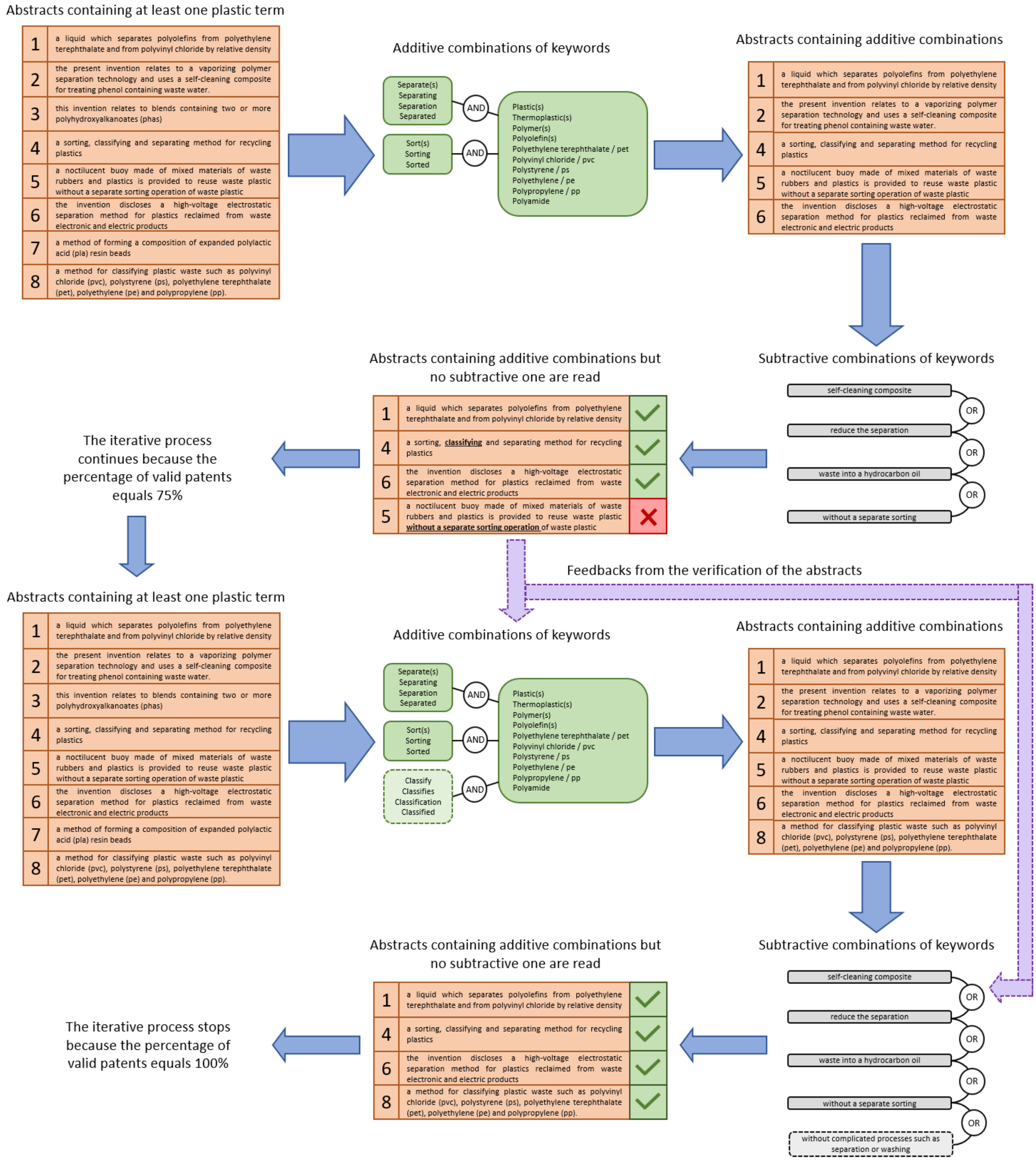
Even with good lists of additive and subtractive combinations of keywords, irrelevant abstracts can be selected simply because they are very long. For instance, consider the following abstract selected by the algorithm that selects patents related to innovation switching towards biobased feedstock:

