CIRCULAR ECONOMY: CLOSING THE LOOPS

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ISWA
International Solid Waste Association

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The International Solid Waste Association (ISWA) is a global, independent and non-profit making association, working in the public interest to promote and develop sustainable waste management.

ISWA has members in more than 60 countries and is the only worldwide association promoting sustainable, comprehensive and professional waste management

ISWA's objective is the worldwide exchange of information and experience on all aspects of waste management. The association promotes the adoption of acceptable systems of professional waste management through technological development and improvement of practices for the protection of human life, health and the environment as well as the conservation of materials and energy resources.

ISWA's vision is an Earth where no waste exists. Waste should be reused and reduced to a minimum, then collected, recycled and treated properly. Residual matter should be disposed of in a safely engineered way, ensuring a clean and healthy environment. All people on Earth should have the right to enjoy an environment with clean air, earth, seas and soils. To be able to achieve this, we need to work together.

Executive summary

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We take recycling for granted. After all, everybody 'knows' about it, and most likely, opportunity given, 'recycles': meaning, invests the time and effort to sort out and clean the material, placing it in the suitable recycling bin. However, whoever works in the waste and resources management sector knows well that this is just the beginning of a long journey for the recyclable material: a series of actions are necessary to convert this sorted item into what is called a 'secondary' raw material, suitable to replace virgin material in a product manufacturing process. One could argue that such a replacement is the ultimate moment of a 'circular' economy: the closing of the loop, the rejuvenating of a used technically engineered material such as a polymer or paper into the 'same' matter state. Whereas there is more to a circular economy than just the technical cycle of recycling, it still occupies the very core of it: the bare minimum if it is to be 'circular', to which other peripheral actions should be organised around.

Here, we revisit the evidence regarding the feasibility of recycling, with a view to what are the bottlenecks of more and better recycling, and with reference to key aspects of sustainability of resource management: technical aspects, markets and environmental performance. We focus on two key engineered materials: one representative of the plastics family (polypropylene - PP) of fossil non-renewable origin, and one renewable biogenic category of materials: paper & board.

There are fundamental underlying similarities (for example, both are used most in packaging short-lived applications; and scrap is traded globally) along with striking contrasts (for example level of collection for recycling) in the two cases considered: with collection for recycling rates at over 70% in Europe and around 50% of new paper/board manufactured utilising recovered material, paper/board recycling is a prominent success story. However, such figures do not consider quantity and quality of fibre: the very backbone of the paper/board material, and just a fraction of its mass. In contrast, PP despite accounting for around one quarter of the world's plastics production, paradoxically or not, currently enjoys very low level of recycling. Estimates of how low is exactly this level are not available, and this demonstrates once again the lack of reliable and widely available information, which impedes resource recovery from waste. UNComtrade collects international trade data for other major recycled polymers (e.g. PET, HDPE), but not for PP.

The reasons behind this lag for PP recycling –and the knowledge about it– can be sought in: extreme variability in material qualities, including complex/composite materials, types of items and sectors – all these reflecting the innovation for functionality and the remarkable adaptability of the basic polymer; inadequate collection infrastructure and use of commingled systems, which impede collected feedstock separability, as for rigid packaging PP; lack of suitable technologies to effectively separate the necessary quality of recycled PP: e.g. separation from similar density PE, food grade fraction, black coloured fraction identification by NIR systems; capital investment cost for advanced sensor-based sorting; absence of globally accepted / well established quality standards; insufficient reprocessing capacity in Europe; unclear technical capabilities and fate in major import destinations, such as China; competition from domestic collection in traditional export destinations; low quality of export standards (traded usually as part of mixed plastics); financially unsustainable advanced recovery technologies (feedstock recycling via thermal processing decomposition); non-transparent markets, including pricing; series of major challenges related to trading in a globalised secondary material value chain, including asymmetry of information; direct completion with virgin materials on the price, and dependence on oil prices. Addressing such issues could enable a substantially increased level of meaningful recycling for PP.

A critically important contribution of the waste management and reprocessing industries lies in keeping the environment clean while closing the loop. In many cases, legacy issues have to be addressed during the recycling process, such as in the presence of certain brominated flame retardant additives in plastics that proved carcinogenic, or compounds associated with inks in paper, such as bisphenol-A (BFA): it is very important to de-pollute the ma-

terial flows and close the loop while preventing dispersion of polluting substances. Such de-pollution function, results in some inevitable losses and sets another limit to what can be sustainably recycled. Notwithstanding this, there is insufficient understanding of the environmental and wider sustainability performance of the closing of the loop. Whereas some life cycle assessment research studies indicate limits to environmentally meaningful recycling, requiring, for example, high level of virgin material substitution, there are no studies for PP, covering the entire reprocessing cycle, the multiple sources and additives, and its export from OECD countries and final closing of the cycle in conditions of environmental protection and manufacturing that may be sub-optimal. Much more comprehensive sustainability assessment is required, including multiple aspects of resource recovery, to substantiate the perceived benefits and address the questions currently raised.

Innovation for high quality sustainable recycling at suitable level of cascade is needed. Indeed, a major finding is that the (perpetual) closed-loop model (recycle in same use and for multiple cycles) may not be feasible in many occasions, because of small but sufficient deterioration of fundamental material properties during its use, collection for recycling and reprocessing: e.g. length of fibres is shortened for paper/board in each reprocessing cycle. As a result, virgin raw material still needs to be added at some percentage while recovering the used paper/board; and a 'cascade' model, by use in less quality demanding applications, is by far more realistic prospect, before an eventual recovery in energy from waste. Newsprint is an intermediate example: whereas one can make newsprint paper from 100% recovered paper, possibly a lot of used paper of much higher quality will end up as recovered for newsprint quality while closing the loop. Food contact packaging PP cannot at present be recycled back to the same use because the legislative standards require very high material purity and there is no automated way to identify it – manual separation is also still necessary as a final stage quality improvement in sorting used paper grades sorting.

Another limit to the closed-loop model stems from the losses that inevitably occur during the multiple stages of closing the cycle: starting with ability to collect sufficient quantities, and continuing with the rejection of unsuitable material (damaged, contaminated) and the limited separation efficiencies of the sorting equipment. There is no concrete evidence about the level of such losses. Similarly, there is no sufficient understanding on the additional resources (virgin material, energy, water, chemical additives) that is required to close the loop per mass unit of secondary PP and paper/board.

Sustainable closing of the engineered material loops remains technically challenging. The potential for recyclability and its sustainability depend primarily on: the material properties; the processing engineering technologies available to perform the closing of the loop; and the societal need and technical quality requirements for the intended use of the secondary raw material. Continued technological innovation on material properties, processing and standardisation is needed to enable the demand for high quality recycled materials. To this, recyclability has to be aligned as far as practicable with innovation in new materials/ additives: on the contrary, some of the newly emerged barriers to paper/board recycling are due to innovations in flexographic newspaper printing and/or digital printing which necessitate novel approaches in reprocessing.

Ultimately, closing the loop depends on market conditions, resulting in major challenges for the sustainability of circular economy. Recycled materials are in direct competition with the equivalent primary (i.e. virgin) raw materials –an underexplored aspect, where plain field is required- and when exported from OECD, they are traded in globalised value chains. Understanding and addressing such market challenges, and underpinning solutions with environmentally conscious technological innovation, could make the difference in sustainable resource management and should, therefore, be prioritised.

Prepared by the ISWA task force on resource management

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Costas is honoured with many international awards for his research papers, including the prestigious Institution of Civil Engineers Terford Premium Award in 2014.

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Introduction

Background and scope

This study was undertaken on behalf of the International Solid Waste Association's Task Force on Resource Management. It comprises a review of the value and potential to enhance the level of recovery of two key materials: polypropylene and paper & board. The overall objective of the study is to support ISWA's work assessing the potential role that the waste management sector can play in achieving greater resource efficiency and moving towards a circular economy.

The study is based entirely on review of secondary data and has involved an extensive review of publicly available literature and data sources. Please note that no primary data has been collected during the source of this work.

There are fundamental underlying similarities (for example, both are used most in packaging short-lived applications; and scrap is traded globally) along with striking contrasts (for example level of collection for recycling) in the two cases considered.

Structure of report

This report comprises two main sections: Section 1 focuses on polypropylene and Section 2 focuses on paper & board. Each of these sections considers the following main issues for these two material streams:

1. Properties and uses: an overview of the material's key characteristics and main applications.

2. Waste generation and recycling: an overview of the estimated quantities of secondary materials generated, processed and consumed.

3. Recycling processes and technologies: A review of recycling processes and technologies including a discussion of the key issues in terms of technical, financial, and environmental themes.

4. International market review: A review of the material's markets, market values and market trends.

5. Barriers and opportunities: a discussion of the key findings of the review, including a consideration of the key barriers associated with maximising the recycling of the material.

The final section of the report presents a detailed reference list.

Polypropylene

Properties and uses

Polypropylene (PP) is a crystalline thermoplastic synthesized by polymerization of propylene and one of the major members of the polyolefin family. PP is used in various grades, and combined with other materials in laminates or metallised film structures[8]. It is available in homopolymer for general use, and is also commonly co-polymerised with other polymers, such as ethylene, where higher impact qualities are required. Key physical / chemical properties of PP include:

- semi-crystalline thermoplastic, high stiffness, good tensile strength and fatigue resistance.
- lightweight and rigid material, easily machined cut and cleaned.
- excellent thermal insulating and dielectric properties, and good heat resistance.
- resistant to acids, bases and solvents.
- low moisture absorption.
- resistant to bacteria and fungi which makes it particularly suitable for food contact applications; and can be steam sterilized for medical applications.
- not resistant to oxidation – it is stabilised with antioxidants.
- high energy content.

Due to its properties, PP (alone or combined with a variety of additives) is used for a broad range of applications with diverse durability and life-span such as packaging (household and industrial/commercial: e.g. trays, bowls, orientated PP films as for crisps, bottle caps/closures), building and construction, automotive parts, and electrical and electronic equipment (EEE).

Packaging is the major single end-use of PP (39.4% of all PP used in the EU[4]), including both flexible packaging (films) and rigid plastic products.[9] Around 70% of PP packaging is used in the form of pots tubes and trays (PTTs) for food-grade applications.[10] PP represents large amounts (~70%) of closure items[2], which usually are coloured and many feature self-adhesive labels.[10]

Regarding less short-lived items, in the building and construction industry PP is typically used to manufacture products with longer lifespans (around 35 years)[6], such as pipes and ducts.[2] PP also is used in the manufacturing of a wide range of EEE. Its uses include components of large household appliances (e.g. washing machines and dishwashers) and small household appliances (e.g. kettles, irons, coffee machines, toys, computers and printers)[6]. PP is one of the major plastics used in the automotive sector and its applications included bumpers, battery cases, etc. The average lifespan of a car is between 12 and 15 years[11] and thus end-of-life-vehicles (ELVs) in the recycling chain today could have been manufactured at the beginning of the 2000s. Vehicle composition at that moment contained around 9-10% of PP. During the last decade, vehicle design made increased use of polymeric constituents, due to their advantages associated with their lower density (resource efficiency via lightweighting).

Tab. 1 Rigid PP waste generation and recovery by sector in Europe

EU 27 + 2 (2009)	ARISINGS		RECOVERY (COLLECTION FOR RECYCLING AND ENERGY RECOVERY) (kt)			(COLLECTION FOR) RECYCLING RATE
	kt	%	TOTAL	MECHANICAL RECYCLING	ENERGY RECOVERY	%
Packaging	1717	71.6 %	972	234	734	13.6
Bottles	187	7.8 %	133	67	65	36.0
Non-bottles	1530	63.8 %	839	165	672	10.9
Automotive	410	17.1 %	133	94	40	22.8
WEEE	140	5.8 %	52	9	43	6.5
Total	2267	94 %	1157 (51 %)	337 (15 %)	820 (36 %)	14.9

Source: PlasticsEurope (2011)[5]

Waste polypropylene generation, recycling and outlets

PlasticsEurope indicate that ca. 2.27 million tonnes (Mt) of rigid PP waste was generated in EU in 2009 (Table1). To our knowledge there are no worldwide data available. Because of its wide range of applications, waste containing PP ('PP waste') originates from many sources. The main sources of PP waste correspond to the most common applications and their relative rate of product useful lifetime: packaging (44%), building and construction industry (19%), ELVs (6%) and WEEE (5%). The remainder 22% is generated from other sources: agriculture, hospital/medical care, protective clothing, sport surfaces, household items.

The short lifespan[6] of packaging products, which are mostly single-use disposable items, results in the generation of considerable quantities of PP packaging waste per year. According to a study carried out in Switzerland in 2011, 10.4% of the recyclable plastics fraction of waste EEE (WEEE or e-waste) is PP[12]. PP waste from small household items is generally mixed with other municipal wastes[6], whereas PP present in larger electrical appliances, such as washing machines and dishwashers, may be often collected separately. PP and other plastics from the agricultural applications have now also started to be collected for recycling in some countries.

