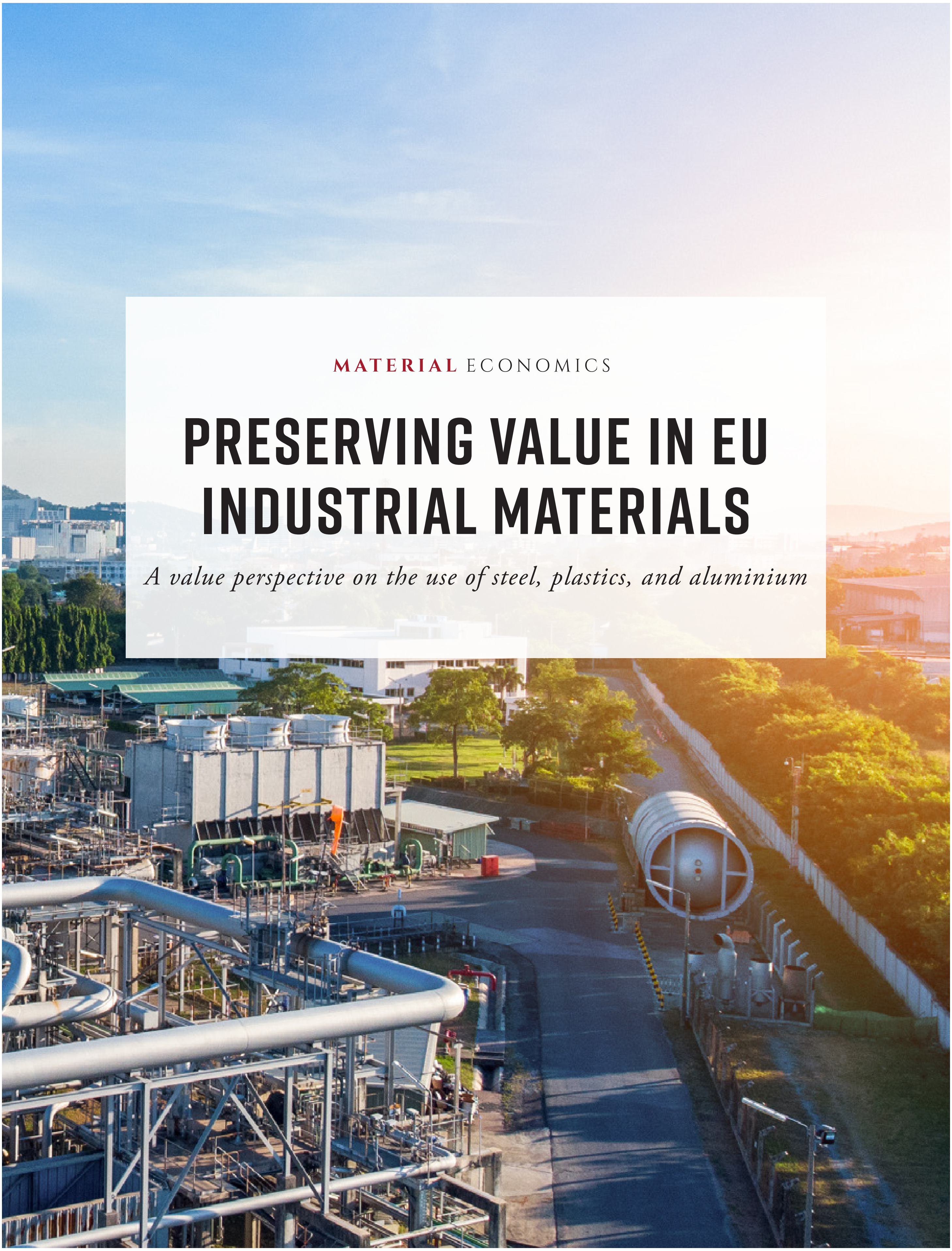
MATERIAL ECONOMICS

PRESERVING VALUE IN EU INDUSTRIAL MATERIALS

A value perspective on the use of steel, plastics, and aluminium



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Publication details

The report was updated in November 2021 to reflect a refined methodology to calculate the value from different sources of end-of-life metals (steel and aluminium).

Please refer to this report as: Material Economics (2020). Preserving value in EU industrial materials - A value perspective on the use of steel, plastics, and aluminium.

PREFACE

Material use and material recycling have been discussed for decades in Europe. And for good reasons – there are many important questions related to our use of materials: What materials should be recycled, and how? What are the environmental benefits of increased recycling? Which policies regarding waste and recycling are reasonable? The debate has intensified in the last several years, not least due to the increased focus on climate change mitigation and on establishing a 'circular' economy; intense work is going on both in the policy sphere and in industry to make our material use more sustainable.

So far, the debate has primarily been held in terms of tonnes, cubic metres, and environmental impact. Public statistics, most academic research and industry reports discuss in volume terms, and 'material flow analysis' is one of the most commonly used tools. This is all, of course, highly relevant, but a focus on volumes and flows also leaves important questions unanswered. For instance, how big is the quality downgrading effect in different material flows? How much primary materials production can actually be replaced by recycled materials with today's recycled materials quality? How close to a 'closed-loop' materials system is Europe actually? Only looking at what share of the material volumes come back may lead users of such statistics to believe our material use is more circular than it actually is.

This report takes a step towards painting a more complete picture. The report takes an economic value perspective on material flows and assesses Europe's use of steel, plastics and aluminium in terms of Euros instead of tonnes. The 'exam questions' we ask ourselves are: If 100 Euros of raw materials is entered into the European economy, how much economic value is retained after one use cycle? What are the main reasons that material value is lost? How could more value be retained? What business opportunities arise as a result[1]?"

These are ambitious research questions, and as far as we know, this is the first broad European investigation of materials value retention. Hence, this report should be read as a piece of initial research, which needs to be followed by much more investigation. There are many methodological and statistical issues to refine, which may also change our estimates of value retention. But we believe the report shows that a value-based perspective has important new insights to offer when discussing what Europe's future materials system should look like and how it can be made more circular and environmentally sustainable.

This study was carried out by Material Economics on behalf of EIT Climate-KIC and RE:Source between March 2019 and June 2020. It builds on a previous similar study of the Swedish material system published in 2018 with the support of RE:Source and the Swedish Recycling Industries' Association. The Material Economics project team included Peder Folke, Axel Elmqvist, Anders Falk, Stina Klingvall, and Gustav Hedengren. We would like to thank all the numerous experts who have provided input to this report.

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[1] This means the report only looks at a subset of the circular economy, namely materials circularity and retaining the value in materials. The report does not assess product circularity opportunities. Take a car as an example: The report does not look at opportunities to re-use or re-manufacture individual components of a car, or the entire car. Instead, this report focuses on what happens to the steel, plastics and aluminium that the car is made from, and asks questions about why those materials, which in principle can be recycled many times, are worth less to the next user.

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EXECUTIVE SUMMARY

Each year, 150 million tonnes of steel, plastics, and aluminium[2], with an original value of €130-140 billion, exits use in the EU economy, after fulfilling essential roles in vehicles, buildings, products, and packaging. Materials in these three categories are almost all technically recyclable (barring a few categories, such as plastic thermosets), and if all these materials were recycled, they could supply as much as 64% of total EU demand in the same categories, even after accounting for unavoidable losses in the recycling process. In other words, the EU could in principle meet nearly two-thirds of its need within these three material categories from recycled materials. Moreover, by 2050, this grows to as much as 86%. If the quality of these recycled materials was similar to that of virgin materials, the original value would also be maintained[3]. In monetary terms, the original value corresponds to approximately €320 per EU inhabitant or, as another comparison, it is similar in size to the export revenues of the entire European automotive industry (€136 billion in 2019).

Today, only about 43% of this original material value remains after one use cycle. In total, the losses amount to €78 billion per year. In practice, when these materials are re-sold as recycled materials, their market value is approximately €43 billion. Another €2 billion of the original value is captured in waste-to-energy incineration plants, and there are about €14 billion in unavoidable reprocessing costs (e.g. remelting) that should not be counted as losses. The difference, €78 billion per year across Europe, are value losses along the use and recycling cycle. This is thought-provoking: Why should more than half of the original material value be lost for materials that technically can be recycled without any major loss in quality? What does that say about Europe's circularity?

The value losses can be divided into two broad categories: volume losses and price (or quality) losses. First, a large share of the end-of-life materials are not recycled, but rather put in landfills or used as fuel (plastics); some are lost in recycling processes; others never even enter the waste collection system. These volume losses represent €61 billion of the total value loss, or 78%. Second, because some recycled materials are of lower quality than their primary counterparts, another €18 billion in value is lost (22%)[4]. Key reasons for these price and quality losses include mixing of different fractions, including different types of plastic or alloys of metals, alloying of metals, and various forms of contamination. This is particularly true for plastics, and it is one of the main reasons for its relatively low recycling rates (10%[5], compared with 85% and 78% for steel and aluminium, respectively) and the lower price of recycled polymers. The price and quality losses, however, are much more important than these numbers suggest, as the low prices are what makes it uneconomical to collect and reprocess some of the materials, which in turn leads to the volume losses.

[2] These three materials were chosen as they are the three largest industrial materials flows in Europe that are technically recyclable many times.

[3] For steel and aluminium, we define original value as the value per ton virgin steel slabs and aluminium ingots, respectively, and for plastics as the value per ton virgin plastic resins.

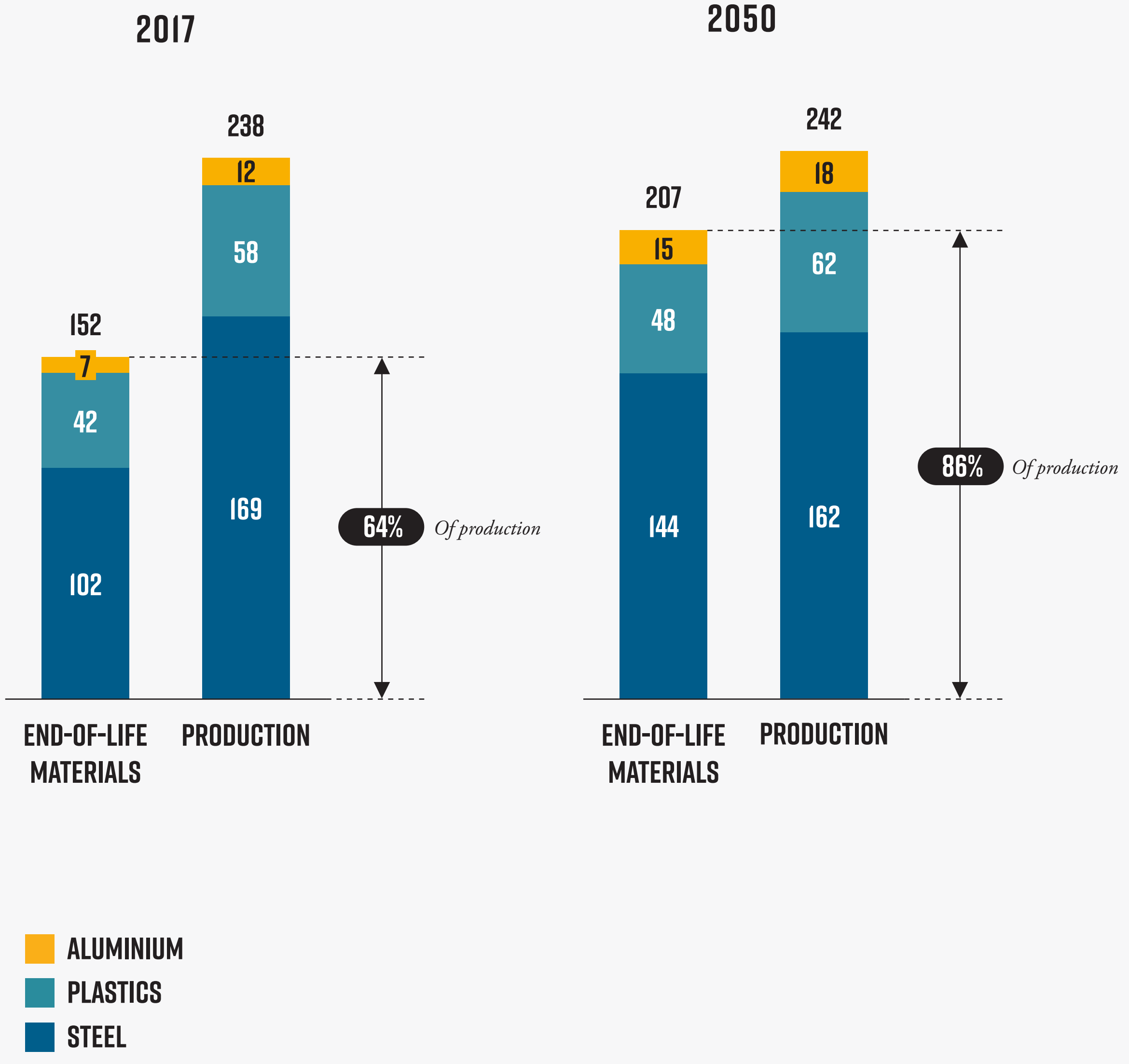
[4] If we first calculated the price losses, these amount to €45 billion annually (57%), while the volume losses amount to €33 billion annually (43%). During the rest of this report, we will first look at volume losses and then price losses, as many of our speaking partners have found that are more intuitive way of explaining the value losses.

[5] The plastics recycling rate includes removing exports of plastic waste, which was not done for the aluminium and steel rates as plastics can generally be considered a one way waste flow while aluminium and steel scrap are essentially internationally traded commodities.

Exhibit 1

END-OF-LIFE STEEL, ALUMINIUM AND PLASTICS AMOUNT TO 64% OF EU PRODUCTION VOLUMES, RISING TO 86% BY 2050

EU PRODUCTION AND END-OF-LIFE MATERIALS
MILLION TONNES PER YEAR

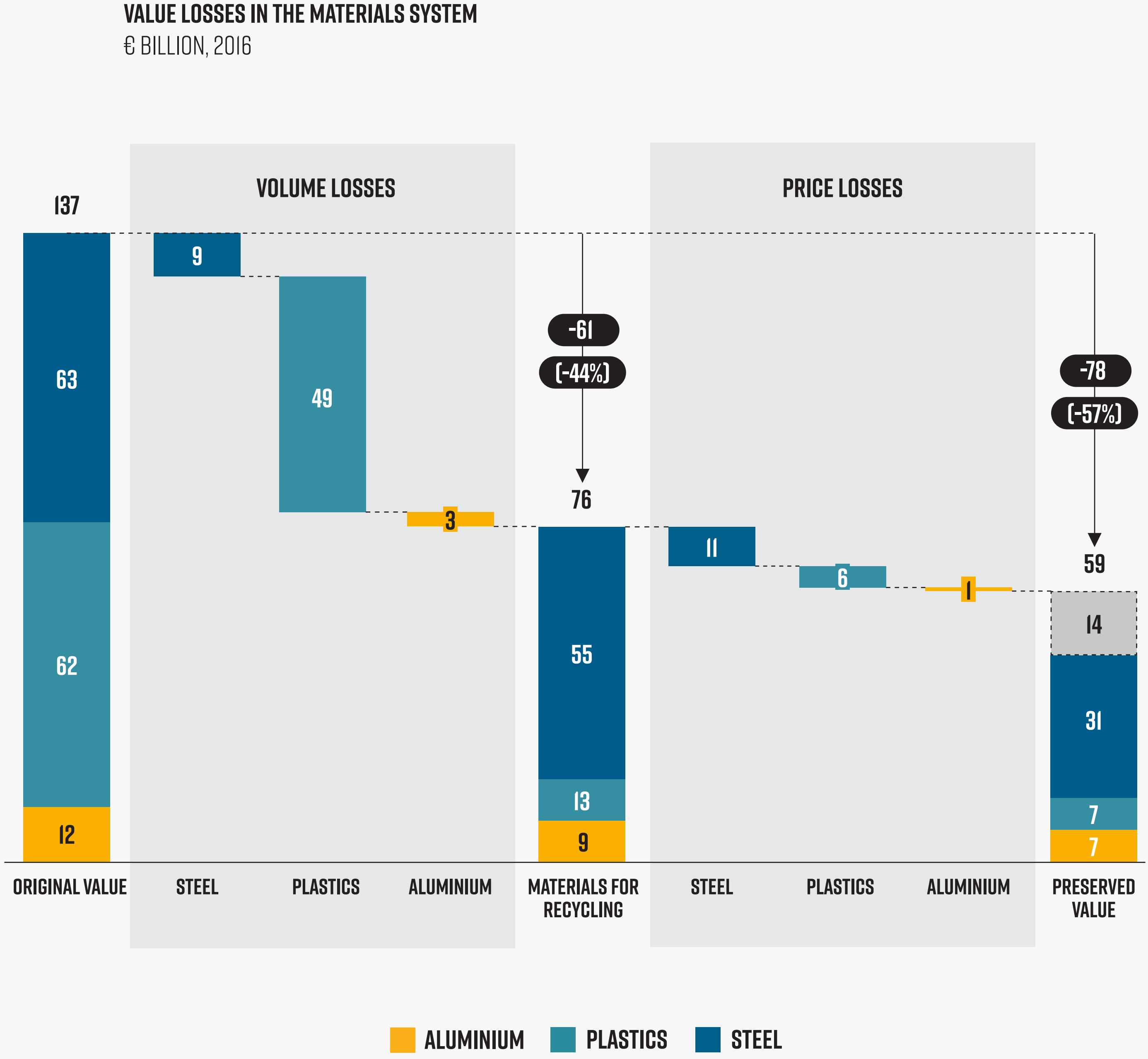


Note: The figure shows total end-of-life (EOL) flows of materials. The estimates include post-consumer scrap, pre-consumer fabrication scrap, and scrap that is not collected, but exclude prompt scrap arising in steel production. Aluminium EOL volumes are based on International Aluminium Instiute's material flow model, and future production volumes follow those in European Aluminium (2020) – Circular aluminium action plan. Aluminium collection rates in 2050 are assumed to be similar to today (78%). For plastics, the end-of-life volumes are derived from Material Economics dynamic materials flow model, using historical and projected data on plastics demand per sector and the economy residence time of different plastic product groups. Historical demand volumes between 2005 and 2019 are derived from Plastics Europe (Plastics – the Facts for each year, respectively). Forecasts for production volumes and end-of-life materials in 2050 follow the scenario described in Material Economics (2019) – Industrial Transformation 2050. End-of-life steel likewise is based on a dynamic materials flow model, using a model developed on the framework described in Pauliuk et al. (2013), The Steel Scrap Age; see Material Economics (2018) – The Circular Economy, a Powerful Force for GHG Mitigation for more details. Production projections follow the scenarios in Material Economics (2019) – Industrial Transformation 2050.

SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS

Exhibit 2

EACH YEAR, €78 BILLION OF MATERIALS VALUE IS LOST IN THE USE OF STEEL, PLASTICS, AND ALUMINIUM



NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP TO TOTAL DUE TO ROUNDING
SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS

Very different value loss patterns can be observed across the different materials. For steel and aluminium, most of the volumes are recycled, but alloying and contamination make the possible uses of the recycled material different from that of virgin materials (what is sometimes referred to as 'open loop' circularity), whereas for plastics only a small share of the volumes are turned into a new plastic product.

• **For steel,** the largest of the three material flows and the most recycled, 69% of value is preserved after one use cycle. Most steel (85%) is recycled, and in many cases recycled steel also can be purified to the point where very high-quality production is possible. However, quality downgrading nonetheless happens. Steel is often alloyed with small volumes of other metals (often highly expensive metals) to give it specific properties. The first time these alloy metals are added, they are 'tailor-made' to produce the desired material properties. In subsequent use cycles, however, they often become a problem rather than an asset. At best, the original additional value is just lost. At worst, alloys or tramp elements become a problem that reduces the value of the scrap steel. Copper is a particular concern: It often gets unintentionally mixed with steel in the scrapping process (e.g. from electric cables still left in a car sent for scrapping or in a household appliance) and negatively impacts the steel's strength. Copper is also very hard to separate from the steel once it has been mixed in. This is one reason that secondary steel often is used for lower-value applications than virgin steels, for instance, construction steels.

• **For aluminium,** 70% of the value is preserved after one use cycle. The effective average volume recycling rate is 78%, due to collection losses (e.g. in packaging and construction) as well as losses in the recycling processes. Aluminium is rarely used in its pure form, but is alloyed with other substances to give the right material properties. However, once different qualities are mixed together, these alloyed materials often cannot be re-used into the same product again. Instead, after one use cycle, much of the volume becomes cast aluminium, a less valuable product with motor blocks in cars as its main application. This is a downgrading effect – the potential applications for cast aluminium are distinctly different and more limited than those of virgin aluminium – which is also reflected in the price difference between virgin and recycled aluminium.

• **For plastics,** contamination, mixed polymer grades and colours, and the mechanical recycling process itself all contribute to quality and volume losses in recycling, to the extent that only 11% the value is retained[6]. Contrary to official statistics and perhaps also to popular belief, the large majority of plastics are never turned into a material again, but are landfilled or burnt as fuel.

Addressing these value losses is likely a major opportunity for Europe, economically, environmentally, and geopolitically. Moving in the direction of increased materials value retention seems very consistent with the EU's Circular Economy Action Plan, and with the ambition in many Member States to move towards a more circular economy. While each potential policy should of course be carefully assessed in its own right, with both advantages and disadvantages analysed, there are a few overall arguments that suggest increased materials value retention is indeed an attractive opportunity for Europe.

• **Increased materials** value retention could become a major business and industrial opportunity, in keeping with the strengths of European industry. A closed-loop system is a major business opportunity for recyclers, industrial materials users, recycling equipment providers, and other stakeholders. It will never be possible to eliminate all the €78 billion of value losses, given the billions of pieces of materials that are placed on the market yearly and the natural losses due to processes such as corrosion, but even a partial recovery represents significant value[7]. For example, circular business models such as take-back schemes and subscription-based business models, together with design for recycling, can enable higher-value recovery and tighter material loops. Partnerships along the value chain and improved waste management and recycling technologies can increase the quality of recycled materials. All these opportunities have strong synergies with digitalisation, as new sorting technologies, tagging and tracking of materials, etc., make it possible to increase volume and quality, while decreasing cost. Moving in this direction also will give rise to significant green job creation across Europe, as imported primary materials are replaced with European recycling and reprocessing. This is especially important today given COVID-19.

• **Increasing the circularity of steel,** plastics, and aluminium can help the EU significantly in meeting its climate targets. The production of these materials today accounts for 10% of total EU CO_2 emissions, and materials recycling is 79-93% less CO_2-intense than primary materials production. Recycling also shifts CO_2 emissions away from hard-to-abate sources such as mining, oil and gas extraction, blast furnaces, and steam crackers, towards sources such as electricity and low- or medium-temperature heat production that are easier to decarbonise.

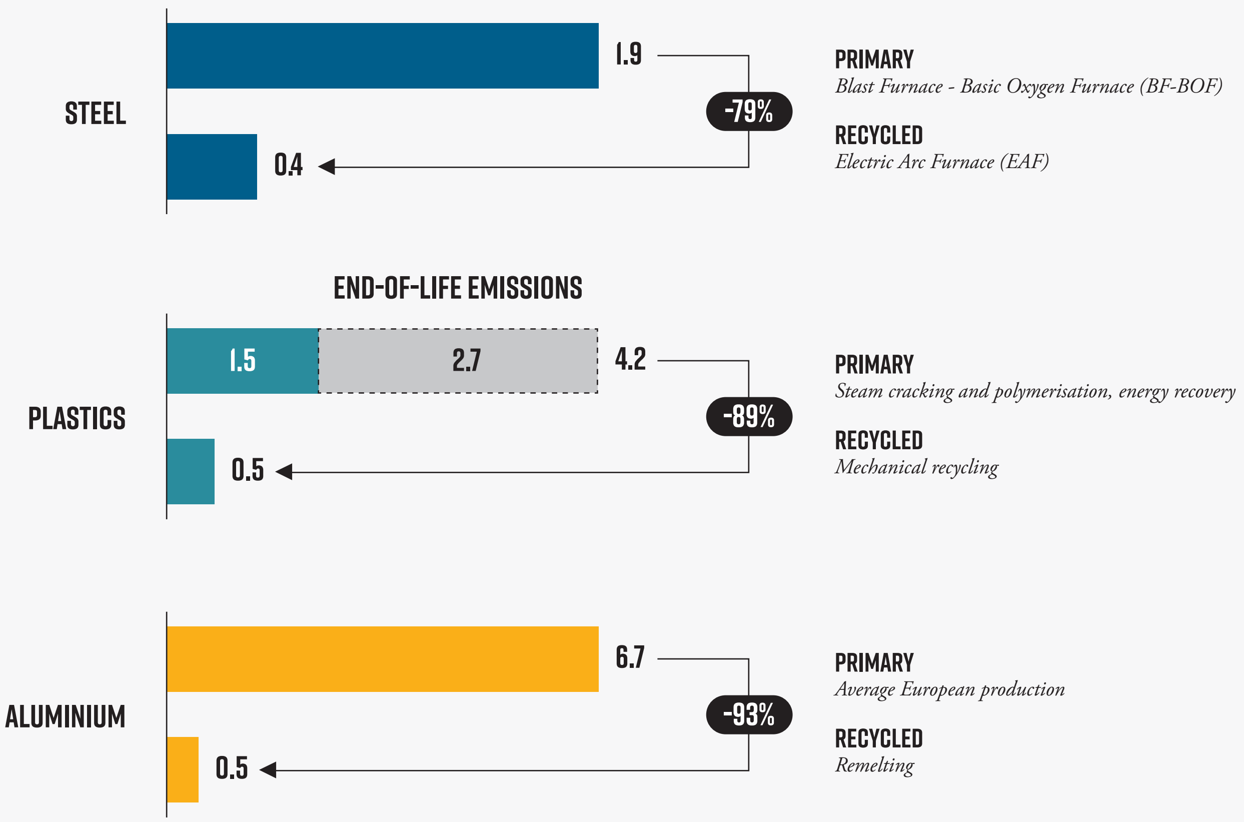
[6] *For plastics, value retention is slightly higher than the recycling rate (10%) since €2.4 billion is also recovered as heat value in waste-to-energy incineration plants.*

[7] *Note that the €78 billion of value losses should be thought of as the total revenue opportunity. Better recovery and reprocessing of these materials will also carry a cost, and for many fractions the costs today outweigh the revenue. But with new business models, better product design, new recycling technologies, and new policy a larger and larger share of the €78 billion will be possible to address profitably.*

Exhibit 3

RECYCLED MATERIALS ARE ~79–95% LESS CO_2-INTENSIVE THAN PRIMARY PRODUCTION

CO_2-INTENSITY OF PRIMARY AND RECYCLED MATERIALS PRODUCTION
TCO_2/T MATERIAL



SOURCE: MATERIAL ECONOMICS MODELLING IN INDUSTRIAL TRANSFORMATION 2050 AND CIRCULAR ECONOMY REPORTS, WORLD ALUMINIUM

• **Building a stronger,** more circular economy for industrial materials also will enable a more resilient EU industry that is less dependent on imports of potentially more polluting primary production. Europe today exports significant amounts of used materials and instead imports primary materials from abroad. Changing this could both improve the predicament of the often challenging economic environment faced by European primary producers by developing a new source of local raw materials, and strengthen the long term resilience of the industry through reduced reliance on imports. For example, the trend towards increased electric arc furnaces in steel production means that having sufficient access to steel scrap will become a strategically important aspect for European steel producers. Likewise, there is a major industrial opportunity in reprocessing growing volumes of end-of-life aluminium, reversing the current trend of increasing imports and crowding out of environmentally superior EU production. In fact, high-quality recycling could supply more than half the aluminium volumes needed in decades to come, even with significant growth.

• **Possible drawbacks include** increased reverse logistics flows, increased complexity and cost in sorting, and transition costs. No change of this scale is possible without any challenges. In this case, the primary questions to address are increased traffic and reverse logistics flows, and the increased costs of higher-quality recycling.

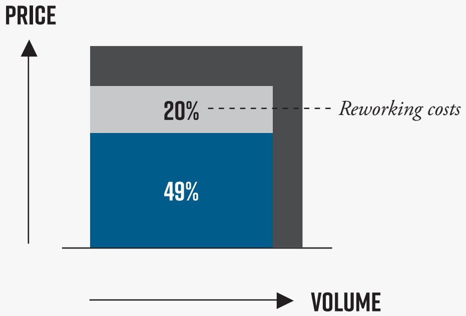
Policy will need to play a major role if Europe wants to capture more materials value. This report has not analysed in detail what policy interventions are needed for Europe to significantly increase materials value retention. However, it is clear that policy will have to play an important role; the changes required are often too systemic for any single company to capture by itself. For instance, the effects of improved product design choices are often seen many years later and in completely different industry sectors, improved scrap sorting likely needs to be based on industry-wide standards, the toxicity issues that plague plastics recycling need an industry-wide answer, et cetera. A possible way forward could be to take the materials value perspective explicitly into account the next time Europe reviews its policies for these materials, or for the main products where they are used. The initiatives launched as part of the Circular Economy Action Plan start to put together many of the frameworks that could be used here, such as a revision of Enhanced Producer Responsibility ('EPR') policies, a more extensive product policy framework, and new regulatory approaches to the major product categories. Of course, the competitiveness of recycled materials would also be enhanced if all materials had to pay their externality costs.

Measuring materials value retention is an important complement to volume-based metrics. We believe this report also shows the importance of economic value-based approaches in addition to the traditional volume-based statistical metrics. The preserved value of recycled materials holds information about quality, price, and the actual replacement opportunities of virgin materials production by recycled materials. It also highlights new revenue opportunities for the private sector, and therefore is likely to stimulate innovation. Public statistics in Europe are already improving, with metrics shifting from what share of materials is being separated out for recycling, towards metrics showing the amount of recycled materials actually being produced and sold. Price and quality data would be excellent complements.

Exhibit 4

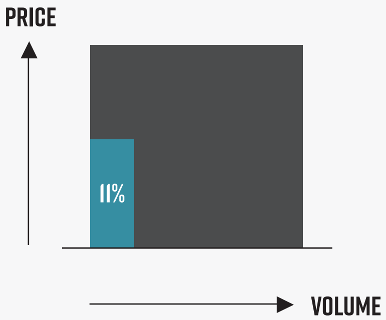
PRESERVED MATERIALS VALUE OF STEEL, PLASTICS, AND ALUMINIUM

STEEL – 69% PRESERVED VALUE AFTER ONE USE CYCLE



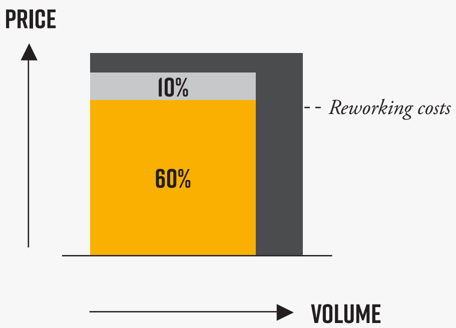
Key value losses: misclassified/not collected waste (e.g. corrosion), alloy losses, quality losses from high copper content

PLASTICS – 11% PRESERVED VALUE AFTER ONE USE CYCLE



Key value losses: significant collection losses, energy recovery, and quality losses

ALUMINIUM – 70% PRESERVED VALUE AFTER ONE USE CYCLE



Key value losses: some collection losses, recycling process losses, quality losses due to high alloy element contents

SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS

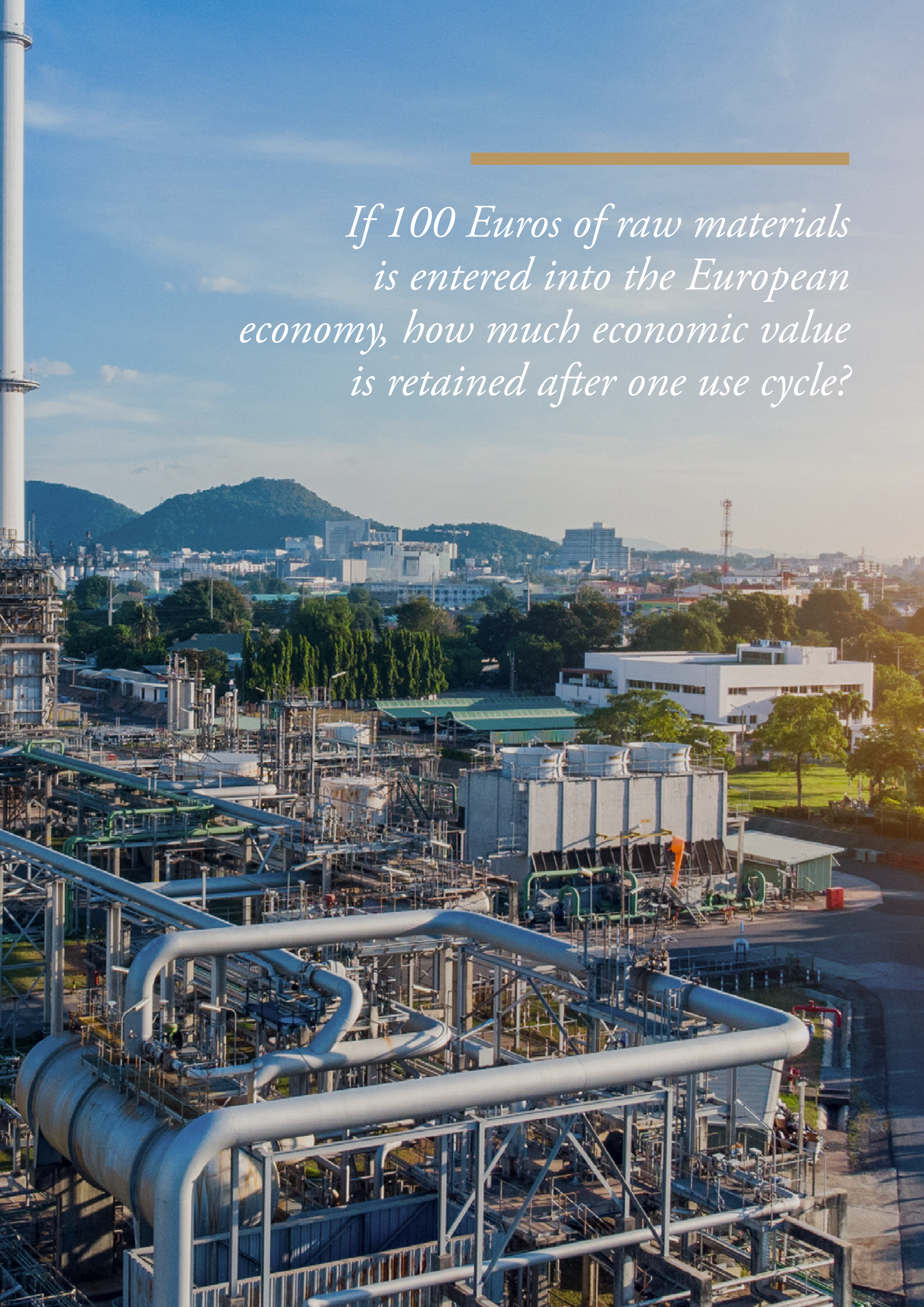
INTRODUCTION AND METHODOLOGY

Making good use of materials is a decades-old challenge that involves economic, industrial, environmental and geopolitical considerations. On one hand, industrial materials play a crucial role in providing many essential products and services, and materials-related industries are large employers in many countries. As an example, the European plastics industry alone employs over 1.6 million people.

But there are also less desirable aspects of our material production and use: Materials production represents 10-15% of total greenhouse gas (GHG) emissions from EU. Water use and littering (e.g. plastics in the ocean) are other areas of concern.

The concept of a 'circular economy' has emerged as a potential solution, emphasizing both the economic and environmental opportunities in a better use of products and materials. The circular economy agenda has gained significant traction over the past 5-10 years in policy, business and civil society. The 2020 Circular Economy Action Plan, as well as corresponding national strategies, now makes up an ambitious programme of action.

If 100 Euros of raw materials is entered into the European economy, how much economic value is retained after one use cycle?



WHY AN ECONOMIC VALUE PERSPECTIVE ON MATERIALS USE?