> *"the invention discloses antitrust paint for improving the brightness of finish. the antirust paint is the characterized by being prepared from 8-12 parts by weight of copal resin, 32-36 parts by weight of organosilicon epoxy resin, 3-5 parts by weight of tetraethylenepentamine, 5-7 parts by weight of 2-hydroxypropyl acrylate, 1-2 parts by weight of ammonium polyphosphate, 11-14 parts by weight of modified asphalt, 4-7 parts by weight of modified waste clay sand, 1-2 parts by weight of fluorescent pigment, 1-2 parts by weight of borneol, 0.3-0.7 parts by weight of a silane coupling agent, 1-2 parts by weight of polyolefin wax, 2-3 parts by weight of light calcium carbonate, 1-2 parts by weight of titanium dioxide, 2-3 parts by weight of cellulose acetate, 1-2 parts by weight of micaceous iron oxide, 10-13 parts by weight of a gasoline solvent no. 200 and 4-6 parts by weight of butyl acetate. by use of the natural resin copal, the antirust paint has the characteristics of nontoxicity and stable properties. the borneol in the paint has a fragrance and effects of relaxing and raising spirit and restoring consciousness, can effectively reduce the peculiar smell of the paint and smells comfortable. the used polyolefin wax can be uniformly disperse a filler to avoid paint quality influence caused by the formation of dust agglomeration. the used micaceous iron oxide has a strong anti-rust effect. the used fluorescent pigments and titanium dioxide can improve the brightness of the antirust paint and give people a comfortable visual enjoyment."*

This abstract would be selected because it contains one additive combinations of keywords that is "cellulose acetate" and no subtractive combination of keywords. However, the abstract contains 251 words. When reading the abstract, one can see that the invention is about antitrust paint that is composed of many different materials in which a biobased polymer plays a minor role. Therefore, the abstract is not really about biobased feedstock. The share of words included in the abstract that are additive combinations is in this case equal to 0.4%. This low share gives us a hint that the abstract is unlikely specifically referring to an innovation for switching towards biobased feedstock. To avoid capturing long abstracts that are unlikely valid, a final step is added to the iterative process described above. This final step consists in removing abstracts that have a share of words that are additive combinations that is lower than 0.5%.[24]

[24] This threshold can be different for some innovations. For instance, the threshold equals 0.75% for biodegradable plastics. Using 0.5% would generate too many invalid patents. The difference between biobased and biodegradable plastics in terms of threshold is explained by the fact that biodegradable plastic must fulfil several conditions: being plastic and being degradable in the natural environment. The condition of biobased plastics is much less constraining, as it only requires that biobased plastics is being produced or used by the patented invention.

Figure A.1. Schematic example of a two iterations selection algorithm in the case of plastic waste sorting



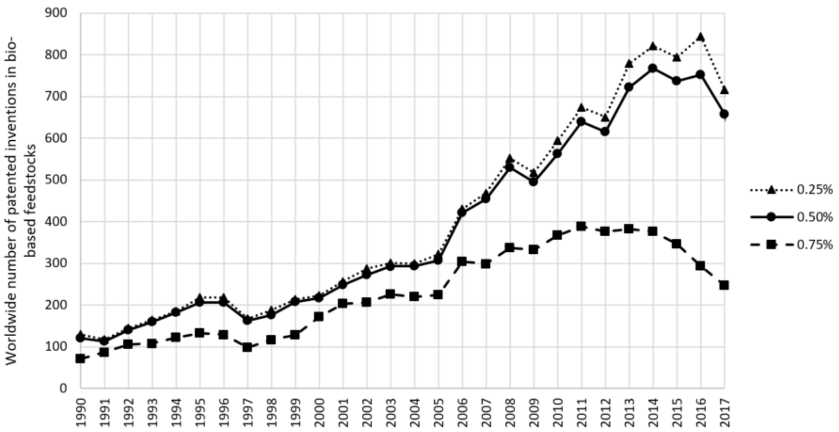
Note: This two iterations process is for illustration only. In reality, the list of abstracts to analyse, the list of additive and subtractive combinations of keywords are much longer and the number of iterations is much greater.
Source: Own elaboration of the authors