There are limited data on collection for recycling, final primary materials substitution, and energy recovery in various forms (EfW, RDF, SRF, feedstock recycling) of PP in Europe. The total recovery rate (collected for recycling and energy uses) was at 51%, split into by energy recovery (dominating at 36 of the % units) and collection for recycling at 15%. This is considerably lower than the 26% or overall post-consumer waste plastics collected for recycling in EU-27 in 2012, which means that waste PP is considerably less effectively separately collected than the average non-PP waste polymer. Whereas most of the waste plastics collected for recycling are destined for mechanical recycling, rather than thermal decomposition or chemical recycling, it is unclear how much of the 15% collected for recycling is delivered to materials recovery facilities (MRFs) and the specialised plastics reclamation facilities (PRFs) within Europe vs. the exported quantity. An ISWA study last year reminded us that regarding all post-consumer waste plastics in EU-27, from the entire quantity collected for recycling almost half of it is exported (46% of collected) and most of it (87% of the exports) to China and Hong Kong Special Administrative region (SAR), where its exact fate is not documented. Based on UK data, it was estimated that PP comprises 2% of exported plastic scrap[13]: whereas this is a rough estimate and may not be generically applicable to all exporting countries, it does indicate the likely scale of PP export for recycling, especially relative to other polymers.[13]

A sub-category of PP waste is in the form of rigid PP. Around 90% of the rigid PP waste generated comes from non-bottle applications, such as PTTs. Rigid plastic packaging from kerbside collection (multiple stream collection) systems usually is sent to PRFs, while plastics collected commingled (either single or two-stream), is sent to MRFs for further separation. Collection for recycling and energy recovery rates of rigid PP waste in the EU are at: 57% for the packaging waste, 32%

for the automotive industry and 37% for the WEEE. A large amount (70%) of the total rigid PP recovered from the automotive sector in the EU is mechanical recycled, while 83% and 76% of the total rigid PP recovered from WEEE and packaging respectively go to energy recovery. Germany had in 2011 the highest collection for recycling rate of rigid PP (~33%), which was around 3 times more than the rate achieved at other EU countries, which were below 13%.[5] Germany has been collecting packaging plastics in the 'yellow bin' along with rest packaging for many years and is now moving to a new system ('yellow bin plus'), which aspires to increase the collection rate by collecting all plastics. In addition to packaging items, this recycling bin also can accept non-packaging everyday items made of plastics and metals such as toys, pans and plastic buckets. Battery cases and bumpers from the automotive industry also play a non-negligible role in rigid PP recycling chain in Germany.[5]

There are some established and evolving markets for recycled PP (rPP), including automotive applications, construction and building products, food packaging and other households articles (bins, buckets, boxes, crates and cradles). Despite the existence of these markets, the overall rates of waste PP collected for recycling are very low compared to other major polymers such as PET and HDPE, because PP is used in various grades and combined with other materials in laminate or metallised film structures making identification and separation difficult.[6] The different sources, types, grades, qualities and shapes in PP products often make also the mechanical recycling a complex endeavour.

Vehicle applications have become a high-end market for rPP. PP allows potentially easier recovery and reuse of components when a vehicle's lifetime is over. Car interior components with up to 60% of rPP, sourced from the automotive industry is currently commercialized – a case of closing the loop. The construction industry also represents an important potential market opportunity for large quantities of rPP.[14] Pipes, wire and cable covering, and wood-plastic composites (WPCs) are uses for recycled polyolefin in general. rPP has been successfully used to manufacture WPCs and plastic boxes.[13]

A new potential market for packaging waste is food-contact PP applications, but there are still important (technological) barriers. Some food packaging has multiple layers of resins or additives that can make recycling technically challenging. A key barrier to successfully developing this end use for rPP is that the quality of food-contact plastics is subject to stringent regulatory requirements to ensure that potential harmful substances which could come into contact with food are not used during manufacturing of the packaging. The European Food Safety Authority (EFSA) established that rPP must be made starting with 99% food-contact PP material (note that the equivalent threshold for PET, for which closed loop recycling is feasible, is at the much less challenging 95%).[2]

To materialise this theoretical potential market, it would require investment and research and development (R&D) efforts in the whole recycling and reprocessing chain: collection, sorting and decontamination steps capable of producing food-contact rPP to replace virgin food-contact PP. Notwithstanding this, important technological advances on turning used plastics into food-grade polymers by removing the contamination were recently achieved, enabling a range of polymers to be used for food-contact applications. For example, the use of rPET in soft drink containers, the use of rHDPE in milk bottles, and, more recently, the use of rPP in pots and trays for food. New EFSA certified technologies were developed for PP use in food-contact grade (e.g. Shroeller Arca, Petra Polymery). A remaining constraint at present is to prove whether pigments from direct printed and in-mould labelled products may create problems for food-grade rPP. In addition to the household PP packaging waste stream, some food contact packaging could potentially be recovered from the catering supply chain by capturing injection moulded PP tubs and pails for fats, pickles and sauces and blow-moulded jars for similar applications.[10] Thus, achieving quality standards and applying effective technologies to this, could allow new outlets for rPP to develop.

Closing the PP material loop: technologies and processing

Mechanical recycling

Mechanical recycling (no chemical transformation involved) is a well-established and widely applied technology for producing rPP. Typically and simplifying, waste PP is separated at source and collected along with other plastics or together with other dry recyclables (single stream or commingled collection). The collected material is processed in PRFs and MRFs where PP is sorted from other polymers by the use of a variety of separation technologies. Finally, the material is transported to reprocessors, where waste PP is re-melted and extruded to form flakes or pellets[2] of rPP.

Feedstock recycling. Feedstock recycling by means of pyrolysis or gasification (thermal processing) can be more suitable than mechanical recycling for contaminated and very heterogeneous mixes of wastes (e.g. automotive and electronic shredder residues) containing PP mixed with other polymers. If applied appropriately, it can provide a valuable and efficient use of the energy and materials value embodied in waste plastics. However, such solutions are not yet at applied commercially: one limiting factor is that large economies of scale are needed for investing in such types of processing. It also relates to the amount of waste plastics collected for recycling, which are still insufficient. Much greater levels of plastics polymer collection would be needed to provide the secure feedstock at the appropriate scale for feedstock recycling to become viable. Feedstock, so called, 'recycling' of non-recyclable PP and other polymers can be also performed by their use as raw material in blast furnaces. PP cannot be degraded by the simple addition of chemicals (through alcoholysis, hydrolysis, glycolysis and methanolysis) to their initial monomers due to the random scission of the C-C bounds[15], so chemical recycling is not an option.

There exist many competitive routes to resource recovery for PP as a fuel, via direct combustion energy from waste (EfW) as part of mixed residual waste, or via the simple sorting for the preparation of a refuse-derived fuel (RDF) send also to EfW plants; or through the much more sophisticated quality assured solid recovered fuel (SRF)[16] suitable for recovery in cement kilns, power plants and other high energy demand industries, customarily replacing coal. Processing solutions to liquid fuels also emerge.[17]

Technical challenges

Hence, mechanical recycling is the most viable and established route for closing the materials loop for PP today. However, there are important technical challenges which impede the effective closing of the loop for PP. A key disadvantage of mechanical recycling of polymers is that it can only be performed on a pure polymer. Separation technologies are needed to sort complex mixtures of plastic wastes into single polymer outputs and at the same time remove (adhesive) contaminants and unwanted items (contraries). The majority of separation technologies for polymer types are based on density separation (air classification, cyclones, hydro-cyclones, centrifuges, float-sink) and/or spectrophotometric properties (Near-infrared (NIR), mid-infrared (MIR), Raman spectroscopy, X-Ray Fluorescence spectroscopy, X-Ray detection, laser sorting). The major polymers currently separated for reprocessing in MRFs are PET and HDPE.

Because the technology to separate PP and PE already exists in the market, in the last few years an increasing number of MRFs have started to sort a wider range of polymers from packaging waste, including PP received in the form of PTTs. Density-based sorting technologies can separate polyolefin polymers (PP, PE) from other denser resins (PS, PVC, PET, PS). However, they are neither capable of sorting polymers with similar density (PP, PE) nor polymers containing physical additives (i.e. PP with fibres used in construction and automotive industries) that may change the density of the single resin. This problem is solved by using sensor-based separation (NIR) able to distinguish between most of the polymer types, PP and PE included. Despite the capital investment cost, in Europe, the use of NIR sorting equipment to separate plastic polymers in MFRs is already widespread. However, the investment required to purchase NIR sorting units for different polymers is high and most of the small material recovery facilities cannot afford it. Separation is further complicated by increased use of multi-layer packaging.

Whereas these technologies are able to successfully sort the major polymer groups[18], they are not capable of identifying carbon-black polymers, which results in a significant reclaim loss for PP materials.[19] A potential solution for sorting black PP, currently tested at pilot scale, is the use of a baffled oscillation reactor using water for the separation. This method, stemming from mixing pharmaceutical liquids, can split the lighter fraction into two plastic types, PP and PE, while the heavier fraction sinks, giving a third output material. Another solution explored is the use of alternative colourants to increase the efficiency of NIR separation technologies. Such colourants would need to be sufficiently stable for repeated reprocessing through conventional processes. However, many of these alternative colourants do not currently match carbon-black for tint strength or price.[18]

Another disadvantage of the currently commercially available technology is its inability to distinguish between non-food and food contact PP. Keeping in mind that around 60-70% of the PP used in packaging applications is food contact this makes it difficult to close the material loop for food grade PP back into same specification applications. This serves as a barrier to provide the material needed for developing new markets for recycled food contact packaging. An alternative solution to NIR can be the use of MIR technology, which is able to detect carbon black plastics; however, this technology is still in commercial development due to technical and processing limitations.[20, 21] In addition, NIR technology finds it hard to distinguish between different grades of the same polymer.

International market review

PP Production and Consumption

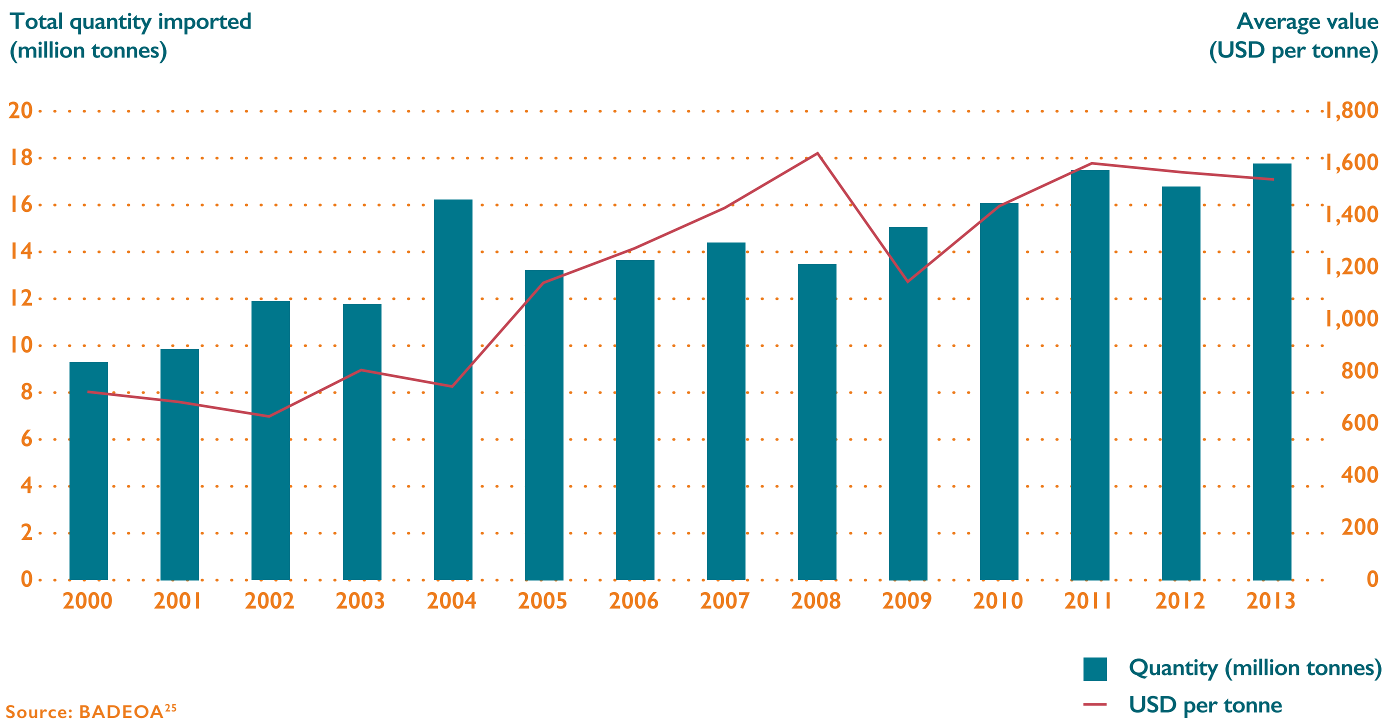
The global PP market is the second largest volume polymer business in the world today, making up 25% of entire polymer demand[22], according to IHS. Assuming a global production of plastics in the region of 299 Mt in 2013, this would be equal to around 75 Mt of PP produced globally per year. Production of PP has gradually shifted from areas where historically demand was high (e.g. Europe) to areas where feedstock costs are low (e.g. Middle East and Asia).[23] The shift is evident also in consumption: China accounted for the 28% of global PP consumption in 2013.[24] Regarding sectors, 'other' applications accounted for 41% of the end-use in 2013, followed by packaging (32%), EEE (14%) and equipment and facilities (13%), based on data from AMI, according to EcoSphere.[17]

The amount of trans-national trade of virgin PP is considerably lower: in 2013, just over 17 Mt of virgin PP was traded (Figure 1). The demand for this polymer has increased consistently over the past decade, rising from just under 12 Mt in 2003, an increase of over 40%. This increase in trans-national trade demand is also echoed in the increasing value of PP since 2000 (also illustrated in Figure 1). These trends are expected to continue.