Materials recycling is a main feature of a circular and low-carbon economy. Recycling is today measured and analysed primarily in volume terms, looking for instance at the share of steel, aluminium, and plastics collected for recycling, or using material flow analysis ('MFA') to trace a tonne of different materials through the economy and assessing what happens to it. As a result, we would argue that the volume aspects of Europe's material use are today relatively well understood and well known.

However, such volume-focused assessments do not capture information about the quality of recycled materials. Quality, in turn, determines what applications the recycled material can actually be used for and to what extent it can replace primary demand, a precondition for truly circular material flows. If the material that comes back is significantly downgraded and can only be used for a more limited set of applications than the primary material, it is hard to argue that the material use is circular.

In this report, we explore whether an economic value-based approach can yield additional insight into Europe's material use. The 'exam questions' we ask ourselves are: If a 100 Euros of raw materials is entered into the European economy, how much economic value is retained after one use cycle? What are the main reasons that material value is lost? How could more value be retained? What business opportunities arise as a result[8]?"

During the work, we have identified important advantages of such an approach: 1) It starts to capture the important quality aspects mentioned above, by using the market price of the recycled material as a proxy for quality. If the quality were similar, it is fair to assume the price also would be similar, 2) Describing the material flows in economic terms makes transparent and highlights all the industrial and economic opportunities inherent in a more circular material use, and makes it easier to compare and prioritize between opportunities. There are, of course, also drawbacks: 1) Market prices of secondary materials do not only reflect the quality of Europe's material use and recycling system, they also are impacted by the price of virgin materials, as virgin and recycled materials often compete in at least some applications. Raw material prices are often volatile, and this creates 'noise' in our analysis. 2) Price data is harder to get hold of than volume data, and often available only at an aggregated level. For these reasons, we in no way suggest an economic-value based approach can or should replace volume-based approaches. Instead, we see them as complementing each other.

The research questions above are ambitious. This report should be read as a piece of initial research, which needs to be followed by much more investigation. There are many methodological and statistical issues to refine, which may also change our estimates of value retention. But we believe the report shows that a value-based perspective has important new insights to offer when discussing what Europe's future materials system should look like and how it can be made more circular and environmentally sustainable.

[8] This means the report only looks at a subset of the circular economy, namely materials circularity and retaining the value in materials. The report does not assess product circularity opportunities. Take a car as an example: The report does not look at opportunities to re-use or re-manufacture individual components of a car, or the entire car. Instead, this report focuses on what happens to the steel, plastics and aluminium that the car is made from, and asks questions about why those materials, which in principle can be recycled many times, are worth less to the next user.

METHODOLOGY USED

The methodology we have used is explained step-by-step in Exhibit 5. Let us here make a few remarks at a higher level about why this methodology was chosen, data sources, and advantages and drawbacks.

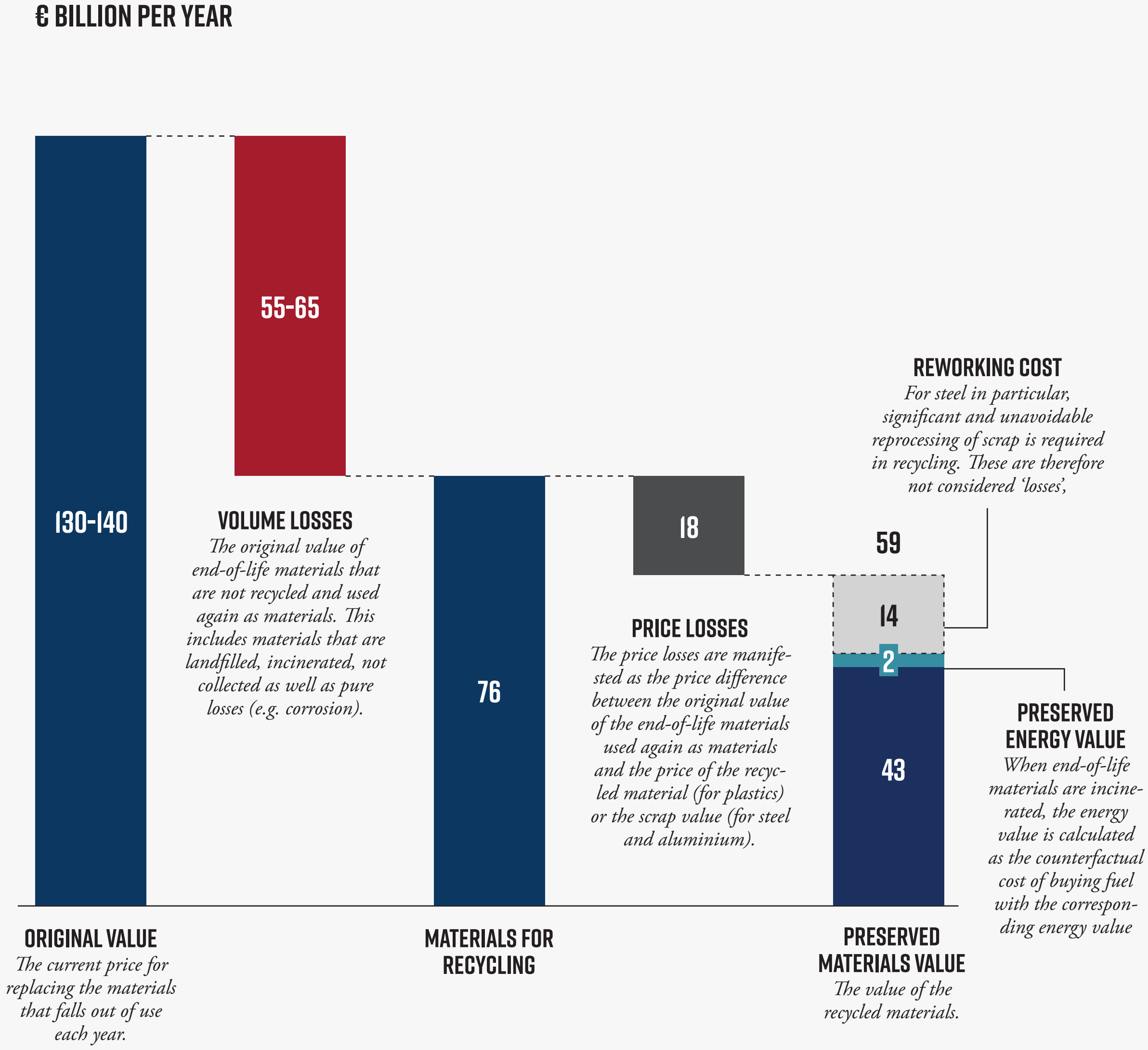
First, it is important what we define as the starting point of the analysis, the 'original value' in Exhibit 5. For the three materials, we start from the value of virgin slabs for steel, virgin ingots for aluminium, and virgin resins for plastics. In principle, in a perfectly circular system, this original value would be recreated when recycled materials come back: scrap steel is remelted to slabs, scrap aluminium to ingots, and recycled plastics to resins. In reality, as the following chapters will show, the recycled versions are worth less. Sometimes, this is due to intentional alloying or additives, done to give the material specific desired properties, but also in these cases it is interesting to understand what this alloying and additives mean for the recyclability and for the next user. In many cases, the value loss is also unintentional, driven by mixing effects, downgrading, and information losses along the use cycle. This original value is possible to estimate quite accurately from public statistical sources and market price data. We adjust for imports and exports throughout the analysis.

Second, we look at what the recycled versions of slabs, ingots, and resins are worth. There is good volume data available, and also price indices for different qualities of metal scrap and recycled plastics, so the 'preserved materials value' can also be calculated with reasonable accuracy. This allows to calculate the total value loss, as the difference between the 'original value' and the 'preserved value'.

Third, we disaggregate and try to explain where and why the value losses occur. Disaggregating the value loss into volume effects (which share of the materials come back at all?) and value effects (how much less is the recycled material worth per tonne?) is a very natural first step. However, since volume and price are mutually dependent, the order in which one subtracts the volume and price effects matters. We have chosen to first subtract volume effects and then price effects, simply because it is easier to explain this approach and it has felt more natural to many of our speaking partners. But we note that this risks downplaying the importance of quality downgrading – it is in many cases the low quality that causes the recycled material's market price to be so low that it is not economically worthwhile to recycle it. Beyond this basic price-volume split-up, our disaggregation analysis becomes a qualitative analysis as much as a quantitative: It involves understanding why different types of mixing and alloying effects occur, what part of them are voluntary and not, and what the value effects of each are.

Exhibit 5

METHODOLOGY FOR ESTIMATING MATERIAL VALUE LOSSES



NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP TO TOTAL DUE TO ROUNDING

SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS

THE METHODOLOGY CAN BE SUMMARISED IN SIX STEPS, AS DESCRIBED BELOW:

1. Focus on three large material categories: This analysis covers three materials – steel, plastics and aluminium – but the methodology is in principle applicable also to other materials such as paper and board, textiles, and cement. It is important to note that the focus of this analysis is on the value of materials, meaning that it does not look at product values and product circularity opportunities. Take a car as an example: The report does not look at opportunities to re-use or re-manufacture individual components of a car, or the entire car. Instead, we focus on what happens to the steel, plastics and aluminium that the car is made from, and ask questions about why those materials, which in principle can be recycled many times, are worth less to the next user.

2. Analyse materials that fall out of use: The material flows that are considered in this study are the end-of-life flows of steel, plastics, and aluminium in the EU. These materials come from products, components, buildings, packaging, etc. that reach the end of their useful lives every year. For example, they include aluminium and steel in scrap cars, plastics in packaging that is discarded, and the steel from demolished buildings. Materials that fall out of use, in principle, become available for recycling or other forms of reuse.

3. Estimate the original value of the end-of-life materials (€130-140 billion): To understand the value losses that arise from our current use of materials, the starting point of the analysis is the price of a corresponding amount of primary materials. This reflects the value these materials would have if no volume losses or quality degradation occurred during their use, as well as the cost of replacing the same volume of materials at today's prices. For steel and aluminium, we define original value as the value per ton of virgin steel slabs and aluminium ingots, respectively, and for plastics as the value per ton of virgin plastic resins. For most of the materials, we have used 2017 as a basis year for prices, as this is the year for which the most complete data are available.

4. Calculate the preserved value (€45 billion): The next step of the analysis is to investigate what happens to end-of-life materials once they become available again. There is a range of different potential fates for end-of-life steel, plastics, and aluminium, including but not limited to recycling, incineration, and landfill. Different treatment methods, in turn, lead to widely differing amounts of preserved value, defined as the market value of the material in its next use, be it as a material or as fuel.

a. Preserved materials value (€43 billion): We define the preserved materials value as the value of secondary or recycled materials. For example, the preserved value of recycled plastics is the market value of recycled polymers made from end-of-life plastics that have been collected, sorted, and reprocessed into recycled plastics. For plastics waste exported for recycling outside the EU, we let the export value of the plastics represent the preserved value. For steel and aluminium, the preserved value is instead the value of the collected scrap, as this is what is traded globally and has clear market prices. Unavoidable reworking costs are separately accounted for, as described in step 6.

b. Preserved energy value (€2 billion): The other value-preserving end-of-life destination for materials is energy recovery (landfill, incineration without energy recovery, and corrosion and other losses do not recover any value). The preserved energy value is defined as the counterfactual cost of buying fuel with the corresponding energy value. Out of the three investigated materials in this study, only plastics are used for energy recovery in a major way.

5. Analyse value losses (€78 billion): The difference between the original materials value and the preserved value is the value loss or value leakage. We go on to analyse the causes for this value loss and identify opportunities to preserve more value in the materials system. The value losses can be divided into two broad categories.

a. Volume losses (€55-65 billion): All end-of-life materials that are not recycled into new materials are considered volume losses, as these materials go to other, often lower-value, uses. The case in point for volume losses is plastics, a significant share of which are incinerated rather than recycled into useable plastics. Other examples include steel that is not collected or that is lost, and aluminium that is not sorted from other waste before incineration (for example, in electric and electronic equipment).

b. Price losses (€18 billion): Price losses occur when the quality of materials is downgraded in various stages of its use cycle, including in product design and manufacturing, in waste collection, or in the recycling process. A lower price is a good indication of limitations in the use of recycled materials.

6. Reworking costs (€14 billion): For some materials, significant costs for reworking waste into new materials are incurred. For steel, costs arise in the remelting of scrap in an electric arc furnace (EAF). These costs are displayed separately, as they are close to unavoidable.

STEEL

TOWARDS A FULLY CIRCULAR EUROPEAN STEEL FLOW

Summary

Steel is a major building block of modern economies, with a crucial role in buildings, infrastructure, vehicles, and many other applications. Globally, almost 1,900 million tons are produced every year, with annual production in Europe relatively stable at 160-170 million tons per year. Both steel and scrap are globally traded.

Steel is already among the most circular material flows: In Europe, around 85% of end-of-life steel is collected for recycling, and steel recycling already accounts for 39% of EU steel production. While this can be pushed higher, it is as important to look to the opportunities to reduce quality losses. In quality terms, the main issue is that through its use cycle, steel gets mixed with small amounts of other metals. Some of this is voluntary alloying, to create desired material properties, but some of it is also a side-effect of how steel is handled. The mixing of different steel grades leads to higher losses of steel, and also to the loss of valuable alloying metals. Where contaminants cannot be removed, the effects are serious. Copper contamination, in particular, could be a long-term problem, as it affects steel strength significantly at low concentrations, and it is hard to separate from the steel once it has been mixed in.

The cumulative effects of these volume and quality losses mean that after one use-cycle around 69% of the original material value is recovered (even after adjusting for close-to-unavoidable reworking costs). Of these losses, approximately 45% are volume losses in the form of misclassified or non-collected waste and yield losses, while the remaining 55% are price losses due to lost alloys, high handling costs, and lower steel quality. There are many things that Europe can do to reduce these losses, including better design for disassembly, improving collection and sorting, and reducing copper contamination.

69%

OF THE MATERIAL VALUE IN STEEL

remains after one use cycle

2.1 INTRODUCTION

Steel is a major building block of modern economies. As the base of many everyday products such as vehicles and buildings, it is one of Europe's most important materials in terms of both volume and value. Europe has a total steel stock of approximately 12 tonnes per person, or in total 5.5 billion tons across the EU. The annual demand for new steel products in the EU is approximately 160 million tons, but slightly more than 100 million tons also exits use every year[3], so that the net addition to the steel stock is about 60 million tons per year, or around 140 kg per person. This demand is expected to increase by around 15% by 2050. The average lifetime of steel in the economy varies by end-use sector, from 15 years for household products to up to 75 years in construction (Exhibit 6).

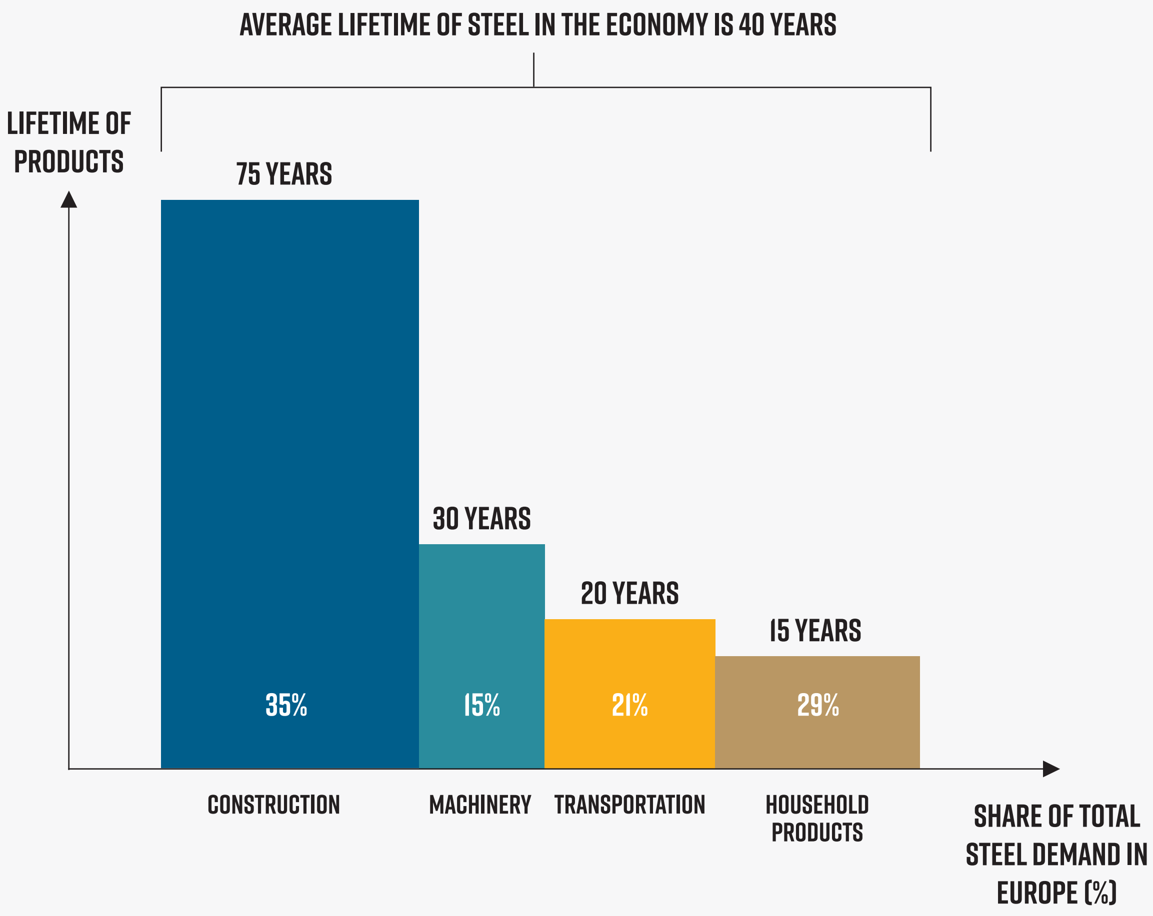
The main European steel-producing countries are Germany and Italy, with more than 40% of total EU crude steel production. There is a net import of steel products to Europe of 3 million tonnes annually. This net import conceals much larger trade volumes: 15% of steel produced in Europe is exported, and 17% of steel consumed is imported. The global steel market is highly competitive, with overcapacity and thin margins. 61% of steel produced within Europe is produced in blast furnaces and basic oxygen furnaces (BF-BOF), and the remaining 39% in Electric Arc Furnaces (EAFs) that principally use scrap steel. Coal is the main reduction agent in blast furnaces, with integrated BF-BOF production releasing on average 1.9 tonnes of CO_2 per tonne of steel produced. EAFs are less CO_2 intense, with an emission factor of 0.4 tonnes of CO_2 per tonne of steel. Due to the high share of EAF steel in Europe, average EU emissions per tonne of steel is 1.3 tonnes CO_2, versus a global average of 1.4 tonnes. Nevertheless, European steel production emits more than 200 Mt of CO_2 per year, corresponding to 5% of total European GHG emissions.