The total number of patented inventions is influenced by this threshold as illustrated by Figure A.2 in the case of biobased feedstock. Mechanically, the higher the threshold, the lower the number of patented inventions. Using a threshold of 0.75% instead of 0.5% divides the number of patented inventions by a factor 2. It is also problematic because it would exclude abstracts that have a low share of additive combinations of keywords per word such as:

> *"the invention relates to a medical polylactic acid composite material and a disposal syringe prepared by the same. the medical degradable polylactic acid composite material comprises polylactic acid (PLA), a toughening agent and a nucleating agent, wherein each 100 parts of the polylactic acid (PLA) contains 10-50 parts of toughening agent and 1-5 parts of nucleating agent. the medical polylacticacid composite material has the advantages that all the blending components of the medical polylactic acid composite material are medical nontoxic products, monomers and corresponding polymer synthesized by the components are safe and nontoxic to human bodies and can be automatically degraded into water and carbon dioxide in 4-6 months under a composting condition, the blended resin does not contain small-molecule plasticizers, and the risks that the small-molecule plasticizers separate out, pollute liquid medicine and enter the human bodies are avoided; the medical polylactic acid composite material can be used as the special material for the disposable degradable syringe and used for preparing the disposable degradable syringe; the antibacterial performance and degradability of the medical polylactic acid composite material are evidently better than those of a pure polylactic acid raw material; the medical polylactic acid composite material is reasonable in formula, stable in performance, free of environment pollution and capable of being produced in clean workshops in a large-batch manner."*

The share of additive combinations per word included in this abstract equals 0.5% yet it is unambiguously about biobased plastics. In contrast, using a threshold of 0.25% instead of 0.5% have a small impact on the number of patented inventions. Therefore, the 0.5% threshold allows removing unrelated patented without significantly affecting the total number of patented inventions.

Figure A.2. Number of patented inventions on biobased feedstock by threshold of the share of additive combinations per word included in the abstract



Note: An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered.
Source: Calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Annex B. Econometric analysis

A brief introduction to synthetic control methods

The synthetic control method is an empirical method that have been used to evaluate a wide range of economic policies (Abadie, 2019[22]). Synthetic controls aim to estimate the effects of interventions that are implemented at an aggregate level affecting large units such as countries on some aggregate outcome of interest.

Conventional regression analysis techniques that require large samples and many observed instances of the event or intervention of interest are often inadequate to estimate the effects of infrequent events such as the introduction of an EPR system. For such events, economists used comparative case studies consisting of comparing the “treated” country to “untreated” countries. However, the selection of the comparison units is not formalised and often relies on ad hoc assumptions.

The synthetic control method overcomes these issues by combining unaffected units in a synthetic group or counterfactual that is more appropriate than any single unaffected unit alone. Untreated units are combined using weights that minimise the difference between the treated unit and the synthetic control for the years before the treatment or policy change on a list of predictors. These predictors generally include pre-intervention values of the outcome variable but also other predictors.

Estimating the effect of Japan’s packaging recycling act

Table B.1 shows the average value of the predictors for Japan and its counterfactual over the pre-intervention period. The differences between Japan and the synthetic control during the pre-intervention are small suggesting that the counterfactual is able to replicate the characteristics of Japan before the policy change.

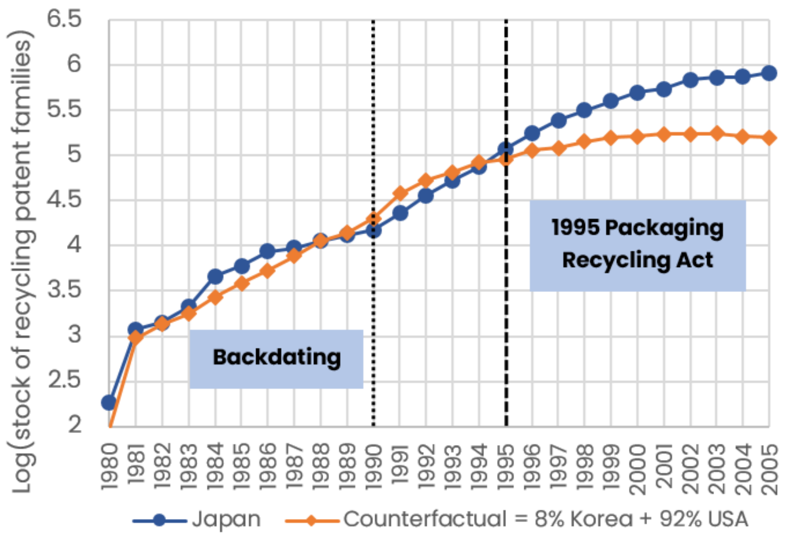
Table B.1. Predictor balance between Japan and its counterfactual