The main exporters of PP are illustrated Figure 2: at 4.1 Mt, Saudi Arabia is the largest exporter of PP, almost four times bigger than the next largest exporter, Germany (1.2 Mt). Saudi Arabia's production of PP experienced major leap upwards in 2007, rising from less than 1 Mt in 2007 to over 4 Mt in 2013. Other producers with rising exports are India, Germany, Singapore and Hong Kong SAR. Exports from the United States has decreased from a peak in 2007.

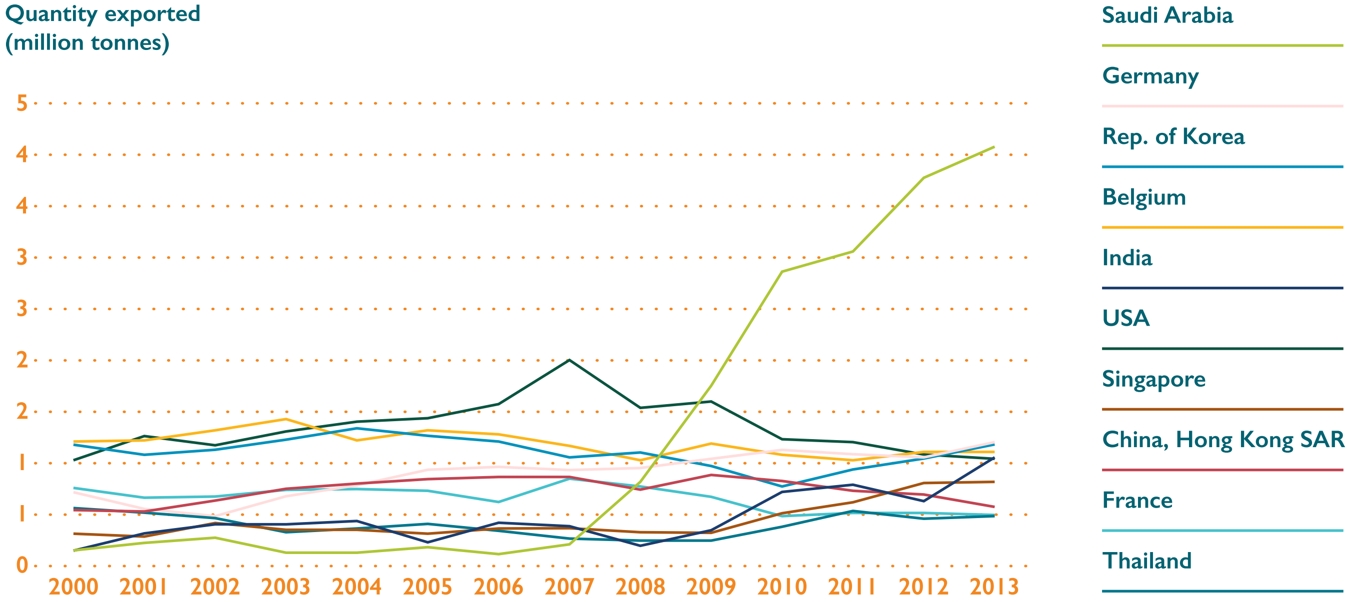
The main importers of PP are illustrated in Figure 3. China is the dominant importer of PP. Its demand for primary PP has increased from 1.6 M in 2000 to 3.6 Mt in 2013, an increase of over 125%. Turkey and Indonesia's demand for PP has also increased steeply, as has Germany's demand for this polymer. These changes indicate that, although increases in manufacturing in emerging economies (particularly China) are driving demand for PP, the overall demand for PP, relative to other materials, is also increasing in well-established manufacturing economies.

Fig. 1 | Trends in quantities of global imports and average price of PP (2000-2013)



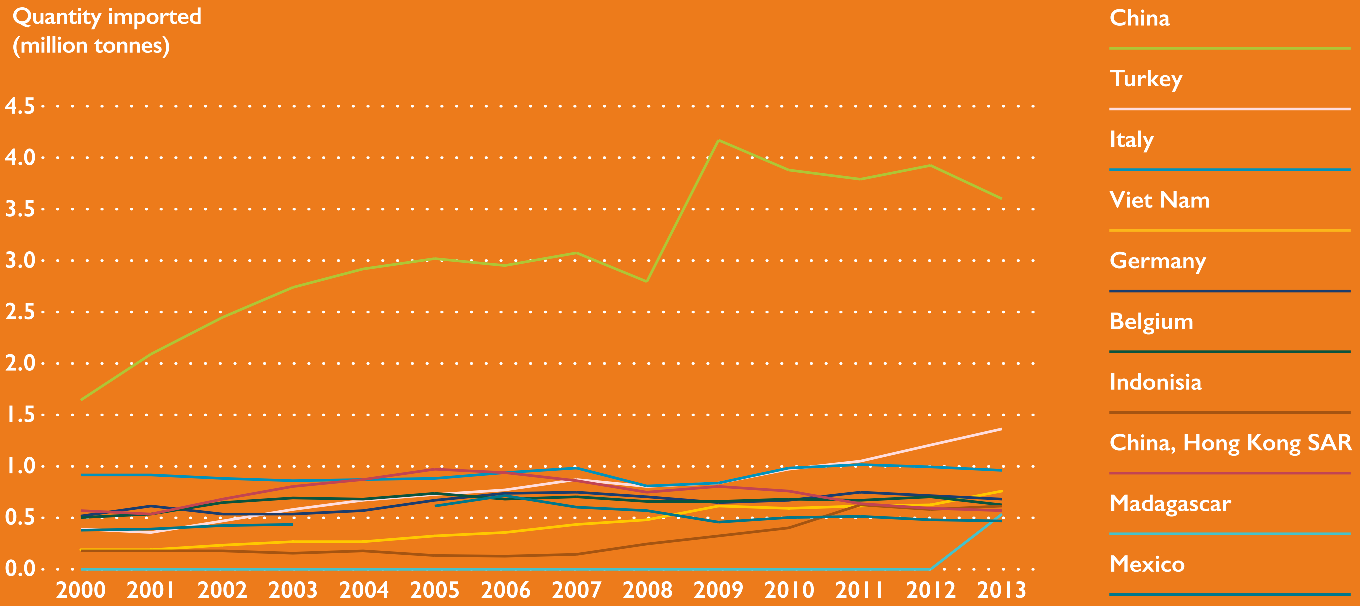
Source: BADEOA[25]

Fig. 2 | Trends in trans-national PP trade: Top ten exporters of virgin PP in 2000-2013



Source: UNComtrade (2015)[25]

Fig. 3 | Trends in trans-national PP trade: Top ten importers of virgin PP in 2000-2013



Source: UNComtrade (2015)[25]

Market realities and trends in recycled PP

There is very little data on the levels and prices of trade in PP scrap. Due to difficulties associated with the separation of this material from other polymers, the majority of recycled PP is thought to be traded as a component of mixed recycled plastics. Given that China and Hong Kong SAR dominated until recently the global imports of plastic scrap[26] most of this material could have been exported to China, where it is assumed to be either separated for recycling or disposed of with rejected materials. According to Zhang, waste PP imported in China mainly comes in the form of mixed plastics and is used to manufacture hangers, pipes, trays, and batteries.[27]

China is the dominant destination for recycled plastics and its demand for scrap plastics has consistently grown over the past 10-20 years. Demand for recycled plastics in China is expected to have grown to 29 Mt by 2015, 65% higher than 2009 figures. If we generalise from the UK situation and assume that PP comprises 2% of mixed waste plastics imported into China, then this would suggest a total of just 75,000 tonnes (t) of PP scrap exported to China in 2013. However, this is highly speculative.

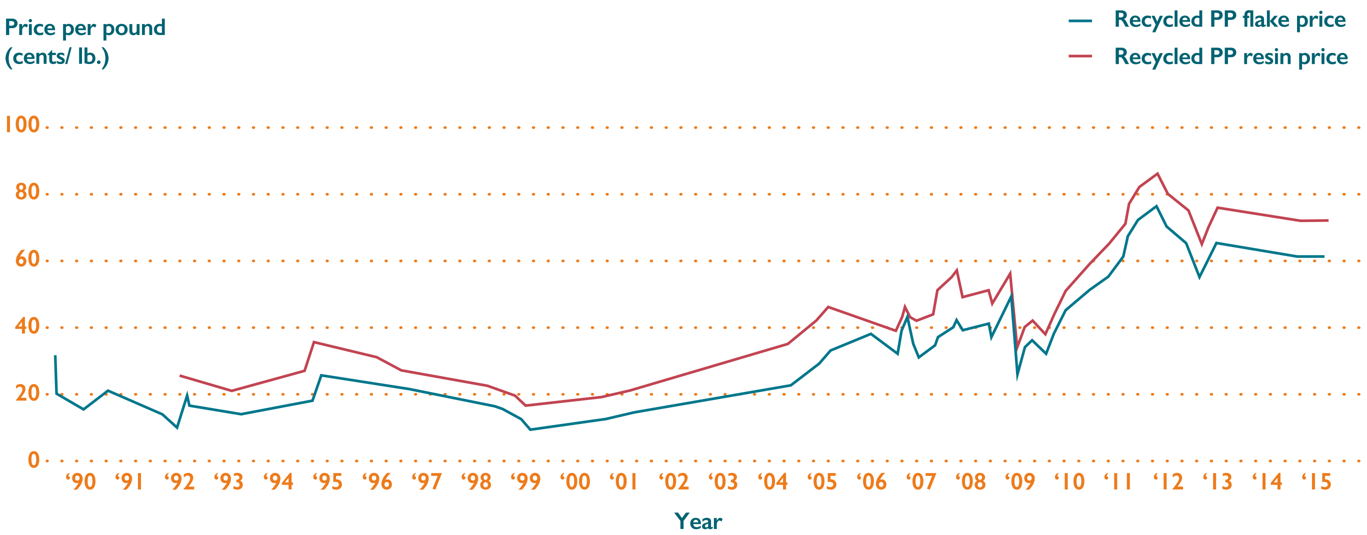
Despite the relatively low level of export of rPP to China, there is thought to be considerable demand in China for recycled PP for use in packaging applications such as fertiliser and cement bags.[13] This demand is likely to grow in-line with the overall growth in plastics demand in China. Commentary in the literature also suggests that the Indian plastics conversion sector is growing rapidly and so is also likely to become a strong market for recovered plastic polymers of good quality, including PP.

This increase in demand is echoed in the increasing value of PP since 2000. The figures below (Figure 4) illustrate the change in recycled PP resin and flake prices in the United States since 1990.

The very limited extent of separate PP recycling and recovery goes some way to explain the lack of data on rPP prices and market trends, at least in sources available in the public domain. For instance, the UN Comtrade database collates data on the overall levels of traded plastic scrap and the quantities and values of PE, PS and PVC, but not for PP. Other sources in the waste sector media (for example: Letsrecycle and Materials Recycling Weekly in the UK) present only information for the most commonly traded polymers (LDPE, HDPE and PET). If the markets for secondary materials, including rPP are to be improved, it would require an effective flow of information, including clear pricing. At present, information on markets and the mechanisms for the effective trade of waste plastics is poor. To facilitate this process, the collection, analysis and provision of good quality data on markets is important. The waste management sector has a role to play in establishing, maintaining the systems necessary to collect the data necessary to allow markets to function properly.

Regarding the commercial monetary value of rPP, similarly to other recycled plastics, it is affected by the price of oil, with recycled plastics being more competitive with virgin polymers if the price of oil is high. This link with oil prices has been most recently illustrated by the steep drop in oil price which occurred at the end of 2014/beginning of 2015, creating turmoil in plastics markets, with a resulting downward slide in recycled polymer prices. This price is currently impacting on recycling businesses across Europe. The effect of this drop on the value of virgin PP prices is shown in Table 2.

Fig. 4 Summary of recycled PP flake and PP resin price (1990-2014)



All prices are estimated U.S. market prices, in cents per pound, for prime resin, unfilled, natural colour.

Source: PlasticNews[28]

Tab. 2 The impact of oil prices on virgin polymer prices in late 2014

POLYMER/MONTH	SEP	OCT	NOV	DEC	REDUCTION
PP homopolymer	1390-1450	1380-1440	1320-1380	1280-1350	105
PP copolymer	1440-1500	1430-1490	1370-1430	1330-1400	105

Price in Euro per tonne.