Of all the materials studied in this report, steel is the most circular by far. An average of 85% of end-of-life steel in the EU is collected for use in the production of new steel. Globally, recycled steel accounts for a third of production, and it is expected to overtake virgin production by 2050. Steel also maintains high quality through the recycling process. Sorting is easier than for many other materials, using simple magnetic processes. As importantly, used steel can be reprocessed to very high quality and serve a wide range of uses. While recycling in the EU predominantly makes 'long' products, in the US it is common also to make flat steels from steel scrap. Finally, the international market for steel scrap is well developed and standardised.

Exhibit 6

STEEL DEMAND AND LIFETIME IN THE ECONOMY VARY BY END-USE SEGMENT

EU STEEL LIFETIME IN THE ECONOMY
NUMBER OF YEARS (% OF TOTAL STEEL PRODUCTION, 2017)



SOURCE: EUROFER (2018) AND PAULIUK ET AL. (2013).[8]

2.2 VALUE PRESERVATION THROUGH THE STEEL USE-CYCLE

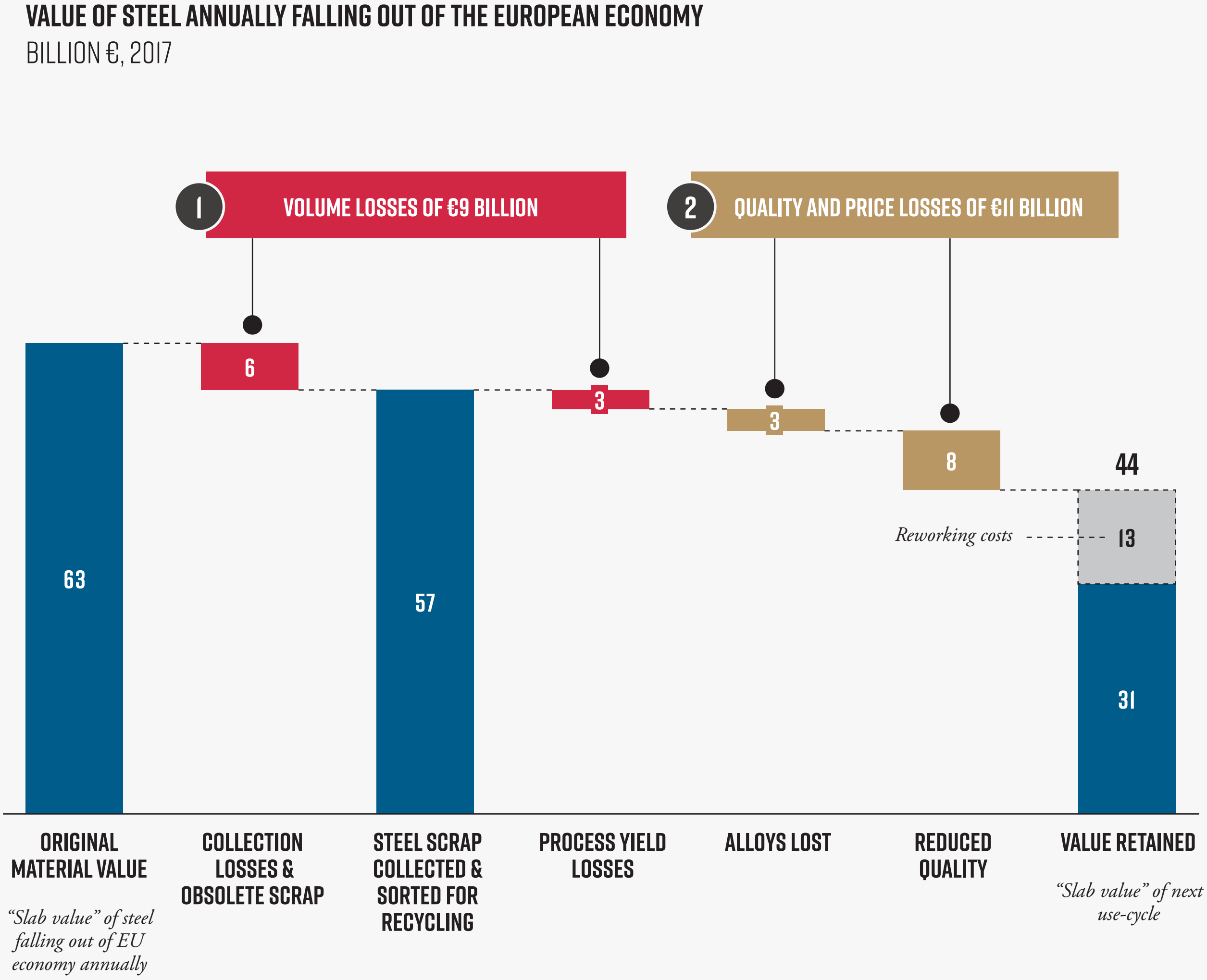
Our assessment of steel's value development is shown in Exhibit 7. It shows that after one use cycle, our best estimate is that out of an original value of €63 billion worth of steel that reaches end-of-life each year, about €44 billion (including reworking costs), or 69%, is preserved in the next use cycle. This section first describes the analysis, and then discusses the results and uncertainties in this estimate.

The original value of steel, €63 billion, that falls out of the European economy each year is defined as the value of steel slabs of different grades (non-alloy, stainless, and other alloys). This is a natural starting point for the analysis for several reasons: First, at the slab stage, no product value from downstream processing (e.g. hot rolling, cold rolling) has yet been added to the steel. Second, scrap-based steel is also turned into slabs before downstream processing, so we can look at a full steel cycle from slab to slab. Finally, slabs are traded, so it is possible to find market prices for them. Concretely, the estimate is based on a backwards calculation from annual scrap volumes produced (from EUROFER) and an estimated collection rate in Europe of 85% for old scrap and over 95% for new scrap and prompt scrap directly recycled in conventional steel making process (from Pauliuk et al. 2013 & expert interviews). The price of the original steel slabs is based on import/export data from Eurostat for different types of primary slabs, from €430-1,800 /t slabs (non-alloy, stainless and other alloys). Note that the collection rates differ depending on the type of metal, for example stainless steel is collected at a higher rate than non-alloy steel, given its relatively high value.

The value retained estimate, €31 billion, is the next step of the analysis. The estimate is based on steel scrap prices from Eurostat's import/export data (from €250-1,050 /t depending on the alloy) and EUROFER data on annual steel scrap produced (105 million tons, after yield losses). On top of this, to make an apples-to-apples comparison with the original value of steel slabs, we add the cost of reworking the scrap into new slabs, €13 billion. This figure estimates the average production cost (€120 /t steel slab) of reworking steel scrap in an EAF, including capital costs, energy, logistics, maintenance, etc. These reworking costs are near-unavoidable, but can be reduced with increased processing efficiency, improved scrap quality, and lower electricity prices.

Exhibit 7

EACH YEAR, €19 BILLION IN MATERIALS VALUE OF STEEL IS LOST

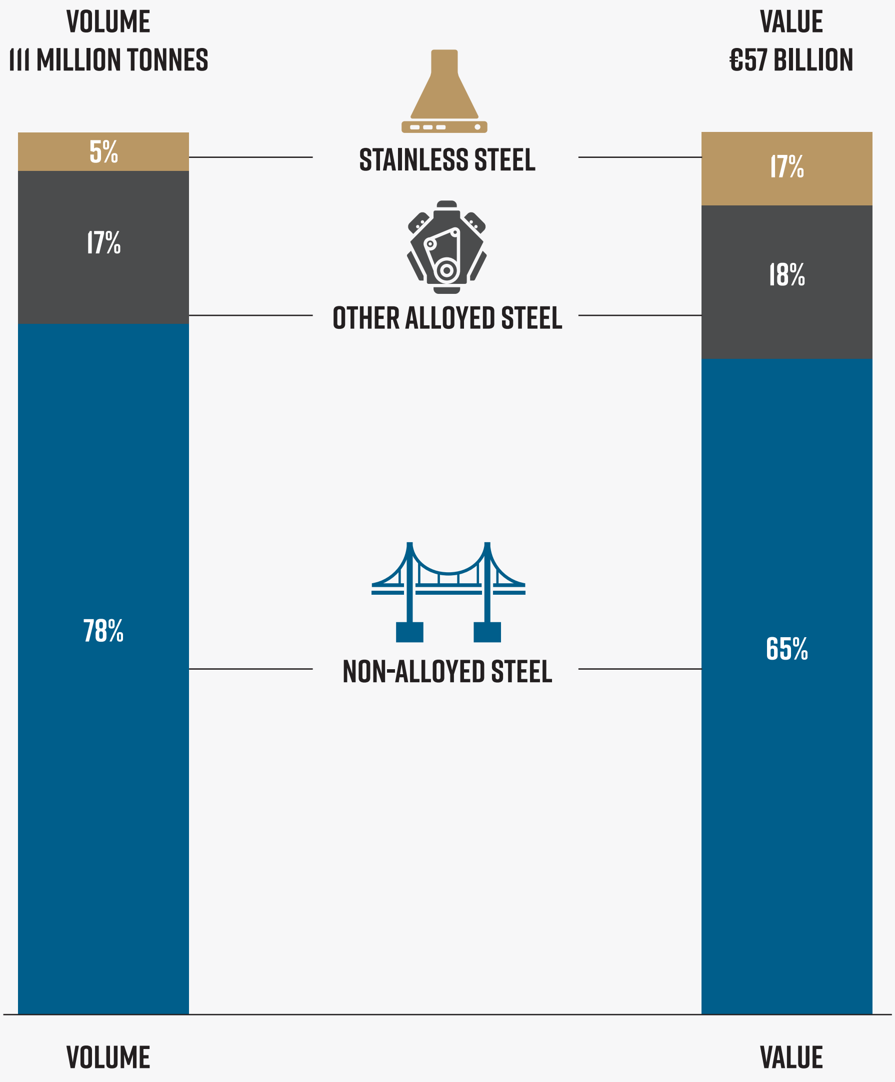


NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP TO TOTAL DUE TO ROUNDING

SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE[9]

Exhibit 8

VOLUME AND ORIGINAL MATERIAL VALUE OF STEEL COLLECTED FOR RECYCLING



SOURCE: MATERIAL ECONOMICS ANALYSIS, BASED ON MULTIPLE SOURCES, SEE ENDNOTE[10]

Collection losses amount to around €6 billion annually. Out of around 124 million tonnes of steel reaching end-of-life (including internal scrap in conventional steel making), 111 million tonnes are collected for recycling, while 13 million tonnes with a value of €6 billion are not recycled. This large amount of non-collected steel may come as a surprise to many in the industry, but shows the difficulty of reaching 100% circularity for any material that is in widespread use. Important sources of losses include steel structures that are abandoned but or left in place (e.g., underground); losses through corrosion; a small share that is landfilled due to incomplete separation (e.g., in construction waste); a small share of scrap from manufacturing that goes uncollected; and some flows that are collected but incorrectly sorted (e.g. scrap in fillers for construction). Exhibit 8 shows a break-down of the scrap collected into different grades, and illustrates the major value differences between grades.

Process yield losses occur when collected scrap is reprocessed into new crude steel. This is a key process parameter for all scrap-based steel-making, and considerable effort goes into minimising it. However, some 4-5% of the metal is lost through vaporisation and iron oxidation. One reason is that the process for 'cleaning' scrap steel (removal of unwanted alloying metals, or other contamination such as coatings) can be very invasive, and therefore comes at the price of some unwanted metal losses.[11] The losses amount to around 5 million tonnes, or €3 billion lost value, per year.

Alloy value is lost when scrap with different alloy content is mixed before being reworked into new steel. Taking a step back: Alloy metals are added to steels to tailor-make their material properties. Common alloy metals include manganese, vanadium, and molybdenum, but there are many others. They are often added in small quantities, but are typically much more expensive than steel and so represent a larger share of the value. When scrap is reworked into new steel, however, alloys are largely lost. Instead of improving material properties, they are often neutral or even detrimental to the next user of the steel, and therefore removed. This, too, is a price paid for the purification of lots of different scrap flows into 'neutral' iron raw materials. The amount lost is €3 billion per year, based on the difference in price between alloyed steels when first produced versus when returned as scrap. Much of this can be accounted for simply through the loss of important metals to the slag formed when remelting. However, some share is likely also due to the composite properties of having the precisely right alloying mix for a given application.

Stainless steel is an important exception to this. In stainless steel, worth much more than non-alloyed steel as shown in the exhibit above, nickel and chromium constitute only 25% of the volume but 70% or more of the material value.[12] Stainless steel is easy to recognize and separate, and it is largely circulated in its own steel loop. This means most of the alloy value is maintained for stainless steel, but according to expert interviews approximately 20% of the alloy value is lost also for stainless steel.

Quality losses estimated at €8 billion annually also occur. The above considerations still leave a residual 8 bn Euro difference between the value of steel scrap and that of steel slabs. A number of factors explain this. One is that some categories of steel scrap are difficult to handle, for example, because their remelting requires heavy processing, or because they contain unwanted elements that are difficult to remove. Another is that some scrap comes in formats (e.g., very large parts) that require additional processing before they can be charged in an EAF. There are many other considerations that complicate the use of scrap, and which thus drag down the average value. This value is the most uncertain in our calculation. The value of virgin steel slabs and of scrap are relatively certain.

In conclusion, the total value losses are around €19 billion annually. There are substantial uncertainties in these estimates; for instance, the underlying research we have used on collection losses gives somewhat different estimates, and the statistical classification into just three overall steel grades leaves out many nuances. The calculation of quality losses is particularly difficult to pin down, given that it depends a lot on other estimates. For example, if reworking costs were €150/t instead of the €120/t that we use here, the 'residual' that we label quality loss would be less than €5 billion instead of €8 billion, or 40% less. Still, we believe the analysis identifies and quantifies many interesting improvement opportunities, and that value opportunities in this order of magnitude should be very relevant to explore in an industry that is plagued by overcapacity and thin margins. Some of these opportunities already are being addressed, e.g. improving the efficiency in EAFs, while others (e.g., the sorting of scrap at source for new scrap) receive much less attention.

2.3 COPPER – A ROAD BLOCK TO A EUROPEAN STEEL MARKET BASED ON SECONDARY STEEL

As noted above, steel is unusually circular also in quality terms. Much of the 'memory' of past uses can be erased in remelting, albeit at the price of some loss of both iron and alloying metals. Secondary steel thus can be used for many of the same things as virgin steel, contributing to low loss of quality and therefore of value.

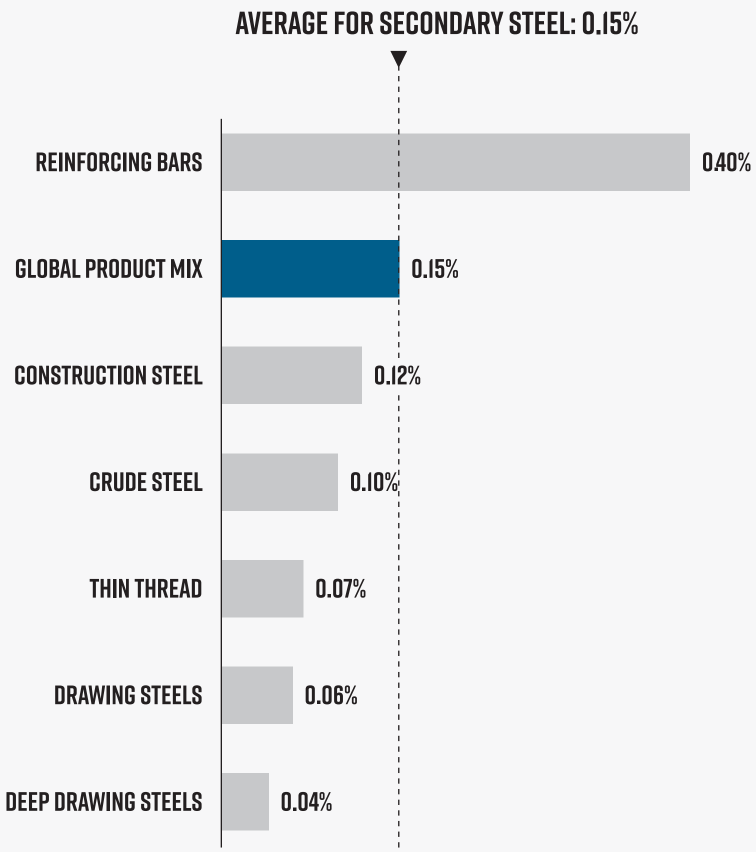
However, there are significant challenges to this. In particular, contamination with copper can significantly reduce steel quality. Unlike many other alloys or tramp elements, copper is very difficult to separate from the steel slag during remelting, and it profoundly affects steel strength and quality. Scrap includes copper both because it is used in rust-resistant steel and, more commonly, due to insufficient sorting that leaves copper products such as small electrical motors and cables in the scrap mix.

Structural steel can contain up to 0.40% of copper, but other steel grades are far more sensitive and, on average, cannot have more than 0.15% copper concentration across product categories (there are exceptions; for instance some roller bearing manufacturers manage to produce high-strength products with scrap-based processes). A large amount of copper already has been added to the European steel stock (e.g. average copper content of 0.22% in Sweden) and more is added every usecycle. Average global scrap currently has a copper content of 0.15% and already exceeds the limit for a large share of high-end steel products (Exhibit 9).