	Japan	Counterfactual
Log(stock of all plastic patents)	10.36	9.84
Log(GDP per capita)	10.40	10.27
Log(energy use per capita)	8.07	8.81
Log(stock of recycling patents)(1982)	3.15	3.13
Log(stock of recycling patents)(1984)	3.66	3.43
Log(stock of recycling patents)(1988)	4.05	4.05

Note: The counterfactual Japan is composed of 92% United States and 8% Korea. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020. Data on constant 2010 USD GDP per capita come from World Bank national accounts data and OECD National Accounts data files. Data on energy use per capita come from IEA Statistics © OECD/IEA 2014.

The absence of estimated effects prior to the introduction of the packaging recycling act provides credibility of the synthetic control estimator, as it demonstrates that the method can reproduce the trajectory of patent recycling for Japan before the recycling policy comes into force. Figure B.1 shows a difference between recycling patent for Japan and its synthetic control counterpart appears around 1995 even when the intervention is five-year backdated in the data and the procedure uses no information on the timing of the actual intervention. The estimated gap with backdating is similar to that of Figure 6.3. The fact that the estimated effect of the EPR system for packaging appears shortly after 1995 even when the intervention is artificially five-year backdated in the data provides credibility to the synthetic control estimator applied.

Figure B.1. The synthetic control method applied to Japan is robust to backdating



Note: The counterfactual Japan is composed of 92% United States and 8% Korea. The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Estimating the effect of the German packaging ordinance

Table B.2 shows the average value of the predictors for Germany and its counterfactual over the pre-intervention period. The differences between Germany and the synthetic control during the pre-intervention are small suggesting that the counterfactual is able to replicate the characteristics of Germany before the policy change.

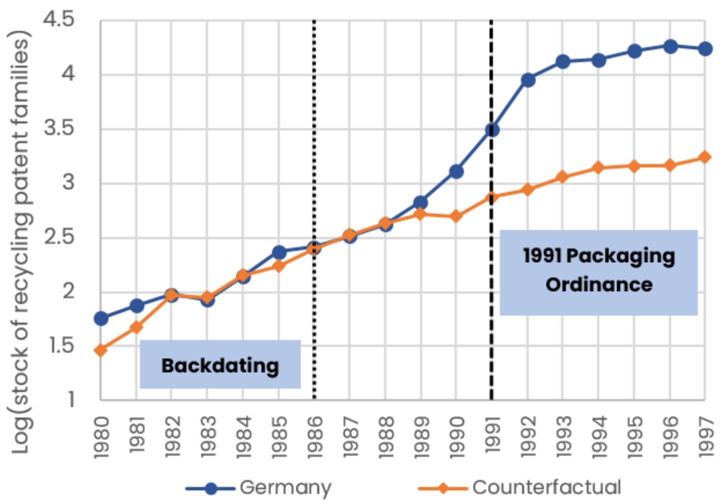
Table B.2. Predictor balance between Germany and its counterfactual

	Germany	Counterfactual
Log(stock of all plastic patents)	7.84	7.72
Log(GDP per capita)	10.25	10.12
Log(energy use per capita)	8.41	8.46
Log(stock of recycling patents)(1982)	1.97	1.96
Log(stock of recycling patents)(1984)	2.14	2.16
Log(stock of recycling patents)(1988)	2.62	2.59

Note: The counterfactual Germany is composed of 28% Canada, 12% Japan, 24% Netherlands, 13% Korea and 23% United States. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020. Data on constant 2010 USD GDP per capita come from World Bank national accounts data and OECD National Accounts data files. Data on energy use per capita come from IEA Statistics © OECD/IEA 2014.