Source: Plasticker (2015)[29]

Barriers and opportunities to sustainable PP recycling

This review of polypropylene highlights a number of key issues associated with secondary materials management and circular economy issues in the context of PP. Key findings of the review we have conducted are tabulated below. We also considering them in terms of: (i) the opportunities to increase the use of recycled PP as a secondary material in a sustainable manner; and (ii) the potential role of the waste management sector in resource management and the transition to a circular economy.

Tab. 3 | Technical barriers to sustainable PP material recycling

BARRIER	COMMENT
DIFFICULTIES IN POLYMER IDENTIFICATION AND SEPARATION	
Plastics complexity: Plastic are mixed with other polymers[6, 8] or with different grades of the same polymer[6] or with different colours	The main contaminant of recovered PP is HDPE from bottles closures and attachments. PP products often contain different grades of PP combined with other materials in laminate or metallised film structures[6]. Moreover, size and accessibility of plastic parts in some products is difficult.[30] Sorting of directly printed PP packaging and PP packaging with printed in-mould labels needs further investigation. Clear or natural PP packs that are surface printed may not be able to be sorted by automated systems.[18]
Food-grade PP	The stringent requirements regulated by the European Food Safety Authority (EFSA) regarding the use rPP in food contact applications, together with the absence of an automated sorting method for sorting mixed PP packaging waste into food grade and non-food grade PP, makes it difficult to have a closed loop recycling into food grade rPP.
Black PP	NIR spectrometric equipment used in most of the MRFs has limitations with separation of coloured plastics (particularly black); and with distinguishing between different grades of the same polymer[18, 31], but new alternatives in material design and various technological sorting solutions are currently being assessed to overcome this barrier.

Tab. 3 | Technical barriers to sustainable PP material recycling

BARRIER	COMMENT
INCOMPATIBILITIES	
Immiscibility with other polymers	Most polymers are not compatible with each other during mechanical recovery (level of miscibility).[18, 31] This is because of the different processing requirements of the polymers[32], which can lead to undesirably heterogeneous recycled products featuring un-melted and/or over-melted areas to the detriment of their mechanical properties.[33]
Limitations of co-mingled collection	Recently, in some EU countries such as in the UK, collection systems are moving towards commingled collection as main channel for household plastics collection to maximise the collection rate of recyclables. This could result in detrimental effects in the downstream processing steps (e.g. in MRFs), and especially while sorting, which is an energy and costly process.[34]
CONTAMINATION	
Hazardous substances (additives such as, certain BFRs) – past legacy	Although certain brominated flame retardants (BFRs) are now forbidden to use in Europe and the US, they are usually found in the shredder residue from WEEE – a legacy form the past. Treatment facilities for WEEE will need to distinguish between plastics that contain banned BFRs and those that do not, to ensure that BFRs do not re-enter the material stream, to avoid dispersion contamination. The separated fraction of waste containing BRFs should be recovered at a facility authorised to receive BFRs.[35] Suitable thermal recovery is an effective way to destroy POPs.
Contaminants such as food, oils, dirt, adhesives, etc.[36]	Many coatings and adhesives (thermoset materials) do not blend well with PP[36] and depending on their end-use, some of them may have no function in the rPP products (UV absorbers, flame retardants).[2] rPP for food applications can be limited by problems with organic contamination adhesion that might alter the odour and colour after the decontamination process.[37] Decontamination is an energy intense process, and it requires wastewater treatment.
DEGRADATION	
During the life cycle of PP products	PP is sensitive to sunlight oxidation and it may need addition of appropriate additives during recycling (rejuvenation). UV additives need to be regenerated before use. In addition, long glass fillers contained in some PP products may break during the recycling process.
MATERIAL AND PRODUCT PROPERTIES TRADE-OFFS	
Light-weighting	The European Plastics Recyclers organisation (EuPR) points out that, although cost savings and the desire to prevent waste have led to thinner rigid bottle designs, these have in fact then led to difficulties in mechanical recovery processes such as grinding, cleaning etc.[31]

Environmental barriers to sustainable PP recycling

PP products newly produce or in the past could contain certain additives such as antioxidants, stabilizers, colorants, fillers and plasticizers that may include toxic components such as heavy metals, phthalate plasticisers and BFRs. However, a recent study has assessed the environmental and health hazards of chemicals used in 55 polymers, concluding that PP and polyethylenes (LLDPE, HDPE and LDPE) are the least hazardous polymers.[4]

Some additives may be bound to the polymeric structure of plastics, while some others may leach out of plastics. Most additives in use are not known to have environmental or health risks. Plastics products is required to fulfil the standards for both quality and safety and thus additives that may represent a risk for the health or the environmental are not permitted in Europe. The presence of these substances in plastic products is handled by RoHS (only for EEE), REACH (and CLP for labelling), the POPs Regulation, and specific food contact legislation.[2] Schemes such as EUCertPlast provide certification for audited plastic recyclers in Europe. The certification works according to the European Standard EN 15343:2007 focussed on the traceability and assessment of conformity and recycled content of recycled plastics that aims to provide standards for environmentally compliant recycling of plastics. However, some of the plastics products used in Europe are imported from other developing countries where less stringent environmental regulation are applied. Table 4 summarizes potential the environmental barriers to sustainably recycling PP.

Tab. 4 | Environmental barriers to sustainable PP recycling

BARRIER	COMMENT
Potentially hazardous additives	PP products contain different types of additives: such as antioxidants and stabilizers due to its high susceptibility to oxidation.[36] Wire and cable coverings used for electrical and electronic applications require long-term heat stabilization or cross-linking and usually they require flame-retarding additives[38] which are hazardous substances. Food contact packaging needs additives to improve heat and impact resistance.[38] In the automotive and construction industries, filler are also added to protect from degradation.[38] Post-consumer PP from food grade applications contains organic contaminants while non-food packaging applications may contain substances from detergents, personal care, and household chemical cleaners.[18] PP tubes and bottles containing mouth wash and shampoo may contains high molecular weight materials such as hexylsalicylate and isopropyl myristate with high boiling points and low volatility difficult to remove at the low temperature used to produce food grade recycled HDPE in the UK.[18] This is a problem for the rPP to meet the European Regulation for plastics in contact with food which aims to ensure the product to be safe and not to transfer any contaminants to the food.[18]
Food grade PP	According to European Food Safety Authority (EFSA) a migration limit of 10 ppb in the food material should be met.[18] In order to avoid this kind of contamination and make feasible recycling PP from food containers it is important to develop and commercialize an automated sorting methods capable of separating food grade PP from non-food grade PP. Results from a recent study[37] performed in UK demonstrate that rPP from dry and semi-dry foods (for example mushrooms) can be used in food grade at up to 100% recycled content. However, in the case of rPP from products like margarine no more than 5% of recycled content can replace the virgin PP. Intermediate levels would be acceptable for rPP from other foods such as fish (15%) or meat (20%).
Emissions during reprocessing	Although the melting temperature in the mechanical recycling of PP (150-250°C) is much lower than the pyrolytic temperature of virgin PP extrusion processes (350°C), various volatile organic compounds (VOCs), due to the aging, long thermal exposure and the interactions between additives and recycled PP, a small fraction of VOCs is still released during the melting extrusion process. Alkanes are the most abundant VOCs for PP, comprising 37.5% of the VOC emissions during PP recycling.[39]

Tab. 4 | Environmental barriers to sustainable PP recycling

BARRIER	COMMENT
Labelling chemistry - Food grade PP	Direct pints and in-mould labels used in PP containers cause problems during recycling. They can contain potentially hazardous substances such as benzophenone, which is used as a photo-initiator in many UV cured inks. Very few printing inks are approved for direct food contact because most of them could decompose to harmful substances during the recycling process. Directly printed flakes end up in the PP flake stream destined for food contact and the ink residues could remain in the final recycled product. Once melted, the ink will discolour the resin and the ink will become dispersed within the polymer melt making removal difficult. If ink is present in the recycled resin, there could be migration of ink residue compounds into foods or beverages.[18]
LCA studies	Whereas there are no LCA studies focused exclusively on PP, a series of relevant scientific publications[40-42] alert towards the actual environmental performance of mechanical recycling of used plastics, for example vs. other resource recovery options such as EfW. Some studies indicate that a very high percentage of virgin material should be substituted with secondary polymer for mechanical recycling to be the most environmentally friendly option. In addition despite that the advanced sorting and reprocessing may occur in countries / situations with less than optimal, or non-existent pollution prevention technology in place[43, 44] (see also next entry below), there is no LCA study accounting for these actual conditions.
Export for reprocessing and manufacturing under less environmentally developed conditions	Sometimes (but not always), the global supply chains of secondary materials may follow a "least environmental protection standard pathway".[43] For plastics in WEEE casings, the EU estimated that, in a worst-case scenario, 41% of WEEE may not be treated appropriately overseas.[31] As it was stated in the relevant ISWA report from the Globalisation and Waste Management Task Force[26]: "[…] the exact plastic scrap grade and the manufacturing conditions should be taken into account if environmental benefits from international plastics recycling are to materialise. Further investigation is necessary to accurately quantify the environmental implications of the global used plastics trade. [there are] concerns for the non-optimal environmental benefits resulting from recycling under poor manufacturing and environmental protection conditions […]."

Economic barriers to sustainable PP recycling

The economic barriers to recycling PP (see Table 5) include costs associated with collection, transport, sorting and recycling, quality of inputs and output quality requirements, market prices and profitability of recycling plants.

Tab. 5 | Economic barriers to sustainable PP recycling

BARRIER	COMMENT
Collection and transport costs	Collection of plastics is an expensive part of the entire material recovery process. The cost of transport for plastic waste is high in terms of unit cost per tonne, because of its low density. This is particularly true in the case of relatively large items containing a relatively small fraction of PP[45]; and in the case of flexible PP packaging with low weigh/volume ratio (e.g. films).
Sorting facilities - waste input and output requirements	Differences in PP sizes, shapes, grades and other aspects of quality of those grades arriving at MRFs can be a challenge for recovering and reprocessing activities. The input material to MRFs and PRFs is a key aspect in the plastics recycling. A considerable proportion of plastic waste may be of too poor quality for a cost-efficient material recycling.[46] Due to the high investment cost, for sorting facilities to become economically viable plastic waste needs to be collected in sufficient quantities to allow them to operate at nominal capacity, the equipment running efficiently at the highest throughput technically possible.[47] The low quality and quantity of the plastic waste arisings impedes low-cost recycling.[38] The potential to increase mechanical recycling is limited to relatively high quality material (relatively clean material, sorted by polymer type).
Sorting costs	Mechanical recycling always requires previous separation by resin type. The production of high-quality recycled resins capable of displacing virgin resins requires sorting the waste to high purity levels. Feedstock recycling has higher flexibility in terms of waste composition, but in most of cases some pre-treatment and/or separation operations are also required.[6] Post-consumer recycling schemes are typically designed for rigid packaging making difficult to handling flexible PP packaging (films), which makes its recycling less profitable.[32] A wider range of PP grades are used in the production of PTTs compared with HDPE and PET bottles, which obstruct the sorting process.
Costs of plastic recycling	Processing costs are determined by the quality of the material, the type of polymer, as well as by the facility and the types of technologies used.[2] In mechanical recycling, re-compounding the recycled material with additives and/or more virgin raw material might be necessary to improve processing and to re-establish the properties of the plastic.[2] Recycling of PP is currently largely mechanical, because feedstock recycling of polymers is still mainly carried out at laboratory scale because it remains economically less viable. Typically, for example gasification plants must hold a licence for EfW plants, and very strict emissions standards should be adhered to. Costs associated with closing of the loop / resource recovery are impeding recycling of PP, and more widely all secondary resources. It is a fact that the secondary materials are competing with virgin ones also on the manufacturing cost, and this should be addressed by creating a level plain field, where feasible, by introducing relevant fiscal policies. The relationship of secondary vs. virgin materials is a currently underexplored theme.

Tab. 5 | Economic barriers to sustainable PP recycling

BARRIER	COMMENT
Required capacities (stable supply)	Mechanical recycling is profitable at comparatively small scale operations, while feedstock recycling is not commercially viable at same throughput.[6] The capacity to mechanically recycle current quantities of waste plastics arising from mixed domestic, ELVs and WEEE sources appear relatively limited in EU. Increasing the coverage of collection schemes, will exacerbate this challenge, but may secure the supply of plastic waste for the reprocessors elsewhere or for economies of scale necessary for thermally-based recycling of PP. However, legally binding limitations on the non-mechanical recycling of packaging plastics currently apply in the EU.
Quality of the rPP - products with recycled content (actual and perceived)	Negative perception of the quality (lower mechanical properties, differences in physical appearance, such as the grey colour of rPP, potentially hazardous material content) of the recycled PP, makes it less attractive for certain applications (such as food packaging)[32] and hampers the development of recycled plastics market.[2] Eco-design can play an active role providing the tools to avoid negative effects on the recyclability of plastic waste; and increased confidence on potential recyclability may be needed. There is limited information on current and future recycled plastic product applications and on the potential substitution processes in the end-customer markets.[48] There is a lack of output specifications for the recycled products[47], such as percentage of target material in the bale and the bale size and binding system, maximum levels for particular contaminants in the material (for example organic waste, WEEE, metals, wood or hazardous material.[49]
Price of secondary materials – competition with raw materials	Recovered plastics prices are linked to the price of virgin plastics[2] and not determined by production costs as they would be in an efficient market.[2] The low price of petrochemical feedstock compared with the recycling plant and the recycling costs[32] as well as the lack of end market demand for the sorted fractions[47] are barriers to increase the recycling rate of plastics. Whereas there is no concrete evidence to date, the economics of raw material production, PP included, may need to be investigated for hidden subsidies, with a view to establish a plain field with secondary raw materials (rPP).
Virgin vs. recovered plastic markets	Only some markets of secondary plastic products are well-established (PET or HDPE) and in general recovered plastics markets are still immature and their viability may be subject to high virgin plastic market and oil prices.[2] A significant decline in the prime prices would be expected to soften demand for recovered material, reducing the incentive on consumers to look to alternatives.[14] The lack of transparency, and the complexity of the secondary raw materials markets[26], including global supply chains[43] with asymmetry of information for the players, could be impeding the maturing of the market.