Exhibit 9

COPPER CONTAMINATION IS ALREADY SO HIGH THAT RECYCLED STEEL REQUIRES DILUTION WITH PRIMARY STEEL TO BE ABLE TO FIT SEVERAL PRODUCT CATEGORIES

MAXIMUM CONCENTRATION OF COPPER IN STEEL FOR DIFFERENT STEEL PRODUCTS
WEIGHT-% COPPER



SOURCE: MATERIAL ECONOMICS ANALYSIS IN (MATERIAL ECONOMICS 2018), BASED ON DAEHN ET AL. 2017

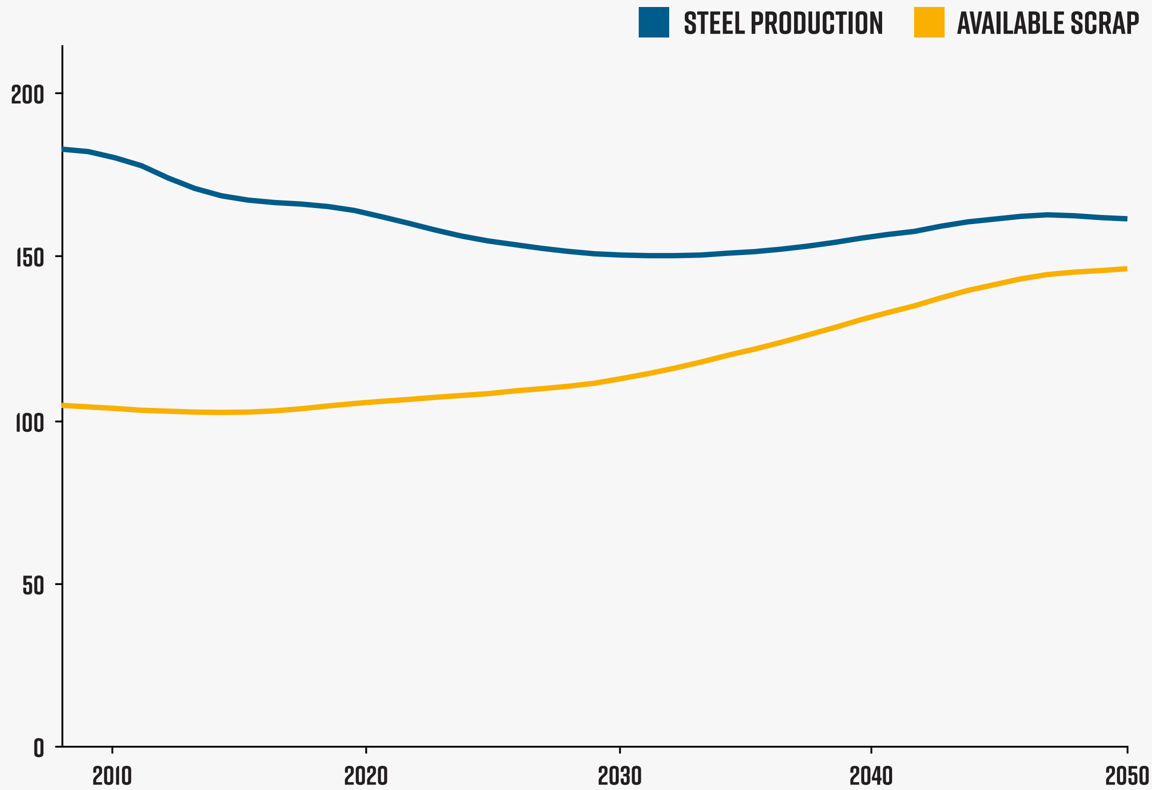
This becomes a problem as the steel stock saturates. As noted, European steel demand already is driven mainly by the need to replace products and structures at the end of their useful life. Looking ahead, end-of-life steel would be sufficient to meet most of the future growth in steel demand. Primary production is still required, but only for net additions to the steel stock, which primarily expands in rapidly growing developing countries. In Europe, as much as 90% of steel demand theoretically could be supplied with scrap by 2050 (Exhibit 10). Well-maintained, circular steel flows thus are a very attractive industrial opportunity.

Using a larger share of scrap in production, however, increases the problem of copper contamination. To date, the copper problem largely has been handled by dilution with primary steel. This has been enough, and has meant that quality losses through copper contamination do not show up as a large effect in the European analysis above. But dilution is not a long-term solution: The dependence on virgin material to dilute the copper content will prevent a closed circular system where steel can be used infinitely. In fact, the effects of copper would limit the circularity of steel globally within 2-3 decades unless corrective action is taken.[13] Limiting copper contamination to avoid this scenario would not only preserve economic value but also reduce future greenhouse gas emissions from steel production.

Exhibit 10

EUROPE COULD OVER TIME FULFIL MOST OF ITS STEEL DEMAND USING SCRAP-BASED PRODUCTION

STEEL SCRAP AVAILABILITY AND STEEL PRODUCTION IN EUROPE
MILLION TONNES PER YEAR



NOTE: AVAILABLE SCRAP NOT INCLUDING PROMPT SCRAP DIRECTLY RECYCLED IN CONVENTIONAL STEEL MAKING PROCESS

SOURCE: MATERIAL ECONOMICS MODELING, SEE ENDNOTE[13]

40 YEARS

AVERAGE LIFETIME OF STEEL PRODUCTS

in the European economy

2.4 A POSSIBLE PATH FORWARD

Both globally and in Europe, steel could be more circular than it is today. This section outlines five action areas that would together address the value losses identified above, and make steel much more circular: see Exhibit 11.

Europe is particularly well-positioned to develop a circular steel industry: (i) It is a mature market where scrap volumes almost match demand for new steel products, (ii) It has an unusually high proportion of scrap from the large European manufacturing industry, and this scrap source is better placed to enable standardised and differentiated flows of different scrap grades than post-consumer scrap, (iii) It already has a well-established scrap market which is relatively sophisticated compared to other world regions, and (iv) a number of major manufacturers are looking at greater use of EAF production as part of the push to make low-carbon steel (e.g., by using hydrogen-based production routes), and could therefore also use more scrap in their products.

Exhibit 11

SUMMARY OF RECOMMENDATIONS FOR A FULLY CIRCULAR EUROPEAN STEEL INDUSTRY

1 IMPROVE SORTING & COLLECTION

- *Improved systems to collect end-of-use scrap*
- *Improved separation at end of life*
- *Techniques for alloy-to-alloy sorting*

2 REDUCE STEEL SCRAP AND CREATE CLOSED LOOPS

- *Closed loop solutions with predictable and known scrap flows*

3 REDUCE COPPER CONTAMINATION

- *New metallurgy to increase copper tolerance*
- *Develop techniques on separation of copper from steel*
- *Improved sorting of steel scrap to minimise copper contamination*

4 DESIGN WITH END-OF-LIFE IN MIND

- *Increased incentives for design and product development with end-of-life value recovery in mind*
- *Techniques for automated and cost-effective disassembly and sorting*

5 DIGITISE THE SCRAP MARKET

- *Scrap market with overview of the scrap falling in near real-time*
- *Effective tracking of steel grades and alloys*
- *Track and measure the value-recovery of steel, not only volumes*

ACTION AREA 1: IMPROVE SORTING AND COLLECTION OF STEEL SCRAP

To retain more material value, losses in the production and collection of steel scrap must be reduced. Systems to collect end-of-life products need to be set up more widely, with expanded capacity and accuracy as volumes of steel scrap grow. New initiatives and incentives will be needed to encourage consumers to recycle their products and ensure that iron and steel products are separated when buildings are demolished. It is difficult to gauge how much more steel could be collected – as noted, very few materials have reached higher collection rates. Nonetheless, some of the value should be possible to recover.

Sorting different waste categories is already far better today than just a few decades ago, but there are still many opportunities for improvement. The technologies used to identify different steel grades has developed immensely in the past three years and are still growing quickly. The market also is moving towards larger players with better capabilities to differentiate between a larger number of steel grades. For example, several companies are now actively helping customers with internal systems to keep different grades of steel separate at the source. At the same time, more advanced sorting and logistics will require a change in processes both in the manufacturing industry that produces metal waste streams and in the major end-of-life flows of car scrapping, building demolition, municipal waste, etc. Car scrapping is especially important as it is an important source of copper contamination.

Alloy-to-alloy sorting is another key component to avoid downgrading and price losses for recycled steel. If the contents of steel used for secondary production are known, steel scrap can be mixed to more closely correspond to end products. A study from Japan found that with a high level of scrap sorting, the amount of chromium and nickel in steel scrap that can be recycled and used in new steel products would be 250% higher than in a system with poor sorting (from less than 30% recovered to more than 70%).[15] The technologies required to achieve this are under rapid development. For example, laser-induced breakdown spectroscopy technologies are improving and quickly decreasing in cost, making it possible to quickly determine the content of alloys. When this is known and more detailed scrap standards are developed, a much more differentiated marketplace could be created, so steel manufacturers can specify and obtain the scrap required also for high-end products.

ACTION AREA 2: REDUCE AMOUNT OF NEW STEEL SCRAP GENERATED AND CREATE CLOSED-LOOP SOLUTIONS

Inevitably there will be value losses in recycling steel, as there will always be process losses and a cost of reworking, which lowers the net value of steel scrap. Therefore, one important objective is to reduce the amount of steel scrap that is generated in the economy. There are several examples where steel scrap is generated but could be significantly reduced.

Manufacturing scrap streams hold a lot of potential as the alloy content is known and provide cleaner streams of carbon steel. There is significant potential for scrap-heavy industries to create closed-loop solutions with scrap flows where contents are both familiar and predictable. Closed-loop solutions would enable the industry to retain larger parts of the embedded materials value, which offers a significant business opportunity. An example where closed-loop solutions could be profitably set up is in the automotive industry, where manufacturing scrap is clean and possible to recycle in a closed-loop system into similar products without losing too much materials value. There are already examples of major consumers and producers that have established essentially closed systems, but there is significant potential in expanding this to more actors and producers across the value chain.

ACTION AREA 3: REDUCING STEEL CONTAMINATION – ESPECIALLY BY COPPER

The effect of copper on steel, as described earlier in the chapter, has been known for a long time. So far the problem has been relatively easy to handle, as primary steel production has substantially outweighed scrap-based production. Copper contamination becomes a much bigger concern as secondary steel is used for a wider range of purposes, including the most demanding uses requiring low concentrations. As noted earlier, without solving the contamination problem, the world would need to produce additional primary steel just to dilute the contaminated steel stock. In fact, unless the copper problem is solved, other circularity measures such as increased collection and reduced losses will have limited impact. Five key strategies can address the copper issue:

- **Improved separation at end-of-life:** The first step is to avoid adding high-copper scrap to otherwise clean flows, something which is often done today with e.g. end-of-life vehicle scrap. Beyond this, it will be necessary to increase the separation of copper and steel in the recycling process. This already happens to some extent, but practices vary widely. The extent of sorting fluctuates with the copper price, due to the costly, manual work of removing copper. To avoid the cost of manual labour, technologies for automated sorting are being developed. More closed-loop recycling also would be necessary to keep certain scrap flows pure and enable the use of scrap in particularly copper-sensitive applications.

- **Product design for reduced contamination:** The design of products also can improve the sorting process. Design principles for recycling and for disassembly could facilitate the removal of copper components by making them easier to identify, access, and remove. Material substitution is sometimes an option, such as replacing copper cables and wires with fibreoptics or aluminium equivalents, which are easier to handle.

- **Metallurgy to increase copper tolerance:** Production processes can be designed to be more tolerant to copper by avoiding the temperature interval at which copper causes problems. Although not in itself a long-term solution, it mitigates the problem.

- **Separation of copper from steel:** There is currently no commercially viable method for removing copper from steel once it has been added, and some assessments are pessimistic that this will ever be possible. Nevertheless, research is ongoing into potential methods such as sulphide slagging, vacuum distillation, and the use of oxygen or chlorine gas.

- **Labelling and obligatory sorting in automotive sector:** As shredding cars is a significant source of copper contamination, Europe could consider whether it is possible to design targeted regulation to reduce this source of pollution. This could include, for example, requiring automotive manufacturers to clearly label certain components with high copper content and make the sorting of these components obligatory. Both the costs and benefits of such regulation needs to be carefully assessed, of course, before such steps are taken.

ACTION AREA 4: PREVENT DOWNCYCLING THROUGH DESIGN AND CHOICE OF MATERIALS

Just as in other material categories, the way products are put together has a major impact on how the materials can be separated and collected when recycled. In most cases, there is little incentive for product manufacturers to consider this, making product design a significant barrier to the production of secondary steel. Particularly important cases are vehicles and buildings, which historically have been designed in a way that makes recycling (and reuse) difficult and uneconomical. To improve the case for the automotive industry, a much more automated disassembly of vehicles is likely required, rather than the fragmentation that currently occurs when shredding vehicles. Improved dismantling is already happening to a much greater extent today in Japan than in Europe, and new automation technology should make it far more economically viable in the future.

The choice of steel grade in products is often optimised based on cost, properties and function, but not on the consequences for the recovery of value at end-of-life. Even relatively simple products such as exhaust systems in cars can contain a wide variety of steel grades, with marginal cost savings that are rational from a production perspective, but which cause major obstacles at recovery. Finding a better solution requires cooperation and a new focus on product development. Already, automakers strive to use recycled materials, but this only has become a widespread priority in recent years. There is a large opportunity in prioritising design approaches that take end-of-life into account – something which today is largely absent from many companies' product development.

ACTION AREA 5: DIGITISE AND MODERNISE THE SCRAP MARKET

Downgrading and other value losses could be avoided to a much higher extent in a sophisticated market for steel scrap with effective tracking of steel grades, scrap supply, and demand for new steel products. There is already a well-developed classification and standardisation at the EU level through the European Steel Scrap Specification. Taking advantage of alloy elements to a greater extent will set additional requirements on the scrap market, which means digitisation will be key and will include a detailed overview of the scrap generation in near real-time and an ability to match it against the ongoing production. This will probably require a larger geographic market to enhance the provision of increasingly narrow product categories. Today's scrap market is still far from this reality, but digitisation can reduce transaction costs and make it possible.

Secondary steel production also needs improvement to reach the quality of primary steel. If secondary production is to serve more demanding product groups, the quality losses in secondary steel needs to be mitigated, and a more developed market is required, matching scrap inputs to secondary steelmaking with the needs and tolerances of high-quality steel production. This is doable, as demonstrated by several producers who rely on a combination of good control of scrap supplies and advanced metallurgy to make some of the highest-quality steels in the world – entirely from scrap. It also would create new sources of value and business opportunity in a more advanced market for steel scrap.

PLASTICS

FROM WASTE TO VALUABLE MATERIALS

Summary

Plastics are important and versatile materials used throughout the economy, in packaging, cars, buildings, and countless consumer products. In the EU, 50 million tons of plastics are used every year, or 100 kg per person.

Most of these materials could, in principle, be recycled into new materials. However, we find that instead almost all of the materials value of plastics is lost in just one use cycle. Just 11% of the original value is preserved, through a mix of recycling in the EU, exports of waste plastics, and by using plastics as fuel. The value lost amounts to €55 billion per year, as plastics are landfilled, incinerated, or turned into materials with much less value than they originally had.

Addressing this must start by asking why so little of plastics – just 10% by volume - is in fact recycled into new materials in the EU. The answer spans the entire value chain – involving product design, collection systems, market regulation, lack of investment, and more. To increase recycling rates, policymakers and companies need to focus on materials value, and especially on the prerequisites for high-quality and therefore high-value materials.

11%

of the material value in plastics

REMAINS AFTER ONE USE CYCLE

3.1 INTRODUCTION – VERSATILE AND LOW-COST MATERIALS THAT ARE CRUCIAL TO OUR ECONOMY, BUT ENVIRONMENTALLY PROBLEMATIC

Plastics are versatile, durable, and low-cost materials that are used widely across modern economies. More than 30 types of plastics are in common use, with dif-ferent properties and applications in numerous sectors: from cars, to buildings, to countless consumer products, to packaging. In the EU, some 50 million tonnes of plastics are used each year, or 100 kg per person.[16] The demand for plastics in the EU continues to grow at an annual rate of 2–3%, driven by trends such as a continued shift to lighter materials in packaging, increased use of plastics in automotive applications, and increased demand for insulation to improve buildings' energy efficiency.

Plastics differ from other material in important respects. One is the short lifetime of products: More than 40% of plastics are used in packaging and consumer products with less than a one-year life-time before they reach their end of life. As a result, the volume that exits economic use (42 Mt per year) is almost as high as the total used every year (50 Mt). These 42 Mt have an original material value of more than €60 billion, and a large share is, in principle, recyclable. Yet, as we discuss below, very little of this value is in fact captured, both because most plastics are not recycled, and because the materials produced through recycling have lower value.

The environmental impact of plastics is another source of controversy. The very properties that make plastics attractive when used in the economy – durability, light weight, etc. – become a problem when plastics leak into nature. The full effects of plastics that end up in the oceans, and especially microplastics, are yet to be understood, but it is clear that current trends could cause major environmental harm. The EU and India, among others, have banned certain single-use plastic products as one response to the crisis of plastics in the oceans.[17] In addition, plastics have a major CO_2 footprint. For one part, major CO_2 emissions are created in the extraction and refining of raw materials as well as in the production of plastic polymers; for another, plastics are literally built out of fossil carbon, which is released if plastics are burnt at their end of life. The carbon flows involved here are substantial: The carbon footprint of plastics used annually is in fact larger than that of all CO_2 emissions from aviation.

This chapter applies the lens of materials value on the plastics use cycle. It aims to elucidate why so much value is lost, and where there is potential for improvement. We find a far-from-circular system today, and identify several innovation and business opportunities to capture more of the value currently lost in the system.

€ 55 BILLION

of material value is lost annually

IN THE USE OF PLASTICS IN EUROPE

3.2 VALUE PRESERVATION – ONLY 11% OF THE ORIGINAL MATERIALS VALUE OF PLASTICS REMAINS AFTER ONE USE CYCLE

Our assessment of the value of plastics is shown in Exhibit 12. The plastics that exit its use cycle each year had an original materials value of €62 billion. However, only €6.7 billion, or 11%, of this value is preserved in a combination of the value of recycled material, and the value of the energy that is obtained as end-of-life plastics are burnt as fuel. To an overwhelming extent, plastics thus are a "use once" material, where the materials value first created in production is lost to the economy as products, packaging, and buildings reach the end of their first usecycle. This section describes the analysis that leads to this finding, and the implications for policy and business.