Figure B.2 shows a gap between recycling patent for Germany and its synthetic control counterpart appears around 1991 even when the intervention is five-year backdated in the data and the procedure uses no information on the timing of the actual intervention. The estimated difference with backdating, similar to that of Figure 6.4 provides credibility to the synthetic control estimator applied.

Figure B.2. The synthetic control method applied to Germany is robust to backdating

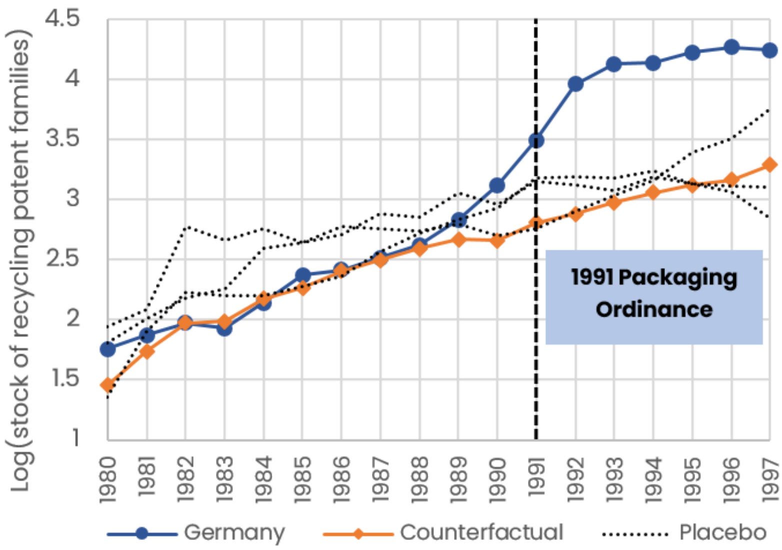


Note: The counterfactual Germany is composed of 62% Canada, 8% Japan, 10% Netherlands and 20% Korea. The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982 and 1984. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

Establishing a permutation distribution of placebos allows assessing whether the effect estimated via a synthetic control method if statistically significant. The permutation distribution is obtained by estimating the placebo effect of the policy change for each of the units in the donor group excluding the treated unit (Abadie, 2019[22]). Figure B.3 shows the permutation distribution for the estimation of the packaging ordinance. The dotted lines correspond to an estimated placebo effect for Canada, Japan and the United States.[25] More specifically, a placebo effect equals the sum between the counterfactual for Germany and the estimated gap for the untreated country. The permutation distribution can be seen as a confidence interval. The effect of the packaging ordinance is Germany (in blue) is way above all the other placebo effects suggesting that it is statistically different from zero. Nevertheless, the few numbers of donor countries and placebo effects limit the strength of this test.

Another robustness check consists in verifying whether the synthetic control estimator is sensitive to the inclusion or exclusion of one or several donor countries. Figure B.4 shows the counterfactuals estimated when one country from the donor group is excluded. We find that the method is not sensitive to the exclusion of most donor countries except Canada.

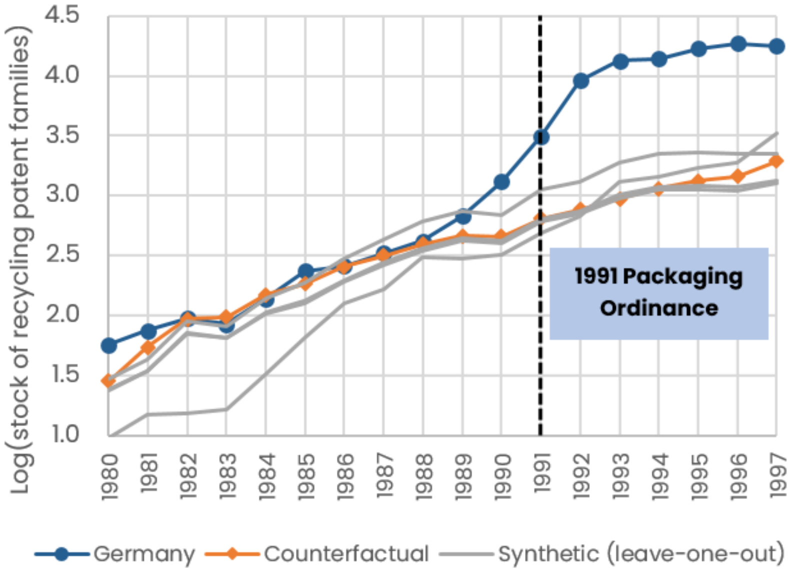
Figure B.3. Inferring the effect of the packaging ordinance using permutation distribution of placebos