Opportunities to increase sustainable PP recycling

Despite the development of new recycling technologies for plastics, the PP waste fraction remains one of the least recycled major polymers due to technical, economic and environmental reasons. However, the increasing demand for PP in different applications, such as the automotive industry, construction and building and most recently in food grade applications enhances the potential for increasing the rPP use, resulting in increased the virgin material substitution. Table 6 summarizes the opportunities to increase such substitution.

Tab. 6 | Opportunities for increasing sustainable PP recycling

STRATEGY	OPPORTUNITY
Technical development of recycling processes	Development of: • Automated sorting technologies able to distinguish food grade PP, which are suitable for food grade recycling, from non-food grade PP. • Convert direct printed and in-mould labels of food contact PP packaging to label types that are removable in the recycling process; and convert more food contact PP packaging from pigmented polymer to natural polymer, to make it easier to recover a separate flow of un-pigmented natural PP with higher value and more end-use applications in the food packaging sector.[10] • New sorting technologies to identify black PP contained in (packaging) waste. • New and more selective catalysts, reactor technologies to make feedstock recycling (thermal processing) profitable by lowering capital and operating costs. • Identification of potential new market segments for rPP, such as food contact applications. • Economies of scale in various stages of collection, enabling subsequent reprocessing.
Dissemination of technical advances and information Clever material selection	Both technological advances and new design processes for plastic materials and products (structure and types of material used) have a key influence on their recyclability. Recoup recently published a new edition of its guide on 'Design and recycling plastic packaging material'[52], aiming at providing a better understanding of the environmental implications of packaging design decisions. The guide contains recyclability tables for each main polymer, including PP and seeks to encourage the selection of the raw materials so that plastics in packaging products can be more easily recycled.
Quality assurance Waste processing as manufacturing	Advanced in-line real-time material characterisation and quality control is becoming more feasible and along with traditional QC/QA and standardisation of outputs approaches can increase the confidence in rPP as a (secondary) raw material fir for purpose for specific end uses. Emphasis should be on guaranteeing rPP quality.[44]
End of Waste (EoW)	The European Commission is establishing end-of-waste criteria for a number of specific recyclable materials including paper waste (EoW criteria for waste paper: Technical proposals[1]) and plastics (EoW criteria for waste plastic for conversion[2]) which define the technical requirements that these waste streams have to fulfil in order to cease to be waste in the EU.

Tab. 6 | Opportunities for increasing sustainable PP recycling

STRATEGY	OPPORTUNITY
Improving material recyclability	Could be more profitable to: design products with extended life span; use more recyclable and compatible polymers in product and packaging design, less harmful chemicals by limiting the use of additives and using plastic parts that are not coated[31] so that can optimize recycling. Good design could in theory prevent the dissipation of value of PP products at end of life.
Design for Recycling and Disassembly	Design to achieve easier disassembling of the materials[38] in the current recycling system. For instance, the design of PP composite products reinforced with PP fibres as well as the use of labels, adhesive, pigments and inks to maximize recycling performance.[32] Reduce the range of polymer types used in packaging to just PET, HDPE and PP in order to improve recyclability, making PP a significant polymer type within the household packaging mix, worthy to be targeted for recycling.[10] Development of alternative black colorants that allow optical sorting; and the development of novel sorting and recycling techniques[50] and less expensive rejuvenators additives, such as alternative fillers from agricultural products or waste organic materials (i.e. scrap leather) or new pigment and fragrances from natural sources.[38] Developing new methods for compatibilizing resins of different morphology or rheology to create useful products with equivalent properties to virgin materials.[38] Currently there are some companies that are selling a rage of compatibilizers that enable plastics that cannot be sorted and remelted, due to contamination with other polymers, to be moulded into finished products with acceptable materials properties (not closed-loop recycling: cascade model of value recovery). The use of fluorescent pigments applied to existing ink products and applied to labels and packaging would allow their identification of food grade PP using a machine readable ink (MRI). This would require the modification of existing sorting NIR/optical equipment. Small capital cost (of the order of 10 to 20% of the cost of the full unit) and low operational costs ae expected due the low power usage and long life of LED's. Ideally the label or marking would be mechanically removed or washed off during further processing. Trial results show a high yield of 74% with a purity of the 93% of the machine readable labelled samples.[51] The use of new labels for PP packaging suitable for food grade recycling, such as peelable in-mould labels, could increase rigid PP suitable for food grade recycling to around 72,500 t y-1 at 50% recycling rates.[10]

Paper & board

Properties and uses

Paper & board is made from the vegetable lignocellulosic fibres from wood and other fibre crops (e.g. straw, bamboo and bagasse) or from paper & board recovered for recycling. Paper is classified by weight in grams per square metre (gsm), with 80 gsm being the weight of average copier paper. Products with of over 220 gsm are considered boards. The majority of paper & board produced globally is used as a packaging material (Indicatively, as estimated for CEPI (Confederation of European Paper Industries) countries in 2014: 47.6%)[53]. Other major applications for paper & board products include (ibid) uncoated graphic papers (16.1%), coated graphics (16.1%), newsprint (8.3%) and sanitary and household (7.6%).

The properties and characteristics of paper & board depend on the raw materials and the papermaking process; they differ in line with the intended use. For example, if used as packaging material, due to its poor barrier properties, paper needs to be treated and impregnated with other materials to be used in food contact applications. Fibres comprise the majority by mass of paper & board products. Non-fibrous materials are added during the papermaking process in order to impart special characteristics to the final product and include starches, clays, coatings and adhesives.

Tab. 7 | Recovered paper grades

PAPER GRADES	DEFINITION
Mixed grades	Broad category with a wide variety of grades with high value fibres (mixed papers and boards). It is costly to sort and contains a wide variety of contaminants. It often requires expensive separation technology to sort into grades of value which may not be economically feasible.
OCC (Old corrugated card)	Sacks and wrapping papers made mainly of unbleached chemical pulp and packaging waste.
ONP & OMG (Old newspapers and magazines)	Newspapers, magazines, brochures and telephone books.
HG & PS (High grade deinking and pulp substitutes)	High-grade, wood-free printing and writing papers that come, for example, from printing houses and offices as well as bleached board cuttings and other high-grade qualities coming mainly from printing plants and converters.

Paper & board waste generation, recycling and outlets

Paper is a relatively easy material to recycle, with well-established closed-loop and/or cascade cycles. Recycled fibres are a key part of the material supply for the manufacturing of new paper & board products. According to European Recovered Paper Council (ERPC), over 60 Mt of waste paper and card are collected for recycling in Europe.[3] Collection for recycling in Europe has reached the level of 72%, according to CEPI, the highest of all continents, resulting in around *'54% of the paper industry's raw material to comes from recovered paper & board'*[54] (the CEPI and ERPC estimates may not cover the same European countries/years). However, the 'recovered' paper collection rates do not accurately reflect the actual situation regarding fibre recycling, because in most cases the paper & board that is collected and delivered to a paper mill and loaded into a pulper does not include only fibre, but also several other substances such as minerals, starch, additives, inks, coating materials, non-paper components etc. Official collection and utilisation rates do not exactly describe fibre resource recovery.

According to ERPC, approximately 70% of paper & board from waste packaging was collected for recycled in 2014, which was the highest collection for recycling rate of all packaging materials.[3] In Europe, 50% of the paper & board waste was collected from commercial and industrial sources, 10% from offices and the remaining 40% is collected from households, either in separate or commingled collection systems together with other recyclates.[3]

Standards and good manufacturing practices have been set up by the paper industry to improve the recycling[3]: (i) the European Declaration on Paper Recycling which promotes the increase in the recycling rate; (ii) the Confederation of European Paper Industries guidelines for recovered paper, (iii) the European list of standard grades of paper & board for recycling (EN 643), which lists different grades of recovered paper and sets limits on contamination, (iv) the Recovered Paper Identification System and the Council of Europe Resolution on paper & board materials and articles intended to come into contact with foodstuffs.

Recently (February 2014) in Europe, the categorisation of types and qualities of the so-called 'recovered' paper (or more accurately 'paper & board for recycling') were harmonised, being classified into 57 grades according to the revised European list of standard grades of paper & board for recycling EN 643. The standard divides recovered paper into five groups: ordinary grades, medium grades, high grades, craft grades and special grades. Each of these groups has further subgroups that specify the recovered paper grade at a detailed level. The EN 643 also defines and sets tolerance levels such as unusable materials, non-paper components, paper & board detrimental to production and moisture content.

However, often a division into four main grades is historically used by industry (Table 8): (i) mixed grades (wide variety of grades with high value fibres which costly to sort and contains a wide variety of contaminants that may require expensive separation technology to sort into grades), (ii) old corrugated card (sacks and wrapping papers made mainly of unbleached chemical pulp and packaging waste), (iii) old newspapers and magazines and (iv) high grade deinking and pulp substitutes (from printing houses and offices as well as bleached board cuttings and other high-grade qualities coming mainly from printing plants and converters).

The recyclability of paper products depends on their re-pulpability and the removability of adhesives and unwanted materials. In the case of white grades paper they must be also de-inkable. In Europe, on average 19% of total paper & board consumption was considered (10 years ago) to be non-collectable / non-recyclable for technical reasons.[55] Broadly, this indicates that the upper technical limit to waste paper collection is around 80%[56], but practically it may be closer to 60% (other 2012 estimates).[57] Long-lasting papers represent 2-3% units of the 19% of the non-collectable fraction of paper waste. They represent the waste paper with longer lifespan that comes back to the waste flow. It is important to take long-lasting papers into account, because when collection for recycling rates are calculated, collection and recycling is compared to the paper put on the market during a particular year.[55] Table 8 shows the non-collectables / non-recyclables by main paper & board grade.

Whereas, all these area estimates of technical limits of recyclability, because the collection for recycling rates are already high in places in Europe, it may be challenging to increase collection rates while maintaining the utility of the collected paper & board as a quality secondary raw material. However, despite the high collection for rates, there is still potential to further increase the quality of the recovered paper. For example, clearly quality of overall process is affected by the collection methods (source-separated collection or commingled systems), with the former clearly favoured by the reprocessing industry.[3]

Paper & board manufacturing is by far the largest sector utilising recovered fibre.[58] However, recovered paper & board can also be used as raw material to manufacture other products, for example insulation, animal bedding, egg cartoons, plants pots, soft furnishings and dust masks. According to the CEPI, in addition to the paper industry use, over 8% of collected paper is used in other applications such as construction materials, animal beddings, composting and energy.[59] For the non (sustainably) recyclable paper & board, there are also well stablished resource recovery solutions, in the form non-material recycling options: waste paper & board has a relatively medium calorific value and is therefore suitable for combustion EfW, SRF and RDF, where it may as well attract subsidies as a source of biogenic carbon-neutral energy. It is also, in most cases, compostable. There is increased interest in the use of waste paper & board in the production of primary products, such as chemicals and fuels, as part of biorefinery processes. In the following sections we focus on fibre recovery for paper & board manufacturing.