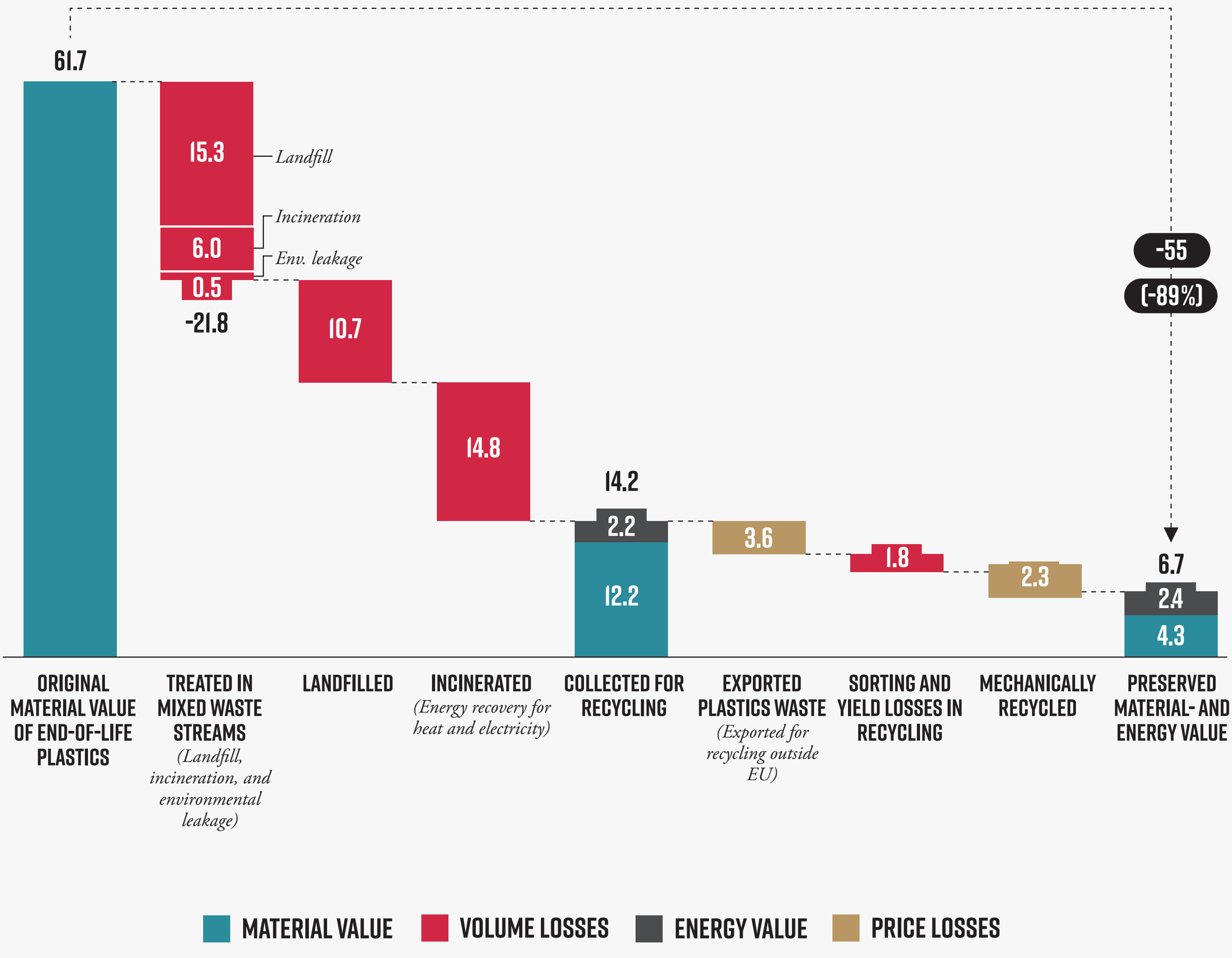
The original materials value of plastics is defined as the value of plastic resins. The price differs significantly between different types of plastics, and the value accounts for this by adjusting for the use-patterns of plastics across sectors. Resins are a natural starting point. It marks the point in the value chain before plastics starts to acquire 'product' (as opposed to 'material') values; for example, converted materials used in packaging derive their value also from additives, physical shape, and various performance guarantees. Resins also is the relevant comparison for recycled products, and are traded through standard contracts that make for transparent price comparisons.

The retained value of €6.7 billion is a composite of the value that plastics have in its various different uses at end-of-life. They range from the price of recycled resins, to the value of exported plastics waste, to the zero value of plastics that are landfilled. This is explained in more detail below.

Exhibit 12

EACH YEAR, €55 BILLION OF MATERIALS VALUE IS LOST IN THE USE OF PLASTICS

ACTUAL END-OF-LIFE VALUE AND VALUE LOSS COMPARED TO THE ORIGINAL VALUE OF END-OF-LIFE PLASTICS
BILLION € PER YEAR



SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.[18]

3.2.1 VOLUME LOSSES

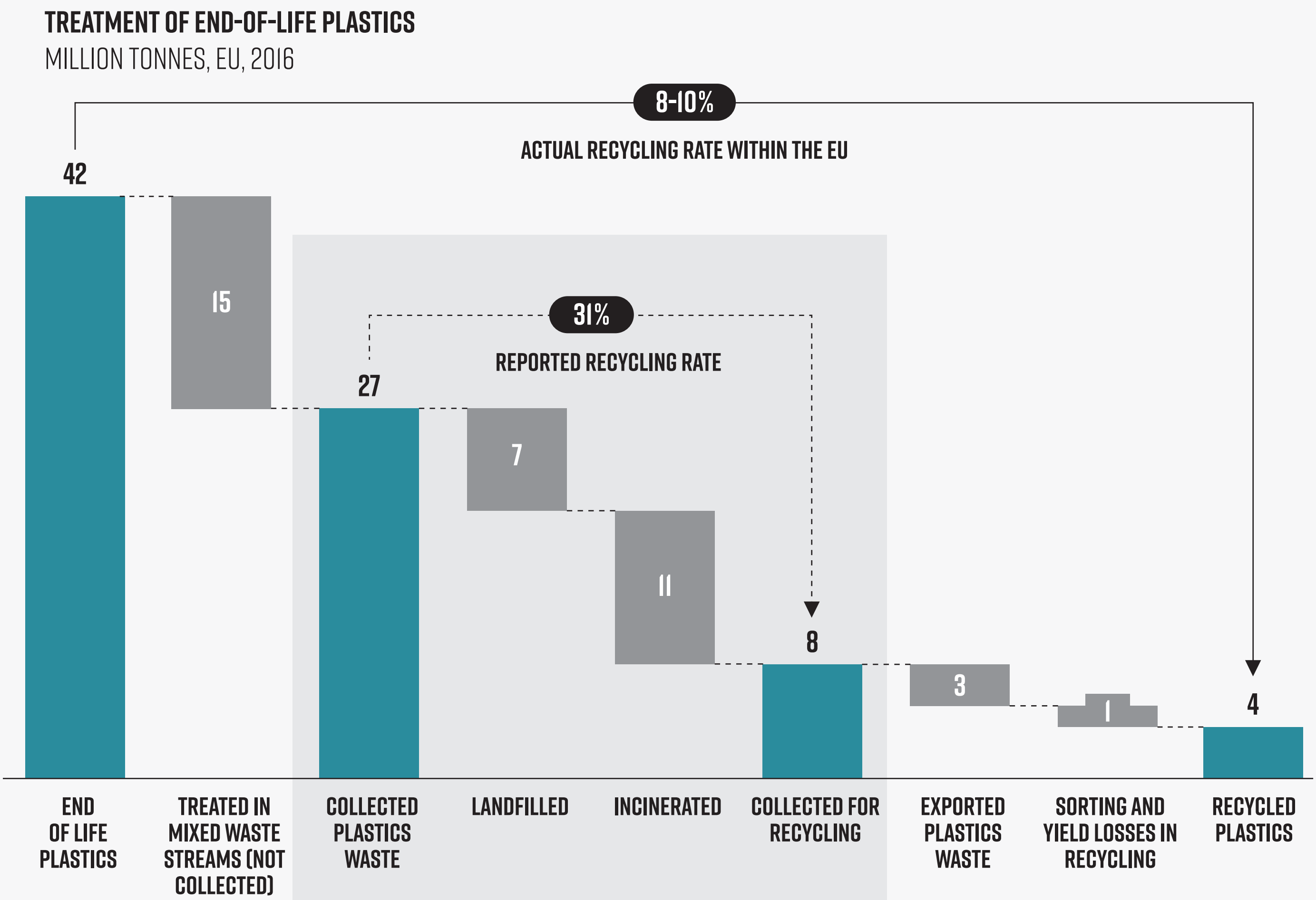
The volume of plastics that reaches the end of its use cycle in the EU is 42 million tonnes (Exhibit 13) . This can be compared with the annual use of 50 million tonnes noted above. While the total stock of plastics in the economy thus increases by some 8 Mt per year in the EU, the large majority of plastics used is replacement of materials that exit use.

The volume recycled is far lower. Our analysis thus concludes that the volume of recycled polymers produced in the EU amounts to just 4 Mt, consisting predominantly of recycled packaging waste.[19] By this measure, the recycling rate for plastics is just 10%. Of the remaining 90%, 11 Mt are incinerated. The balance – making up nearly two-thirds of the total – is either exported or landfilled, or otherwise treated as general mixed waste.

This number may come as a surprise. After all, the most cited number for plastics recycling in the EU is that almost one-third (31%) of plastics are recycled. Two factors explain the large difference in estimates. In brief, the official rate is based on the share of separately identified plastics waste that is sent to recycling. In contrast, our estimate is based on the share of total end-of-life plastics that actually becomes recycled plastics.[20] As we discuss below, the EU has realised that the current measure is an unhelpful metric to steer by, and official estimates therefore also will be revised.[21]

Exhibit 13

THE ACTUAL PLASTICS RECYCLING RATE IN THE EU IS JUST 8–10%



NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP TO TOTAL DUE TO ROUNDING
SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES [22]


100 KG
OF PLASTICS PER PERSON
are used every year in Europe

First, this measure does not capture all plastics.

Plastics in mixed waste streams. Waste statistics report some 27 Mt of plastic waste annually. However, bottom-up accounting of waste fractions is known to yield incomplete measures. A standard way to estimate end-of-life flows is instead to combine estimates of the total amount of materials used with the typical lifetimes of the diverse group of products, packaging, and structures for which it is used. Such stock-based models are the standard way to estimate recycling rates for steel, aluminium, and more. Doing this for plastics, we find that the end-of-life volume is 42 million tonnes, as noted above. This also implies that waste statistics fail to capture some 15 Mt of end-of-life plastics. These flows become part of mixed waste streams, and therefore also are handled much like these are, through a combination of landfilling (10.5 Mt) and incineration (4.5 Mt).

Landfill. In addition to these mixed waste streams, 7.4 Mt of plastics are directly reported as landfilled, bringing the total to 17.9 Mt. The materials value of these flows is entirely lost, with zero residual value. Indeed, any landfilled plastics impose a cost rather than capture a value, by adding to the total expenditure on waste management.

Energy recovery through incineration. Of the collected plastics waste, about 11 million tons of plastics are reported as incinerated. Together with the plastics, incinerated in mixed waste streams, incineration thus is the second most common destination for end-of-life plastics with 17.2 Mt per year. This in turn takes many different forms. Plastics are a major component of refuse-derived fuels that have become a major energy source for the cement sector. They also are used in the production of heat and power, with more value captured when used in combined heat-and-power plants as opposed to the electricity-only plants that make up one-third of EU waste-to-energy capacity. These uses thus capture some of the value, but in all applications, the value of energy is much lower than the value of the material. Indeed, as much as 90% of the original value is lost when plastics are incinerated, as we discuss below.

Exports of plastic waste. Accounting for the above, some 8 Mt of plastics enter some form of recycling process. In 2018, 3 Mt was exported. The fate of exported plastics has become a major point of controversy. For example, one study found that as much as 7% of exported polyethylene, the most common form of plastic resin, ended up leaking to the ocean. In pure value terms, mixed plastics waste exports command a low price, being in rich supply but having few valuable uses.

Recycling in the EU. The plastics remaining in the EU are handled in recycling plants, where further losses occur. The installed capacity of LDPE, HDPE, PP, and PET recycling in EU was 6.1 Mt in 2018/2019, corresponding to just 15% of the total end-of-life plastics (42 Mt).[25] These plants face a formidable challenge. There are tens of types of plastics, and they are often used in combination with other materials. This makes a lot of it difficult to recycle to a high-quality output with today's technologies. Plastics waste that is contaminated, mixed with other materials such as aluminium and paper, laminates of different polymers, and thermosets are examples of plastics that are sorted out in recycling. Plastics types for which there is no secondary market, such as low-quantity polymer streams, are also sorted out and sent for incineration or landfill. For these reasons, as much as 26% of the plastics processed are lost either in sorting or in the recycling processes. These 'yield losses' are either incinerated or landfilled. Remaining after this are the 4 Mt of recycled plastics noted above.

3.2.2 PRICE LOSSES

The above account describes what happens to plastics – but it does not explain why. To understand this, it is necessary to adopt a value perspective. After all, the fact that the effective recycling rate for plastics is so low is because current systems do not manage to produce materials at the quality and price required. The loss of value therefore also is often the root cause of the volume losses – i.e., that plastics are landfilled, incinerated, or exported.

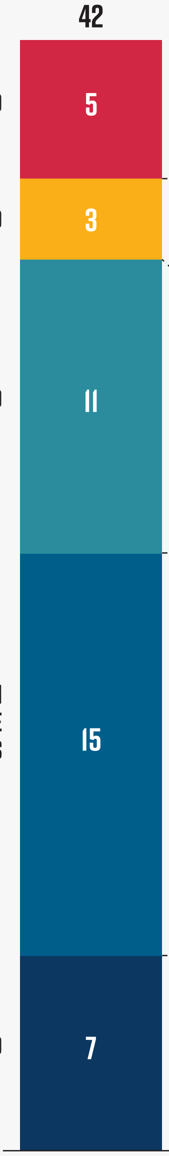
Putting the above volume flows in value terms is highly illuminating. The original value of plastics existing use is as much as €62 billion. Of this, material with an original value of €12 billion makes it into a recycling system. However, further losses then accumulate: because exported plastic waste commands low prices, because many of the materials that are processed cannot be turned into materials with any value, and because the prices obtained for mechanically recycled plastics are much lower than those of their virgin equivalents. Accounting for all this, the value of exported or recycled polymers is around €4.3 billion, while that of energy recovery is €2.4 billion. In total, this makes up the €6.7 total recovery noted above.

A more detailed overview of value recovery for plastics is seen in Exhibit 14. As this shows, most of the original materials value is lost in the most common destinations for end-of-life plastics. Landfilled plastics retain no value, but impose costs. Perhaps surprisingly, incineration ('energy recovery') also retains very little value, corresponding to just 10% of the original value that the plastics had as resins. Finally, recycling – either via exports or within Europe – also sees most of the value lost

Exhibit 14

LESS THAN HALF OF THE ORIGINAL VALUE IS PRESERVED IN THE END-OF-LIFE TREATMENT OF PLASTICS

TREATMENT PLASTICS
MILLION TONNES, EU, 2017



	Million tonnes	PROCESS & VALUE LOSSES	VALUE RECOVERY
RECYCLED	5	• *Mechanical recycling of plastics (quality downgrading and yield losses), including losses from plastics that are collected for recycling but sorted out (non-recyclable, small polymer streams, aged and contaminated plastics, etc.)*	45% *(incl. yield loss)*
EXPORTED	3	• *Plastics that are collected and exported for recycling outside of the EU, e.g. Malaysia and Indonesia* • *Losses due to low export prices and uncertain handling*	20%
INCINERATED	11	• *Plastics that are used as fuel to produce heat and electricity for district heating, cement production etc. Losses as energy value lower than plastic value* • *Incineration of plastics without energy recovery, hence 100% value loss*	10%
TREATED IN MIXED WASTE STREAMS	15	• *Plastics waste that is not sorted out separately but part of e.g. municipal waste and sent to landfill, incineration etc. (loss of potential value)* • *Unmanaged plastics waste that ends up in nature and oceans (damage to humans and natural life)*	0-5%
LANDFILLED	7	• *Sorted plastics waste sent to landfill causes loss of potential materials value* • *Landfill also has negative impact on local environment and risks of leakage*	0%

SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.[26]

On average, we estimate the total value recovered through mechanical recycling to be 45%, based on a weighted average of different recycled polymer streams. This includes the yield losses, so is calculated on the basis of plastics sent for recycling. The reasons for the lower prices is that recycled plastics rarely can be used for the same application in the second use cycle, but have to be 'downgraded' to less demanding applications. The reasons vary, but include that difficulty in guaranteeing performance or provenance limits their applications, or just that their physical properties are either worse (in terms of colour, smell, strength) or unpredictable. As a result, even the small quantities of high-quality flows typically trade at prices of 50-75% of the corresponding virgin polymers.[27]

This average hides significant variability. At one extreme, food-grade recycled PET plastic ('r-PET') is in fact worth more than virgin PET ('v-PET'). This is because it is one of few polymers where a closed loop can be established, and for which there is a very substantial demand signal, with major bottled beverage companies having pledged to significantly increase their use. Policy also drives this, with a minimum recycled content in plastics bottles mandated under the Single Use Plastics Directive. As a result, food-grade rPET has gone from trading roughly at parity with v-PET to, commanding a premium of as much as 40-60%. However, this is still a small market. Around 80% of PET bottles that are instead downcycled become polyester fibres for clothing, carpets, strapping, and other non-packaging applications.[28] Nonetheless, the value loss is smaller for PET than for other polymers.