Note: The counterfactual Germany is composed of 28% Canada, 12% Japan, 24% Netherlands, 13% Korea and 23% United States. The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

[25] The placebo effect cannot be estimated for Korea and the Netherlands because the pre-intervention fit is not good.

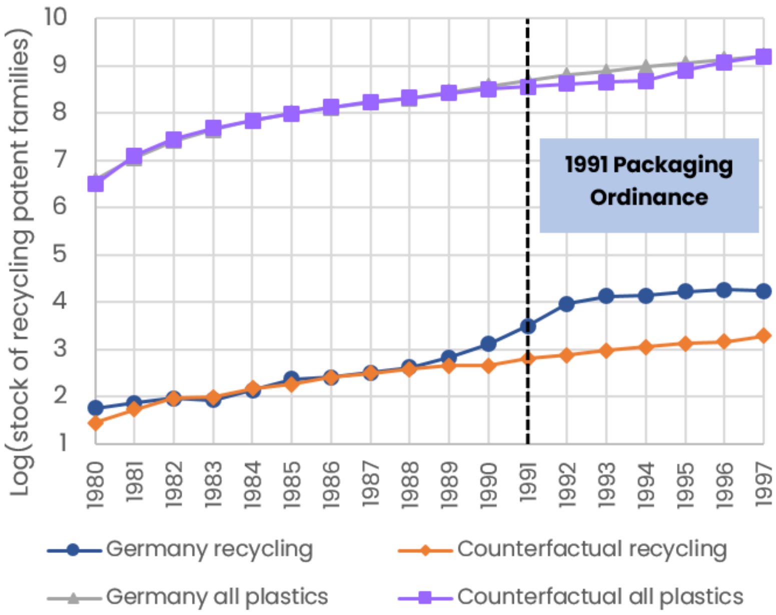
Figure B.4. Robustness of the synthetic control method for Germany to the exclusion of donor countries



Note: The counterfactual Germany is composed of 28% Canada, 12% Japan, 24% Netherlands, 13% Korea and 23% United States. The predictors used are log(patent stock in all plastics innovation), log(GDP per capita), log(energy use per capita), log(recycling patent stock) in 1982, 1984 and 1988. An invention corresponds to a single patent family. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.

A final check consists in conducting another type of placebo test. Instead of estimating the effect of the packaging ordinance on recycling innovation, we estimate its effect on all plastics innovation. In theory, the packaging ordinance should not have any impact on all plastics innovation. Figure B.5 shows the effect of the packaging ordinance on both all plastics innovation and recycling innovation. We find that the estimated difference between Germany and its counterfactual in terms of all plastics innovation is not significantly different from zero. This contrasts with the estimated effect on recycling innovation.

Figure B.5. The packaging ordinance did not increase innovation in all plastics



Note: The counterfactual Germany is composed of Canada, Japan, Netherlands, Korea and United States. The predictors used are log(GDP per capita), log(energy use per capita), log(patent stock) in 1982, 1984 and 1988. An invention corresponds to a single patent family. When the dependent variable is log(patent stock in plastic recycling innovation), we also use log(patent stock in all plastics innovation) as predictor. The year of the invention corresponds to the application date of the priority patent. Only granted patents are considered. Plastic recycling patents include mechanical recycling, plastic-to-plastic chemical recycling, sorting and other pre-treatments.
Source: For the patent data, calculation of the authors based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2020.