Tab. 8 | Collectability and recyclability

PAPER GRADE	NON-RECYCLABILITY
Newsprint	0 % Technically 100% collectable and recyclable
Uncoated mechanicals	2 % (part of books)
Coated mechanicals	11 % (part of books and magazines)
Uncoated wood-frees	20 % (part of books, archiving materials, specialities)
Coated wood-frees	15 % (part of books, magazines and other printed matter)
Tissue	100 % (Italy 98%, UK 95%, converting losses)
Carton boards	6 % (contaminated materials)
Case making materials	5 % (contaminated materials)
Sack and wrapping papers	51 % (contaminated materials, specialities)
Other packaging paper & board	8 % (part of solid boards, specialities)
Other paper and board	96 % (specialities, only converting losses is collectable)
Total paper and board	19% (based on average CEPI consumption structure)

Limits for recycling – as estimated in Europe (2003)[55]

Tab. 9 | End-markets for recycled paper & board

END MARKET	COMMENT
Papermaking[59]	Feedstock for other paper grades: A high percentage of the total recovered paper is brown recovered grades recycled for the production of case materials, mainly from old corrugated cartoon (OCC).[59] White recovered paper grades and some high quality paper grades are recycled in newsprint, tissue and other graphic paper grades as well as in whip top layers of packaging papers after a deinking process. Many newspapers and issues contain 100% deinked pulp.[59] Mixed recovered paper grades are used with OCC for grey solid board layers which are no deinked.[59]
Other applications[60]	Cement/asphalt/etc. production, insulation in buildings (softboard production), feedstock for tiles, land management, animal bedding, Anti-dust agent, Fibre/plastics recovery (VAR technology) to obtain board products from coarse rejects, production of synthetic Calcium Carbonate from paper sludge ash (CalciTech process under development). The Bio-BTX technology converts rejects into industrial grade benzene, toluene and xylene (BTX). Hydrolysis of ligno-cellulosic materials to individual sugars, intended to be used as (2nd generation) feedstock for fermentation processes towards bio-ethanol or higher added value bio-chemicals (i.e. Bio-Rights technology, under development. Deinking sludge is suited for the production of mineral products with cement like properties (CDEM Holland BV, industrially applied). Combustion of deinking sludge, waste water treatment sludge and coarse rejects for electricity production or steam production (industrially applied). Direct digestion of screen rejects, deinking rejects and secondary sludge (no industrial running application). Torrefaction of coarse rejects to obtain a product with high energy density that can be used in coal based power plants for coincineration or as a substitute for wood pellets (no commercially operative torrefaction plants). Coarse rejects have a high calorific value and are therefore suitable as RDF.

Closing the fibre material loop: technologies and processing

The paper (fibre) recycling requires a series of processing steps which depends on the paper grade and the end product. The main steps in the recycling process of paper are[61]: (i) collection, (ii) sorting into a variety of categories or grades, (iii) washing to eliminate water soluble inks and fine particles, (iv) cleaning and screening to eliminate the dirt, sand and other materials such as metals and plastics, (v) re-pulping to break down paper into individual fibres using water and chemical and (vi) dewatering to remove excess of water from pulp to be further processed. Additional processing steps that can be used in some cases are: (i) deinking, which is the process used to remove the ink and to increase the brightness of certain grades of papers such as printed-paper and some packaging grades such as cartonboard[62], (ii) fractionation to separate fibres by length, (iii) bleaching to enhance brightness of pulp using chemical agents, and (iv) refining to change fibres surface characteristics (by mechanical action) to promote greater fibre-to-fibre bonding.

Collection

Collection of paper & board waste is the first step in the recycling process. There is no reliable basic collection data available in most countries, owing to the large number and various sizes of organisations involved in the collection of recovered paper. As a result, usually collection quantities are calculated through recovered paper consumption and trade statistics.[63] The type of collection system has an effect on quality of the recovered paper as it impacts on the subsequent steps of recovered paper processing, especially during sorting.[62] Paper & board from household are usually either collected separately or together with other dry recyclables (commingled), while paper & board from commercial and industrial sources are typically collected separately. The quality of recovered paper is far lower in commingled collection systems compared to selective ones, due to the higher contamination with other materials (glass, metals, plastics, etc.), resulting in higher sorting costs, lower process yield and higher maintenance costs.[62]

Sorting

Paper sorting can be manual or automated. Automated technologies can be either mechanical or sensor-based, or a combination of both.[64] The sorting method and its efficiency and effectiveness determines the quality of the recovered paper supplied to the paper mills.[65] Each sorting facility has a different configuration, optimised for the specific requirements of the indented recovered output uses. Although the sorting of recovered paper is mainly performed manually, which is very labour-intensive, and can therefore be costly, efforts are being made in Europe to move towards automated systems to reduce such costs (automatic mechanical screening and new optical sorting technologies). However, in some cases automation may generate grades that do not correspond exactly to the EN 643 list[66] and a final manual sorting step at the end of the process may be still required.[62] Automatic optical sorting technologies use different types of sensors based on different characteristics of the materials (colour, gloss, thickness, stiffness, size etc.)[64] showing reliable efficiency, but requiring "relatively clean" input waste.[67] Table 10 summarizes the main optical sorting technologies.

Pulping

The pulping process aims to detach printing ink from fibres, remove other contaminants, and keep the particle size of the inks, 'stickies' and other impurities suitable for their efficient removal. Adhesives disintegrate during pulping to so-called 'stickies' that can re-agglomerate and tend to stick to paper machine parts, causing problems for the paper production and affecting the quality of the recycled paper[58] by creating weak spots in material. Adhesives, inks, fillers, coatings, and other contaminants are removed from the fibres after pulping based mainly on physical and chemical properties such as size, shape, deformabilitiy, specific gravity and surface chemical properties. The removability of the adhesives depends on the composition and the characteristics of the adhesive.[69] Deinking is the process that allow inks to be detached from the paper by using warm water and deinking chemicals. Then the ink is removed by screening, cleaning, flotation and washing, to minimize its reposition on cellulose. The removal efficiency of the technology depends on the ink characteristics (particle size, shape density and surface properties). There is a wide range of deinking technologies and deinking chemicals, such as caustic soda, sodium silicate and soap, which are used in the pulping stage to facilitate ink release from the fibres.

Deinking

The main deinking technologies are: (i) screening to remove large and stiff contaminants including plastic films, shives, paper flakes and macro stickies[70], (ii) centrifugal cleaning, (iii) washing deinking and screening used in deinking to separate particles smaller than fibres with water through a screen[70], (iv) flotation and deinking to separate hydrophobic particles particularly ink particles.[70] Froth flotation is the most common deinking process in Europe, (v) magnetic deinking for deinking waste officer paper, (vi) ultrasonic deinking to remove new inks that resist conventional deinking and (vii) enzymatic deinking, which uses less chemicals that can increase the Chemical Oxygen Demand (COD) level as well as concentration of chemicals in the effluent water, compared to conventional deinking processes. The inks used in conventional paper processes usually break down easily in alkaline conditions, producing detached ink particles that can be easily removed by flotation. Smaller ink particles are removed by washing and higher ink particles by screening and centrifugal separation. Neutral deinking has great potential to lower chemical usage and cost, to reduce water treatment cost, to improve the recycling process and the quality of the recycled paper. There is no need of using leaching chemicals such as peroxide, because fibres are not yellowed or darkened.[71]

Flotation and washing

After deinking, a combination of flotation and washing stages to remove inks is required. Despite new advances in flotation cell design, utilization of new surfactants and the better understanding of deinking chemistry, the rapid advances in printing, coating and other modifications of paper (new materials and new printing technologies) make deinking more difficult. This is a characteristic case where innovation for improvements on an aspect of functionality and /or cost, results in increased problems for the potential for closed-loop or

Tab. 10 | Advanced sensor-based sorting technologies

PRINCIPLE	COMMENT
Ultrasonic sensor	It is contact basis. Not suitable for industry.
Lignin sensor	Only used to separate the newsprint papers from other forms of paper and board. Performance of lignin sensors seriously affected by colours. Commercialized by MSS.
Brightness sensor	Separate white papers containing optical brighteners, white papers without optical brighteners, and the rest.
Gloss sensor	Separation of glossy paper from others. Commercialized by MSS.
Stiffness sensor	Separate the card board from others paper grades.The sensor could not distinguish between a stack of newsprint and a single paperboard. Commercialized by MSS.
Colour sensor	Identify white papers by measurement of the radiation of the paper surface. Commercialized by MSS, RedWave, Bollegraaf, Lubo.
Visual imaging sensor (VIS)	Comercialized by TiTec.
Near-infrared (NIR)	Comercialized by TiTech, MSS, RedWave, Bollegraaf, Lubo.
Mid-infrared (MIR)	Comercialized by Pellenc.

Sources: [64, 68]

cascade model material recycling. More effort is needed to understand the flotation behaviour of new types of waste papers.[71] Flotation chemistry plays the most important role in determining the ink removal efficiency. The increasing use of new inks formulations such as water-based flexo inks, new toner-based inks, fused toners and UV-cured inks, fused toners might further negatively affect the existing deinking processes. Water-based flexo inks cannot be efficiently removed by flotation due to their low particle size, which might cause loss in the pulp brightness. Alternatively they can be removed by washing but this requires high volumes of water. New toner-based and UV-cured inks are more complex to be removed than conventional inks. Fused toners cannot be separated by conventional screens, centrifugal separation (due to the similar density to water), and above 150 µm they are too large to be separated by flotation and they are also resistant to the alkaline environment used in conventional deinking plants.[72] Conventional deinking plants have introduced dispersers or kneaders to help the detachment and size reduction of ink and other non-fibrous particles[71], the efficiency of this treatment depend on the little dispersion ability of the contaminants such as adhesive particles from labels or tapes.[70] UV-cured inks are extremely difficult to detach from paper fibres resulting in wasteful loss of fibre. Ultrasound deinking is a technology used to recycle paper printed with new ink formulations. Modern deinking lines in paper-recycling mills operate with various deinking loops involving multiple dispersing stages.[72]

Bleaching

In addition, for some grades of paper the bleaching of the fibre is required to increase the brightness of the fibre by the use of different bleaching chemicals such as hydrogen peroxide, hydrosulfites, formamidine sulfinic acid (FAS) or less ideally chlorine which can be combined with the organic matter producing toxic pollutants. Hydrogen peroxide bleaching is generally added to avoid yellowing of wood-containing pulp, and/or at the inlet of dispersing and kneading and it is carried out in the presence of NaOH, sodium silicate and sometimes chelating agents. For almost wood-free secondary fibre stock so-called unconventional bleaching chemicals oxygen and ozone can be used.

Paper recycling generates various solid wastestreams, including primary and secondary treatment sludges, deinking sludges, and coarse and screen rejects.The majority of these wastes are generated by the pulping and the water treatment stages of the process and are commonly landfilled. The costs for landfilling / other waste disposal are high in the majority of Europe; so, in order to stay competitive and become an increasingly sustainable industrial sector, the paper industry is seeking to take advantage of the potential value of the waste streams produced by the paper recycling process. For example, paper sludge is used as a fuel in combined heat and power systems to generate energy for the paper recycling process at a number of paper mills.

International Market Review

Paper & board production and consumption

A summary of paper & board production and consumption globally is illustrated in the figures below Table 11. Information comes from CEPI, which provides publicly available headline data for the paper & board industry in Europe. Asia is the largest paper & board producer and consumer, with North America and Europe also major producers and consumers of paper & board products. In particular, China's paper production has grown considerably over recent years and, on some measures, has overtaken the United States as the largest producer of paper & board products.[13]

Market trends and realities in 'recovered' paper & board

The recovery and utilization of recovered paper has increased over the last decades in developed economies, driven by regulatory requirements and targets, and parallel improvements in the collection of waste paper and cardboard from household and commercial sources, estimated[53] in 2013 in Europe at 47.5 Mt. This growth is illustrated in Figure 5, which shows the increase in use of recovered paper & board in Europe. This figure also illustrates the effect of the global financial crisis in 2008, with levels of trade in recovered paper & board dropping dramatically, before recovering, albeit not to their former levels.

The majority of recovered paper & board is used in the manufacture of packaging and newsprint. A global market operates in the trade of recycled paper & board secondary materials. Based largely on data obtained from the UNComtrade Database using the category 'Recovered (waste and scrap) paper or paperboard' (UNComtrade Ref: 4707), the dominant exporter of recovered paper & board is the United States which exported almost 20 Mt in 2013. Other major exporters are Japan, The UK, The Netherlands, France and Germany (Figure 5). Notably, these are all nations with well-established paper & board collection for recycling schemes. Exports of recovered paper & board have generally increased since 2000 (Figure 5), the quantity of recovered paper & board from the US increasing from 10 Mt in 2000 to close to 20 Mt in 2013. This trend reflects both the increasing supply of recovered paper & board from recycling collection schemes, and also the demand for this material from major importers, mainly China. Note that Hong Kong SAR is reported as a major exporter only because it is a major staging post for the transfer of recovered paper & board to mainland China – a situation similar to the overall plastics scrap.[26]