At the other extreme, many other fractions in principle available from recycling plants are in practice of no or little value. Rather than adding value, these can become unwelcome side flows that recyclers have to handle. The fraction that has no value becomes the 'yield loss' noted above, but there also are fractions that can be sold only at a low value as fuel. They also include some low-grade materials that can be used in bulk applications, often away from consumer exposure. These flows also risk some questionable side effects. By definition, low-quality, low-value materials are incapable of replacing virgin materials on a 1:1 basis. Mandating their production therefore risks a 'rebound' effect whereby total materials use in fact increases, compromising the environmental value.

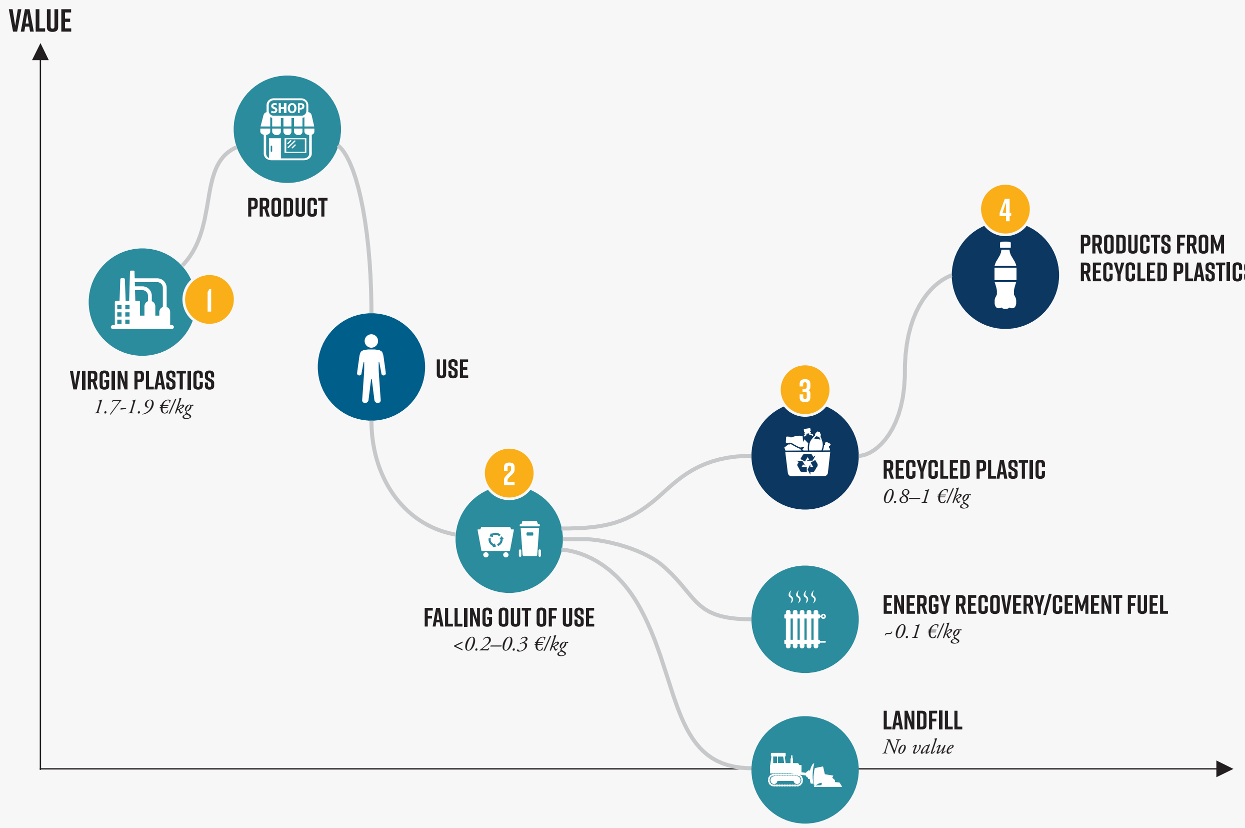
The value of exported plastics waste illustrates this dynamic. Some 3 Mt of plastics are exported annually. These are sold at around €180–250 per tonne, compared with €950–1950 for primary plastics of the major polymer types, implying a value loss of 80%.[29] This loss is also likely to increase, as China and other Asian countries have introduced bans and drastically reduced the volumes of plastics waste they are willing to import. This lowers prices and means EU exports will likely decrease, and flows will shift to other countries (mostly in Southeast Asia).[30]

These low value recovery rates make the business case for circular plastics handling very challenging. They have to be set against the cost of plastics waste collection, sorting, and recycling, and also against low current market prices of virgin polymers. As long as value losses are this substantial, increasing true recycling rates also will be highly challenging.

In conclusion, current practices are capable of retaining just 11% of the original materials value in one use cycle. There are of course uncertainties in these estimates, but the broad picture is clear: a circular system where recycled materials can take the role of their virgin counterparts is a long way off in the case of plastics. To resolve this, the crucial role of materials value and quality must first be recognised.

Exhibit 15

USED PLASTIC CAN HAVE DRAMATICALLY DIFFERENT END-OF-LIFE VALUE: FROM NEGATIVE TO 100S OF € PER TONNE



1 VIRGIN PLASTIC

- *Value: 1.7–1.9 €/kg*
- *Large variation between plastic fractions, with special plastics worth up to 4€/kg*

2 PLASTIC FALLING OUT OF USE (END-OF-LIFE)

- *Clean plastic fractions can have a value of 0.2-0.3 €/kg*
- *Coloured and mixed fractions <0.1€/kg*
- *Plastic that cannot be recycled has little value or even represents a cost for handling*

3 RECYCLED PLASTIC

- *Material recycling: Lower quality vs. virgin plastic (50-60% of the value), ~0.8-1€/kg*
- *Energy recovery: Value compared to cost of replacement fuel ~0.1€/kg*
- *Landfill: without value, in Sweden negative value in the form of a landfill tax*

4 PRODUCTS FROM RECYCLED PLASTIC

- *Recycled plastic only used rarely in the same products (closed loop)*
- *Downgrading often occurs where recycled plastic is most often used in bags, flower pots, and other products with lower value*

SOURCE: PLASTICS EUROPE 2018; DELOITTE AND PLASTICS RECYCLERS EUROPE 2015; GEYER ET AL. 2017[31]

3.3 A POSSIBLE PATH FORWARD

The EU could sustain a much larger recycling industry than the few million tonnes of capacity that are in place today. But to get there, a major change on past practice will be needed. Today's recycling has its roots in waste management: specifying how volumes (e.g., of the plastics in packaging, or end-of-life vehicles) should be treated, and that it must be sent to recycling. The push has been almost entirely on the supply side, with much less attention to demand, or to the value of the materials produced. The potential is there – materials value could become the foundation of a lot of economic activity. But for this to happen, profound change will be required across the entire plastics value chain, as summarised in Exhibit 16.

Exhibit 16

IMPROVING PLASTICS RECYCLING WILL REQUIRE TRANSFORMATION ALONG THE ENTIRE VALUE CHAIN

	FROM	TO
1. RAW MATERIAL	**VIRGIN PLASTICS** *do not carry cost of externalities*	**VIRGIN PLASTICS** *carry cost for embedded carbon and other extealities*
2. DESIGN & PRODUCTION	**PRODUCT DESIGN** *does not bear costs for downstream externalities and costs*	**MATERIALS CHOICES** *design and business models with reuse and recycling as intended destination at end of life*
3. USE & DISPOSAL	**CORRECT SORTING AND DISPOSAL** *often inconvenient for consumers and businesses*	**CONVENIENT SORTING AND DISPOSAL** *of waste for consumers and businesses that enables high collection rates*
4. COLLECTION	**POLICY AND SYSTEMS** *focus on collection volumes – similar to other 'waste' flows*	**FOCUS ON ENABLING** *raw material flows for secondary materials production*
5. END OF LIFE	**END-OF-LIFE TREATMENT** *and dismantling without focus on retaining material value*	**PRODUCTS DESIGNED** *for disassembly and recycling to preserve secondary material value*
6. SECONDARY MATERIAL PRODUCTION	**LOW-QUALITY** *inputs and investment uncertainty results in low yields and small-scale, fragmented industry*	**LARGE-SCALE INDUSTRY** *with high-quality outputs with high preserved value and the ability to replace primary plastics one-to-one*
7. MARKET FOR RECYCLED MATERIAL	**INCENTIVES** *focused on supply into recycling process*	**RELIABLE PRODUCTS** *and demand-side incentives create market certainty and stimulate investment in capacity*

ACTION AREA 1: DESIGN CIRCULAR PRODUCTS

Achieving a significantly higher recycling rate for plastics will require changes throughout the value chain. Above all, the potential for high-quality recycling must be built into the design of the main product groups. Better design could simplify separation into different types of plastic and make used plastics easier to clean, for instance. This represents a major change from today's practice, where plastics recycling comes mostly from a waste handling logic, with little or no adaptation "upstream".

Many plastic items are designed in ways that make recycling difficult or impossible. Different plastics may be used and fused together; plastics may be dyed (black plastics are difficult to recycle, and colors reduce the quality and commercial value of recycled plastics); there may also be hard-to-remove additives, as well as adhesives. All these factors reduce the recoverable value, but producers do not bear the cost.

This is a major, unrecognised market failure. There is no realistic mechanism for the secondary materials industry to coordinate with those upstream in the value chain to induce changes that would retain more material value. Regulation therefore can play a role, as foreshadowed in the EU Circular Economy Action Plan and its focus on product policy. It also is a new agenda for policy, with an urgent need to evaluate the costs and benefits of different options to address it – whether the gradual introduction of product regulation, voluntary agreements, standards, industry design protocols, financial incentives, etc.

ACTION AREA 2: CREATE DEMAND PULL AND ENABLE INVESTMENT

The current policy framework has been developed largely without attention to the demand for recycled plastics, focusing instead on targets for how flows are treated, and on promoting supply. Yet both supply and demand must be in place if we are to go beyond today's recycling levels.

The conditions for doing this are now coming into place. Discussions with a range of companies for this study suggest that there is significant latent demand from companies that increasingly seek to use secondary materials. Indeed, companies are now making public commitments to use recycled plastics, sometimes even at a premium, but often find that the volumes and qualities they need are not available. Meanwhile, recyclers find that they would need to undertake major investments to produce the type of recycled plastics required. There thus is a chicken-and-egg dynamic at work, where a fragmented and small-scale recycling industry cannot produce the consistent quality and volumes required for large-scale use, even as lack of demand holds back the investment that would enable such production.

Technology suppliers interviewed for this project are convinced that high-quality recycling that could serve a much larger demand pool already is technically feasible – with today's often problematic mixed waste streams as a starting point. However, major investments would be required, something that has not proven possible in a sector that historically has made very little money.

A demand signal can make a major difference in this situation. The EU has taken some first steps in the case of plastic bottles, with recycled content and collection requirements that, by 2030, will require a step-change on current practice. This in turn makes it possible for users of plastics packaging (such as beverage companies) to set their own targets, knowing that policy will support their efforts.

Using the same dynamic in other areas could be a major part of reaching higher recycling rates, at higher quality – thus tapping into the materials value pool that currently is lost.

ACTION AREA 3: GET RAW MATERIAL PRICES RIGHT

Recycling also would be more attractive in a policy environment that levelled the playing field of materials prices. Today's virgin plastic prices are driven largely by raw materials costs, and especially that of fossil feedstock. Already before the COVID-19 pandemic, an investment wave and resulting supply glut globally looked set to lock in low prices for the major plastic resins for many years to come. With low oil prices and uncertain demand following in the wake of the pandemic, prices will likely be lower still.

Meanwhile, prices of virgin plastics do not reflect the negative externalities of their production and use. One example is that of CO_2, where carbon prices similar to those in the EU Emissions Trading Scheme would increase the price of major polymers by as much as 20%.[9] However, as prices are set in global markets, regional CO_2 prices in the EU have little effect with current policy.

The cost gap between virgin and recycled plastics thus would be closed to some extent if the negative environmental consequences of their use were accounted for. More broadly, low taxes on resources and pollution relative to those on the inputs to recycling (notably, labour and transport fuels) reduce incentives for recycling. The EU is now taking some steps in this direction, including with a new tax on non-recycled packaging waste to be introduced from 2021. The "pledging" mechanism in the Plastics Strategy also sought to address this.

If policy-makers discover that more far-reaching intervention is warranted, options to evaluate could include quotas for recycled plastics in selected product categories, financial instruments linked to the use of secondary materials, and market creation through public procurement.

[9] *Accounting for both production and 'embedded' emissions that are released upon incineration*

Improving plastics recycling will require transformation along the entire value chain.

ACTION AREA 4: ACHIEVE SCALE AND QUALITY IN THE SUPPLY OF RECYCLED FEEDSTOCK

While the real bottleneck now is in demand, there also are important actions that can be taken to improve the supply of feedstock on which the plastics recycling industry will depend.

One area is that of regulation that currently limit the development of secondary materials markets. The legacy systems for collection are small and fragmented, having often sprung out of municipal waste management. Moreover, efforts to aggregate these flows often run into administrative or regulatory barriers, such as ones restricting restricting cross-border trade in waste, or institutional arrangements that create ambiguity about future material ownership. To foster a raw materials industry, a different mindset is required, where the handling of end-of-life plastics can lead to a consistent and large-scale supply of feedstock for either mechanical or chemical recycling.

Much also can be done to avoid downgrading of materials at an early stage in the value chain. The dismantling of products at end-of-life often takes little account of the implications for secondary materials production. For example, shredding cars results in plastics that are too mixed and contaminated to recycle (and in some cases, even to incinerate safely). Similarly, when buildings are demolished, plastics are often not recycled (with the exception of PVC recycling in some EU countries).

Waste collection systems and practices for handling end-of-life products therefore will need to be revisited to account for their impact on high-value recycling. Today's collection systems are fragmented, with patchy coverage of plastics streams and end-use segments. Much of infrastructure is optimised to meet policy targets that are not necessarily conducive to actual production of high-quality secondary materials. An area to investigate therefore is more sophisticated dismantling end-of-life products, notably the demolition of buildings and shredding and mixing of materials from end-of-life vehicles.

ACTION AREA 5: DEVELOP BETTER TECHNOLOGIES FOR SORTING, AUTOMATION, AND CHEMICAL RECYCLING

Technology already is available that could achieve much higher rates of recycling than are seen today, as noted above. At the same time, plastics recycling is undergoing a quiet technology revolution. Technologies for marking, sorting, separation, etc. are already improving fast, with recent plants significantly more capable than ones available only a few years ago. Digitisation is a major force to harness, with applications across marking, remote sensors, real-term tracking, and automation. In parallel, there is a need for materials development, notably to find long-term solutions for plastics that are hard to recycle, such as engineering plastics and thermosets.

Policy can support this development both through fundamental research, development and demonstration, and by supporting new technology deployment – analogous to the approach taken to renewable energy technologies or other long-term key solutions to climate mitigation.

3.3.6 ACTION AREA 6: USE THE RIGHT METRICS

It will be difficult for policy to steer this system without using the right metrics. Plastics management policies today target collection rates, not actual production of high-quality secondary materials. The collection systems that have sprung up are therefore far from optimised for recycling plastics into high-value materials, increasing the cost of recycling, with low outputs and low revenues for the industry. The result, as we have seen, is low recycling rates and a major destruction of materials value.

The EU is now in the process of revising this, as noted above. The more future targets can focus value retention, the more likely policy is to reach its goals of promoting high collection rates, minimal materials loss, and high-quality outputs that can replace primary plastics use.

ALUMINIUM

TOWARDS FULL CIRCULARITY

Summary

Aluminium is a versatile material with many different applications in packaging, buildings, vehicles, and other sectors. Primary aluminium production is highly energy-intense, but once produced, aluminium can be recycled countless times and re-melting requires only 5% of the energy of primary production. In Europe, almost 80% of aluminium is already recycled, so in volume terms, aluminium is already highly circular. Recycled metal offers an exciting industrial opportunity ahead, as the amount of end-of-life metal is set to grow substantially.

However, a value and quality analysis adds an important perspective. Aluminium is typically alloyed to create the many specific material properties required. This adds value to the first user of these alloyed materials, but when these materials are eventually recycled, there is a downgrading effect as different alloys are mixed together. The result is that the applications for recycled aluminium are distinctly different than those for primary: Most recycled aluminium can be used only for cast products, with vehicle engine blocks as the largest application. Due to its more limited uses, recycled aluminium is sold at a discount compared to primary. Beverage cans are an important exception to the downgrading; in most countries, they are circulated in a much more closed-loop system.

The downgrading effect looks to become increasingly problematic in Europe, for several reasons: First, electric vehicles don't use aluminium engine blocks, so the largest source of demand for cast aluminium will decrease. Second, the supply of recycled aluminium is increasing, as long-lived aluminium products are now also starting to fall out of the economy. Third, once alloys have been mixed into the aluminium, it is very difficult technically and economically to separate them. So far, dilution with primary aluminium has helped address the downgrading issues, but this is not a long-term sustainable solution.

If Europe wants to move towards a long-term sustainable aluminium use, it should find ways to improve collection rates and address the downgrading effects through improved product design and scrap sorting. EU companies are already investing into sorting that could stop the downgrading and preserve more materials value. Pushing this further is both an industrial and an environmental opportunity.