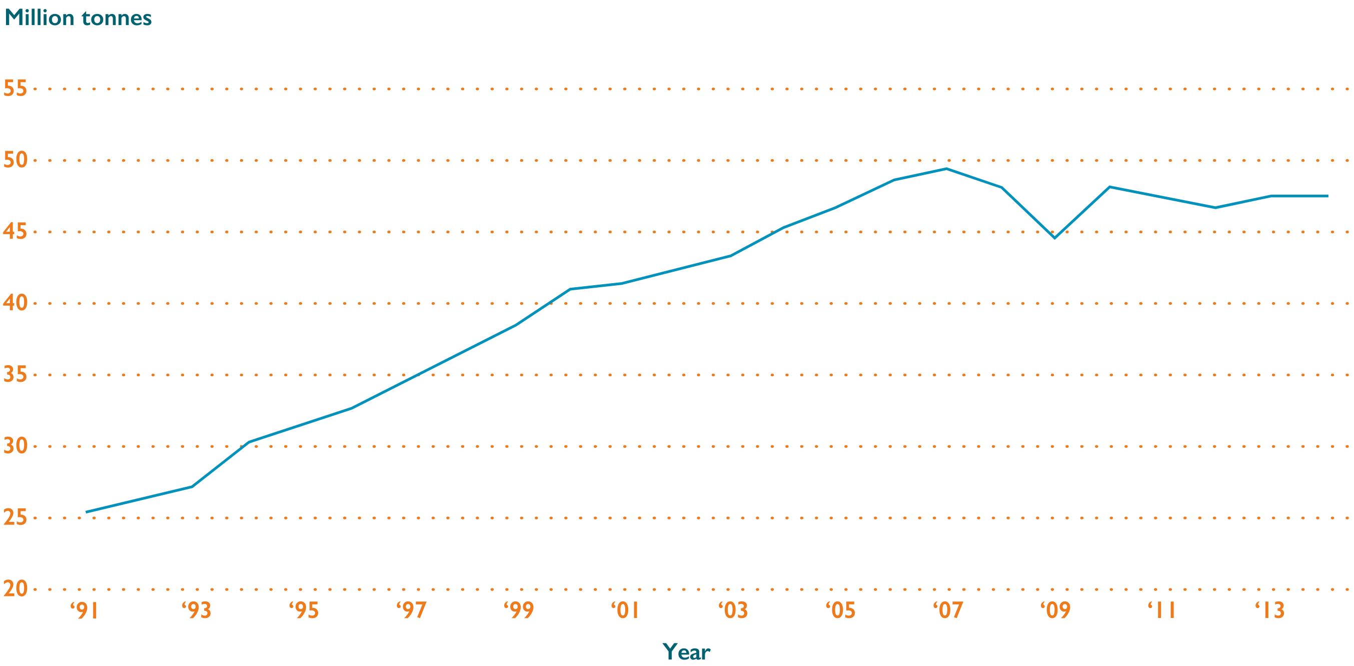
The overall quantity of recovered paper & board traded trans-nationally has more than doubled since 2000. Approximately 110 Mt of these materials was imported in 2013 (Figure 6). This trend is expected to continue, because major import markets can be anticipated to increase their demand for recycled paper & board.

Tab. 11 | Summary of global paper & board production and consumption

REGION	PRODUCTION (%)	CONSUMPTION (%)
Asia	44.7	46.1
Europe	26.7	24.2
North America	21.3	19.4
Latin America	5.2	7.1
Rest of the World	2.1	3.3

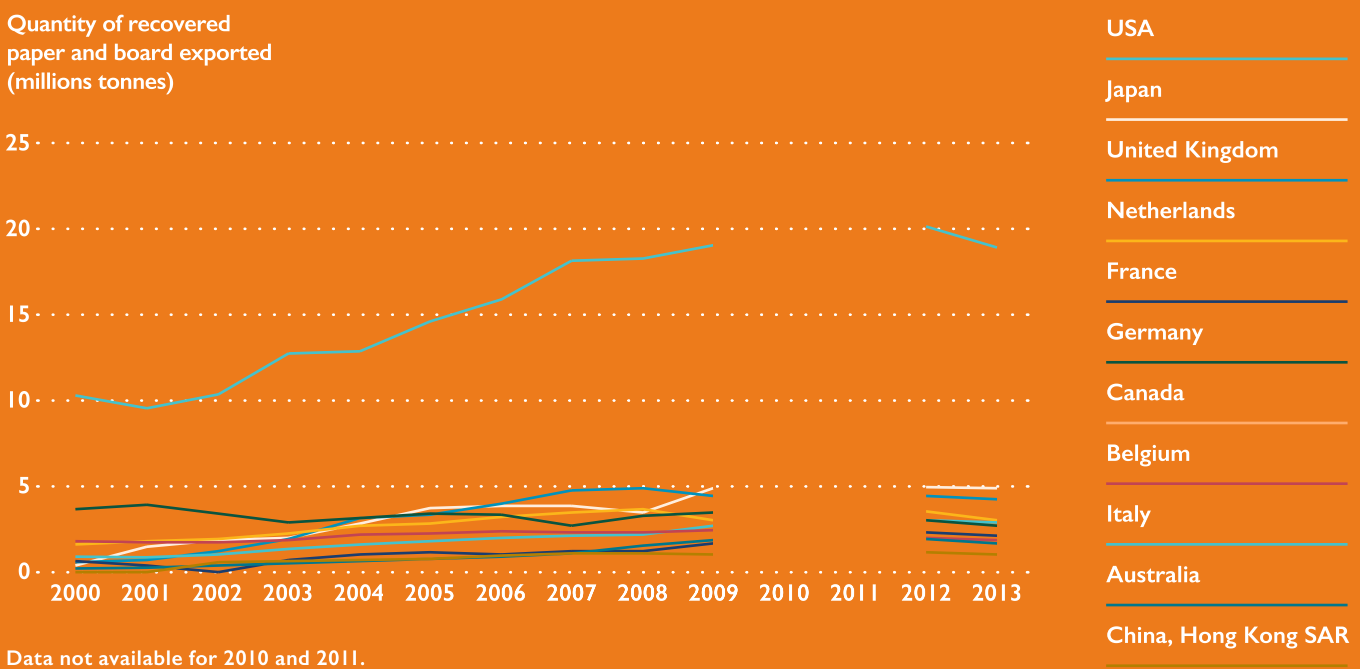
Source: CEPI (2013)[73]

Fig 5 | Use of recovered paper & board in Europe (1991-2014)



Source: CEPI (2014)[53]

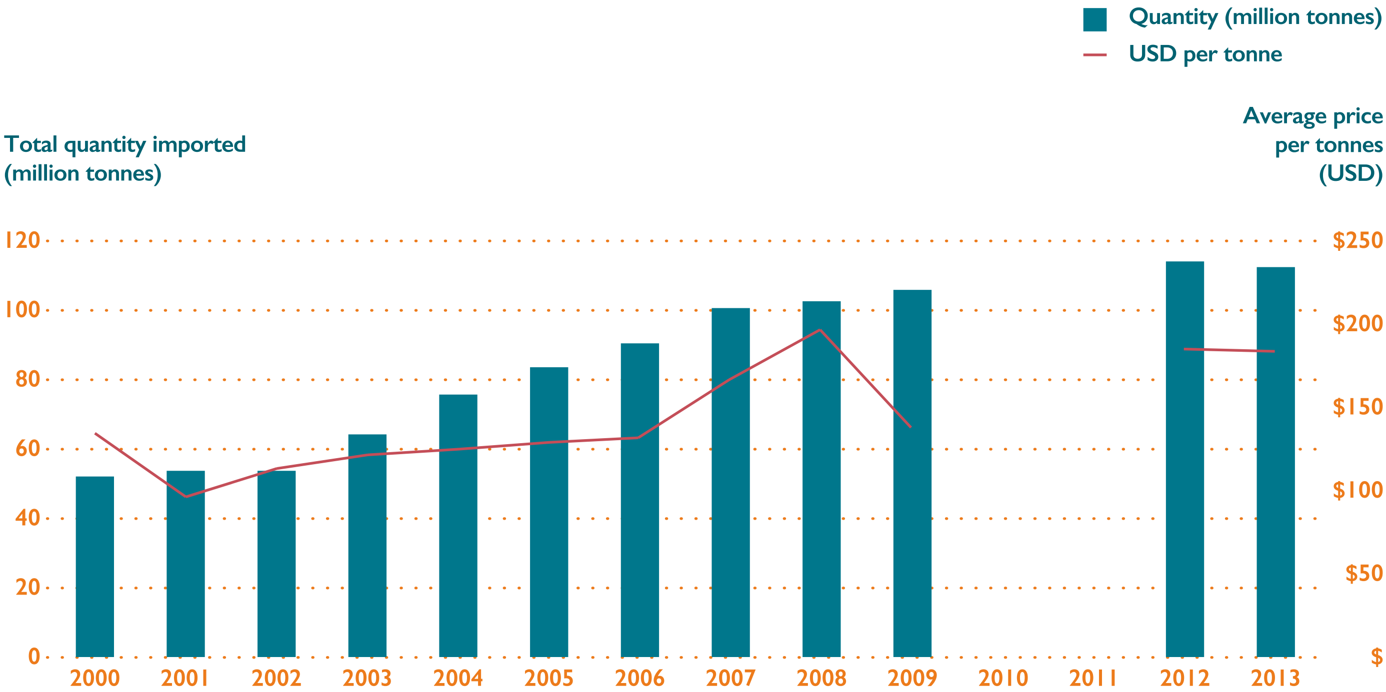
Fig 6 | Trends in the export of recovered paper & board (2000-2013)



Data not available for 2010 and 2011.

Source: UNComtrade (2014)[25]

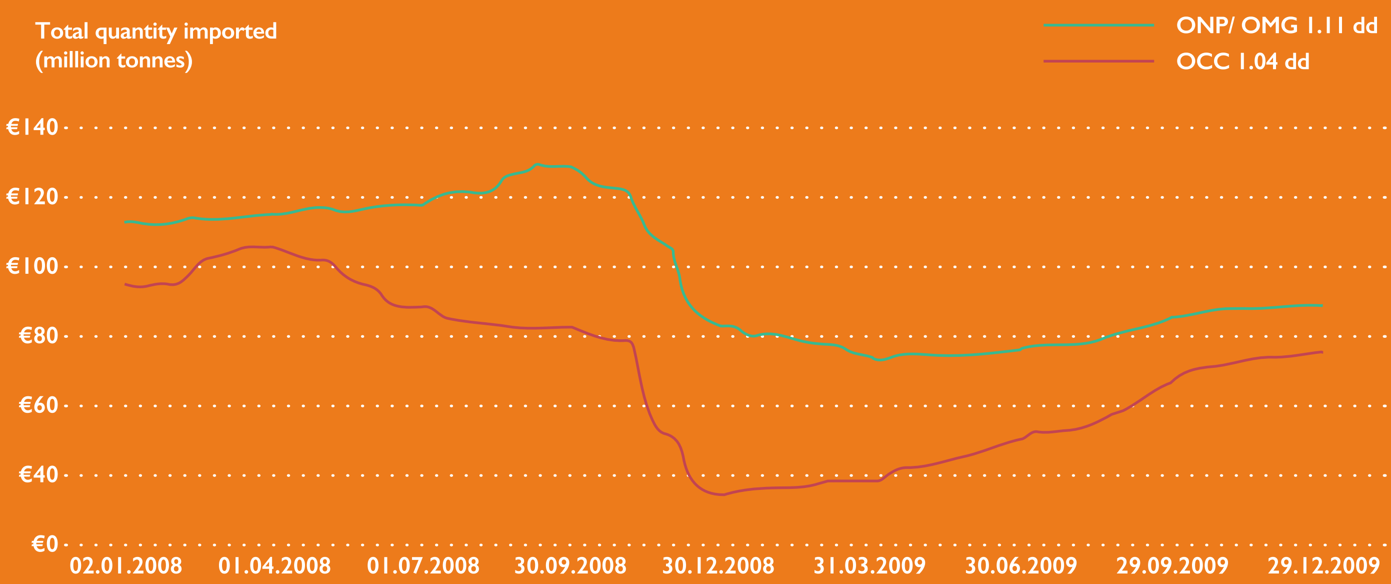
Fig. 7 | Trends in quantities of imports and average price of paper & board (2000-2013)



Data not available for 2010 and 2011.

Source: CEPI (2014)[73]

Fig. 8 | Recovered paper prices Europe (2008-09)



Source: FOEX (2015)[74]

China is the dominant importer of recovered paper & board, particularly for old corrugated containers, old newspapers and magazines, mixed paper grades (Table 12 and 13). In 2013, China imported over 29 Mt of material, over seven times the quantity of the next largest importer of recovered paper & board (Germany). This reflects China's rapid increase in demand for recovered paper & board, which has grown from 3.7 Mt in 2000 to almost ten times this quantity in 2013 (Figure 7).

Other major exporters include Germany, Netherlands, India and Indonesia. Quantities of imported recovered paper & board have generally increased amongst these major exporters. Germany and India have shown the greatest growth since 2000. These two countries now import three times as much of these materials as they did in 2000. India, in particular, is expected to become a more dominant importer of recovered paper & board as its demand for paper & board products increases and the nation invests in reprocessing capacity. Imports from other major importers have shown far more modest increases and, in the case of Indonesia, South Korea and Mexico, slight decreases.

Overall, the average price of recovered paper & board materials has increased since the turn of the millennium. However, the price dropped significantly following the recession in 2008 and has still not yet recovered to its earlier level (see Figure 8). This trend is also reflected in other data sets and has been particularly marked in Europe. The effect of the 2008 recession can be seen in the trend of recycling, particularly amongst European importers (Germany, the Netherlands and Spain), but also in South Korea. Quantities of imported materials dropped sharply and then recovered again in 2010.

However, it is important to note that China, in particular, is seeking to become more self-sufficient in producing these materials. UNComtrade Data (Figure 7) and information from the Bureau of International Recyclers (BIR)[75] suggests that China's import of recovered fibre has actually started to decrease.

So, whilst the overall demand for good quality recovered papers and board (e.g. high-grade, wood-free printing and writing papers) is likely to continue to rise, there is likely to be reduced demand for low quality grades such as mixed papers. In short, China is likely to become more selective in its imports. This is likely to drive the increase in quality standards for major exporters in the US, Europe and Japan.

Tab. 12 Summary of Chinese imports of paper & board by country of origin (2010)

COUNTRY OF ORIGIN	PROPORTION (%)
United States	42
Japan	14
United Kingdom	11
Netherlands	7
Other EU	12
Others	14

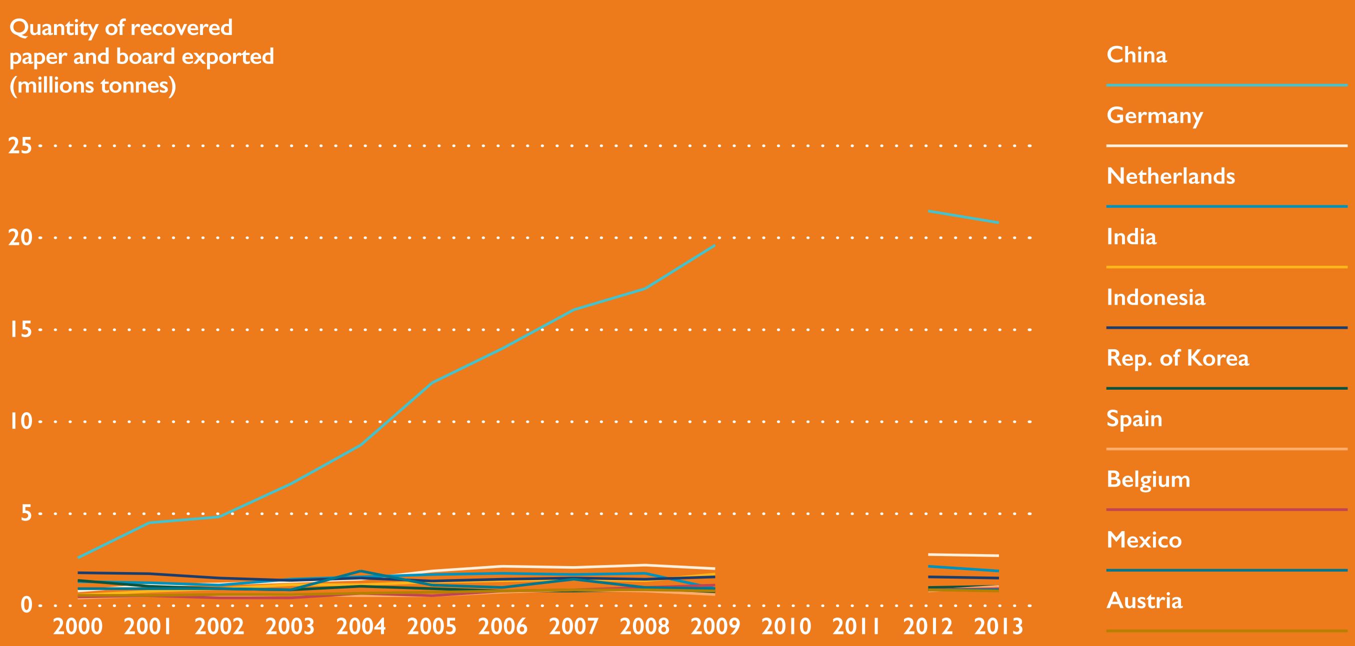
Source: WRAP, based on Chinese Customs, Business and Trade Statistics (2010)[13]

Tab. 13 Summary of Chinese imports of paper & board by grade (2010)

GRADE	PROPORTION (%)
Old Corrugated Containers	58
Old Newspapers and Magazines	24
Mixed Grades	16
High grades	2

Source: WRAP, based on Chinese Customs, Business and Trade Statistics (2010)[13]

Fig. 9 | Trends in recovered paper & board imports (2000-2013)



Data not available for 2010 and 2011.

Source: UNComtrade (2015)[25]

Barriers and opportunities to sustainable paper & board recycling

Technical barriers to sustainable paper & board recycling

Fibres from recovered paper & board are key raw materials in the paper & board sector. In Europe, for instance, over half of the pulp used in paper & board manufacture comes from recovered sources. However, recovered paper & board is often associated with contaminants and mixed grades, limiting the applications for which it can be used. Removal of contaminants from recovered paper & board to produce secondary fibre requires multiple stages of cleaning, washing, screening and deinking, which are not required for primary fibre produced directly from wood. Table 14 summarizes the current technical barriers that the recycling industry of paper and paperboard is facing.

Environmental barriers to sustainable paper & board recycling

Paper waste may potentially contain a large number of chemical substances, many of them associated with the printing industry. According to a recently published research.[76] half of these substances are classified as persistent and potentially bioaccumulating, and around one third of them are identified as critical for removal during the recycling process. Special attention should be paid in the case of food packaging applications, because of potential migration of these substances into food. There is need for more comprehensive study and quantification of these potential hazardous substances in the paper waste. Table 15 summarizes some of the current environmental barriers the recycling industry of paper and paperboard is facing.

Tab. 14

Technical barriers to sustainable paper and paperboard recycling

BARRIER	COMMENT
Recycling cycles limit	A fibre cannot be recycled indefinitely - the limit is estimated between five and seven times, because fibres get sorter each time they are recycled.[63] Wear and degradation of fibres during recycling reducing their strength and bounding ability causing degradation in the paper properties made from recycled fibres which limits the amount of recycled fibres added[61] and each time a paper is recycled virgin fibres must be added. The share of non-collectable and non-recyclable paper is, for technical reasons, estimated to be 19% of the total paper and board consumption.[55] Consequently, the theoretical maximum collection for recycling rate would be 80% (or practically at 60%[57]) instead of 100%. The closer we get to this threshold, the less benefits can be achieved. Many countries have already reached this threshold.
Cross-contamination and mixes of fibre types	Make it difficult to be handle, effectively sort and bleach the mixed waste.[63]
Paper grades	Lack of metrics for paper grades or fibre types.[63]
Sorting technologies	Lack of methods to monitor and sort paper types efficiently.[63]
Quality perception	Perceived as lower than the virgin materials.[63] Such lower quality of recovered paper could have a strong negative impact on sustainable recycling in the production of different paper grades: The processing yield decreases and the volume of solid waste increases, resulting in negative economic and environmental impacts.
Recycling technology	Not sufficiently advanced to achieve high energy efficiency, low operating costs and higher fibre quality.
Increasing use of commingled collection systems	Commingled collection systems result in far lower quality of recovered scrap compared to selective ones. This is one of the major threats for extending the current limits of paper recycling and substantially limiting their end-markets.[62] Higher recovery rates at lower cost, but low quality material, which cannot be fully exploited for graphic paper recycling, where the main potential for increasing the use of recovered paper in papermaking lies.[62]
Variability in quality standards for recovered paper	Quality specifications vary from country to country; the criteria can also vary considerably within a country by different end-user (e.g. papermills). The EN 643 grading schedule is known and used in many cases, but often the Chinese paper mills define quality and set levels for acceptable contamination, without considering of EN 643.[58]
Contamination	Higher contamination of recovered paper grades, resulting from sorting mixed recovered paper grades from household waste collection. Great variety of contaminants (unusable material and non-paper components) coming with recovered paper that render difficult the recycling process, and limit the uses of the secondary fibres.[62]
New inks and paper grades	Such as flexographic newspaper printing, digital printing with liquid toners and inkjet printing and UV cured inks and varnishes, which may need non-conventional removal techniques.[62, 65]

Tab. 15 | Environmental barriers to sustainable paper and paperboard recycling

BARRIER	COMMENT
CRITICAL SUBSTANCES	
• Mineral Oils	Main Source: Printing inks (solvents in particular) are the main source of mineral oils in paper mainly from newspapers). Parafins, naphtenes and aromatic hydrocarbons from crude oil refining process. Potential hazardousness: significant number of them can be classified as persistent (bioaccumulation problem), carconogeneous and some are also mutagenic substances. Deinking process do not remove them efficiently, but paper drying remove around 30%.[77] Not removed in water-based processes during recycling (hydrophobic substances) can be reintroduced into recycled products. Difficult to identify and quantify due to the wide diversity of them.
• Phtalates	Mainly present in: board, waste paper from offices, specialty paper and papers containing relatively high amounts of glue. Main source: adhesives could be the main source of phthalates. Potential hazardousness: Some of them are classified as persistent and hey have tendency to accumulate.
• Phenols	Bisphenol A present the highest concentration ranges used as biocide in paper production, ink preparation. Main source: both printing and paper sectors. Potential hazardousness: Potential spreading of BFA during recycling. They show high affinity o solids and are persistent. Deinking process can removal 50% of BFA but still results in high concentration of BFA in board produced.[76, 78]
• Parabens	Mainly present in: preservatives and biocides. Potential hazardousness: Endocrine disrupting chemicals that can be removed in the wet end of paper production. Only butyl and propyl parabens show a partial affinity to solids which may constitute an issue in paper recycling.
CRITICAL SUBSTANCES	
• Inorganics	Mainly present in: Journals and magazines.Main source: pigment and coatings. Potential hazardousness: The removal in the recycling process may vary. Pb can be observed in recycled paper. Sn and Sb can increase during paper recycling but they do not pose health hazards, even for food packaging.
OTHER SUBSTANCES	• Polychlorinated biphenyls are persistent organic pollutants no longer used in paper production. • Diisopropyl naphthalene in office paper. • Organochlorine compounds such as dioxine, furans (present in chemical additives used for paper production and paper conversion[63] are generated during the chemical pulp bleaching with elemental chlorine and chlorine compounds (chlorine dioxide, hypochlorite and chlorination of fresh water) specially in emerging economies.
EMISSIONS	
• CO_2	The production of recovered paper pulp uses less energy (10-13 GJ) per tonne than the production of virgin pulp, depending on whether the recovered paper is de-inked and whether mechanical or chemical pulp is being replaced.[57] Although less energy-intensive, the production of recovered paper pulp is generally more CO_2-intensive, as the production of chemical pulp, by using biomass for energy, is CO_2-neutral. In many cases, the energy used for the production of recovered paper pulp comes from fossil fuels. As a result, higher levels of recovered paper utilisation can significantly reduce energy intensity in the sector, but at the cost of higher CO_2 emissions.[79]

Source: Information from Pivnenko et al. (2015)[76]

Economic barriers to sustainable paper & board recycling

Recovered fibre is cost competitive with fibre from wood and there is a demand for recovered paper and a good collection system. However, contaminants and mixed grades of paper limit the markets available to them and reducing the value of recovered fibres. Table 16 summarizes the financial barriers that the recycling industry of paper and paperboard is facing.

Tab. 16 | Economic barriers to sustainable paper and paperboard recycling

BARRIER	COMMENT
Comingled collection systems	Higher processing costs (sorting) due to the higher levels of contamination of the products[62] and low quality recovered paper.
Transport costs	Materials are not sorted properly producing higher transport costs.[63]
Sorting costs	Manual sorting operations are very intensive in labour and, consequently, its cost is high. However, the investment for automatic systems is high.[62] The compatibility of polymers used and layered plastics in packaging can create cost externalities for the recycler at the sorting stage.[31]
Recycling Costs	Taking into account all the costs along the paper recycling chain are considered, commingled collection systems could not be the most economic collection method as previously believed.[62] It is challenging to ensure energy and water at low price to make profitable the recycling process.
Quality of recycled fibres	Which depends on the amount of undesirable components, the state of the art of the recycling technologies, the level of accepted impurities in the finished pulp and residues produced during the recycling process.[63]

Opportunities to increase sustainable paper & board recycling

The recovered paper market is well established with significant global trade flows. A summary of key opportunities for increasing material recycling is presented in Table 17.

Tab. 17 | Opportunities for increasing paper and paperboard recycling rate

STRATEGY	OPPORTUNITY
Technical development of recycling processes	Simplification of the flow processes by the development of new technologies with single units that provides higher yields and lower energy and water use, with lower capital costs.[63] Optimisation of collection methods promoting source-separated collection systems.[62] Improvement of automated sorting techniques and in-line quality control[65] that can effectively reduce the sorting costs[62] as well as the energy consumption and environmental impact of sorting operations. Development of new sampling and monitoring techniques and a better characterization of fibres.[63] Simplify deinking processes without deteriorating the quality of DIP and search for new ways to improve ink detachment in pulping and search for pulping methods that could efficiently process recovered printed papers with various inks.
Improving material recyclability Design for recycling	Limiting the content of hazardous substances. Development of new inks easily removed by current technologies. Further technical innovations and improvements in paper production technologies: printing technologies to produce deinkable prints, developing eco-friendly adhesives easy to be easily removed in the process as early as possible.[62]
End of Waste (EoW)	The European Commission is establishing end-of-waste criteria for a number of specific recyclable materials including paper waste (EoW criteria for waste paper: Technical proposals[1]) and plastics (EoW criteria for waste plastic for conversion[2]) which define the technical requirements that these waste streams have to fulfil in order to cease to be waste in the EU.

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