70%
of the material value in aluminium
IS PRESERVED AFTER ONE USE CYCLE

4.1 INTRODUCTION

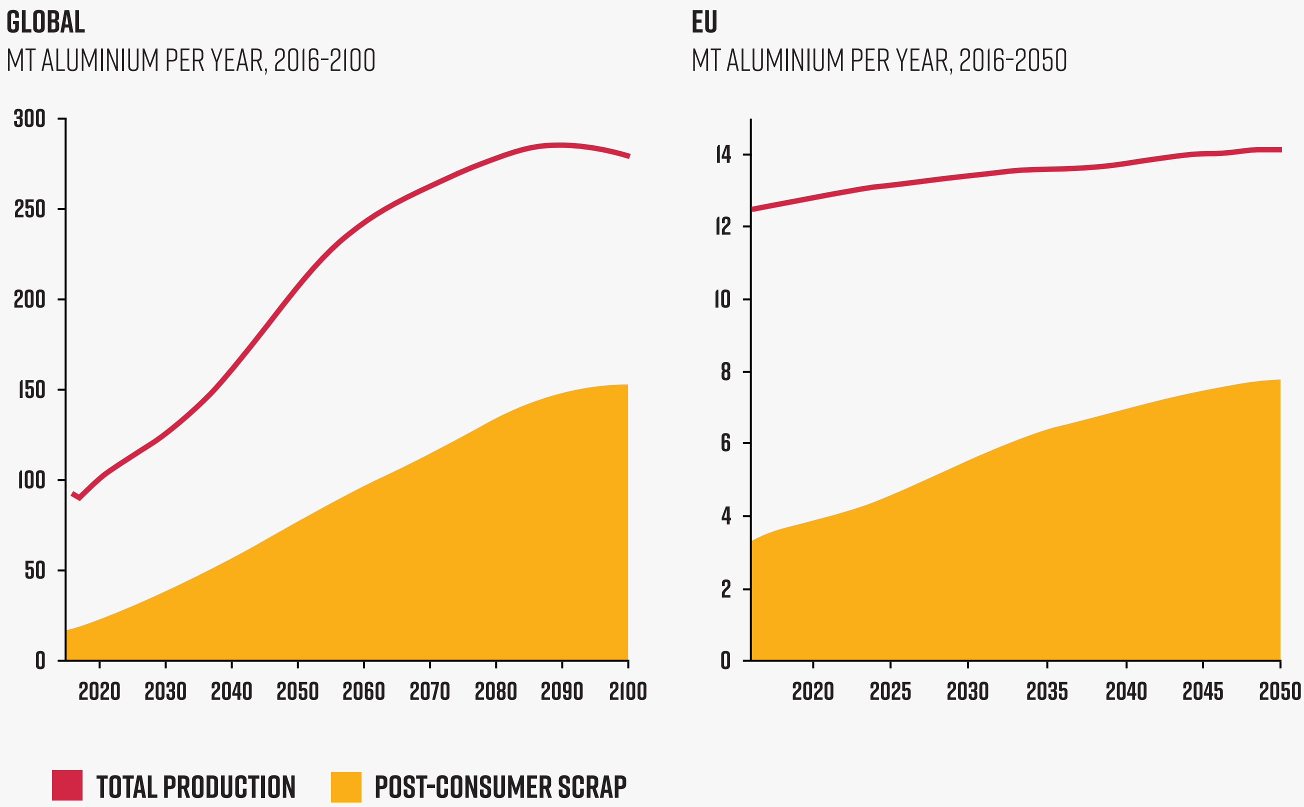
Recycling has long been part of the aluminium value chain, with well-established take-back schemes for aluminium cans, for instance. Producing aluminium is energy-intensive, with production using the Hall-Héroult process requiring about 15 MWh of electricity per tonne of aluminium. Once made, however, aluminium can be remelted with just about 5% of the original energy used, and potentially reused numerous times.

The EU aluminium industry covers the full range of production, from primary production through to a rich set of products and then recycling at the end of life. However, imports of aluminium have been increasing during the period that China built up a substantial market position that sees it make the majority of aluminium in the world. In recent years, European primary production has made up 16% of the market, recycled aluminium 34%, and imported aluminium the remaining 48%.[32] Recycling thus is one-third of the total market, but this is set to increase as the amount of end-of-life metal grows. By mid-century, the EU economy will generate enough metal for recycling that it could cover 50% of its own demand, even with substantial growth in aluminium use.

Exhibit 17

GLOBAL AND EU DEMAND OF ALUMINIUM AND AVAILABLE POST-CONSUMER ALUMINIUM SCRAP

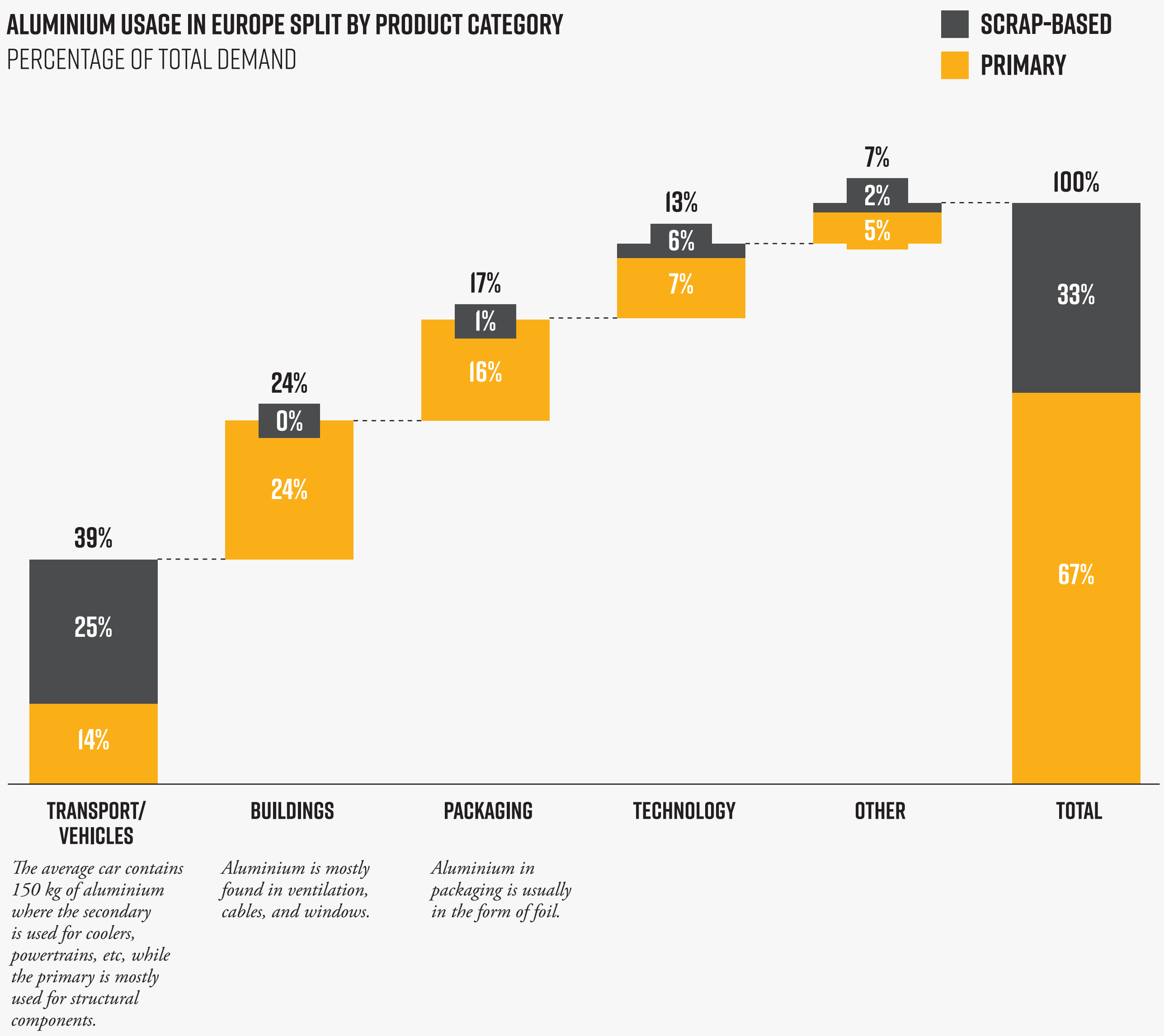
AVAILABLE ALUMINIUM POST-CONSUMER SCRAP COMPARED TO TOTAL PRODUCTION



SOURCE: MATERIAL ECONOMICS ANALYSIS IN MATERIAL ECONOMICS (2018) - THE CIRCULAR ECONOMY: A POWERFUL FORCE FOR CLIMATE MITIGATION

Exhibit 18

VEHICLES, BUILDINGS, AND PACKAGING TOGETHER MAKE UP 80% OF ALUMINIUM DEMAND



SOURCE: M. CULLEN, M. ALLWOOD (2013), MAPPING THE GLOBAL FLOW OF ALUMINUM: FROM LIQUID ALUMINUM TO END-USE GOODS

In Europe, 80% of aluminium is used for buildings, transport, or packaging. However, the production techniques and requirements differ a lot between transport/vehicles sectors. Buildings and packaging use almost only primary aluminium. Secondary aluminium is used principally in the vehicle and sectors, where cast aluminium components are an important feature.

Exhibit 19

THE USE FOR ALUMINIUM IS HIGHLY DEPENDENT ON THE ALLOY CONTENT

PURE ALUMINIUM	CANS	AIRPLANES	ENGINE BLOCK
LOW DENSITY HIGH CONDUCTIVITY CORROSION RESISTANT SOFT	LID: 2.6 % MG 0.25 % CR CONTAINER: 1.2 % MN 1 % MG	2 % CU 3 % MG 6 % ZN	17 % SI 5 % CU 0.5 % MG 1 % ZN

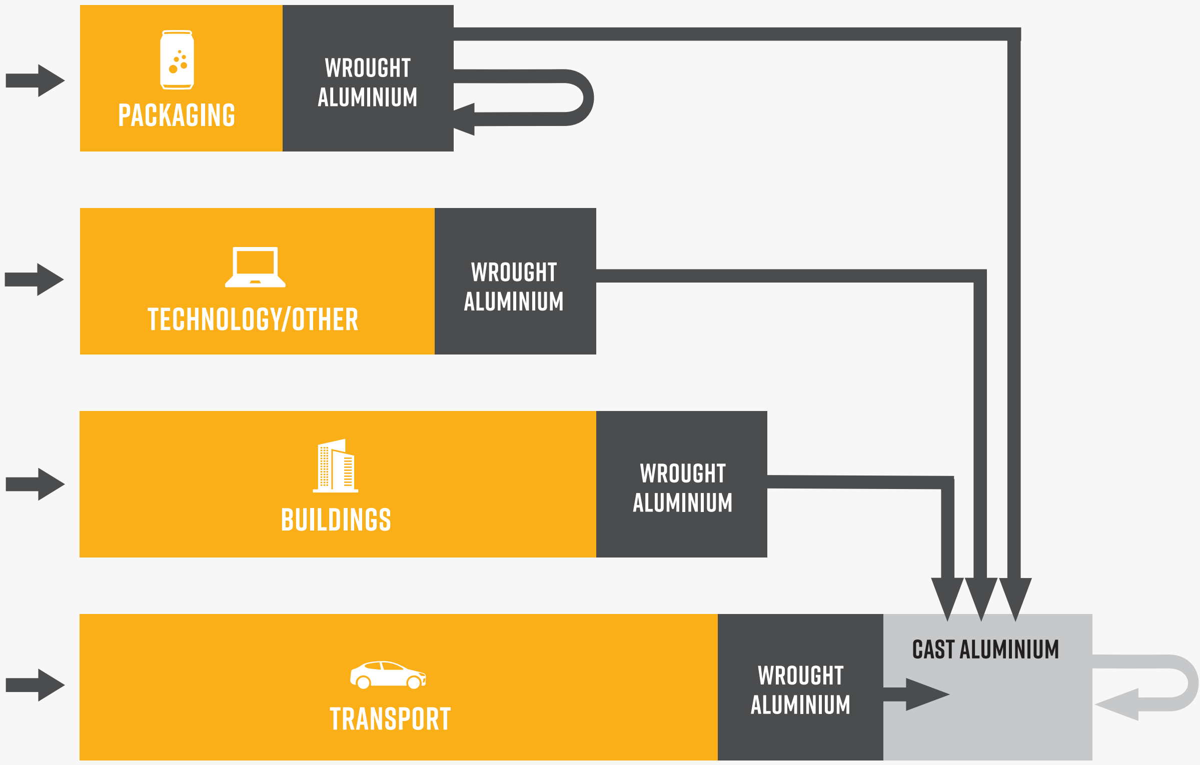
FOIL	WINDOW FRAME	BICYCLE FRAME	RIMS
> 99 % ALUMINUM	0.4 % SI 0.05 % CU 0.8 % MG	0.6 % SI 0.25 % CU 1.2 % MG 0.2 % CR	7 % SI 0.4 % MG

SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MÜLLER (2017).[33]

Aluminium is rarely used in its pure form, but is combined with other metals and substances to produce a range of aluminium alloys with very different properties (Exhibit 19). The metal used in cans, airplanes, engine blocks, and window frames thus differ substantially from each other. Cast aluminium products often require – and can handle – highly alloyed metal.

Exhibit 20

PRIMARY ALUMINIUM OFTEN ENDS UP AS CAST ALUMINIUM DUE TO THE INCREASING ALLOY CONTENTS



SOURCE: THE GLOBAL ALUMINUM CYCLE: CHALLENGES AND SOLUTIONS OPTIONS, DANIEL B. MÜLLER (2017)

Unlike in the case of steel, it is not possible to remove alloy elements from aluminium in the recycling process. Once different types of metal are combined in collection, the challenge instead is to combine different fractions, dilute with new and pure metal, and add any missing alloying elements. This refining process typically makes it possible to produce highly-alloyed secondary metals suitable for casting, but not for other production processes. Aluminium recycling therefore has two challenges: It relies on dilution by primary metal, and it generally can only serve the minority of the market that relies on casting in the production process.

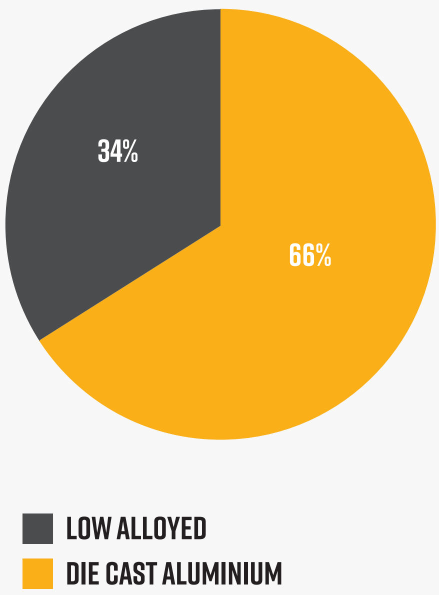
The result of all this is a system that is circular – but with qualifications. The use pattern can be observed in Exhibit 20. Primarily aluminium is used for wrought and extruded applications in packaging, technology, buildings, and some car applications, but after one use cycle it is used as cast aluminium, where it can circulate many times but cannot be returned to its previous uses. This system has so far been economically rational. Sorting is expensive, and cast aluminium is valuable. Meanwhile, there has been sufficient demand for cast aluminium products, not least in vehicles.

However, this system is now showing signs of strain. The vehicle industry is the by far largest user of cast aluminium demand today, but that cast aluminum demand is changing due to electrification. Electric vehicles do not contain several of the components that use most cast aluminium in a gasoline or diesel car (Exhibit 21) and these components together use about 50% of the cast aluminium in gasoline and diesel cars. Forecasts for the penetration of electric vehicles as a share of total vehicle sales vary, but almost all point to a significant increase by 2030, and especially by 2040. At the same time, strong growth in the supply of aluminium scrap is expected, due to an increasing aluminium stock. The combination of declining demand and growing supply already is creating a price differential between primary metal and secondary foundry alloys produced from scrap. Already today, the price delta between primary and secondary aluminium is at €250 or more per tonne, and growing. Finding ways to use post-consumer aluminium for high-value applications thus is a major opportunity for the industry.

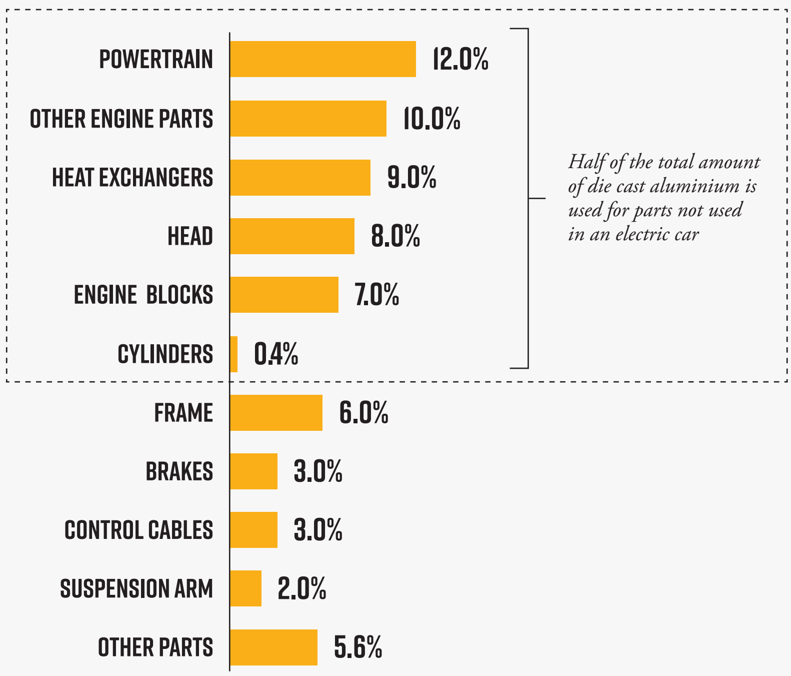
Exhibit 21

CAST ALUMINIUM MAKES UP 66% OF CURRENT ALUMINIUM USAGE IN CARS, 50% OF THIS IS NOT NEEDED IN ELECTRICAL CARS

DIE CAST MAKES UP FOR THE LARGEST VOLUME OF ALUMINIUM IN MODERN CARS
SPLIT BASED ON ALUMINIUM CONTENT



ELECTRICAL CARS CHALLENGE THE USEFULNESS OF DIE CAST
SHARE (%) OF DIE CAST ALUMINIUM OUT OF TOTAL ALUMINIUM



SOURCE: MATERIAL ECONOMICS (2019) – INDUSTRIAL TRANSFORMATION 2050

Aluminium can be remelted using only 5% of the energy needed for primary production, and can potentially be reused several times

4.2 VALUE PRESERVATION ACROSS THE ALUMINIUM USE CYCLE

Our value preservation analysis of aluminium is shown in Exhibit 22. In total, approximately two thirds of the original value of aluminium is left after one use cycle. This section starts with explaining our estimates and calculations, and then discusses the overall results.

Original material value. Aluminium with an original value of €12 billion falls out of use in the EU every year. For aluminium, we have defined the 'original material value' as the value of ingots. This is the standardised form for traded aluminium, with a well-defined market price. It also is the point where value is entirely due to the material and its properties, as no product value has yet been added. Based on data from International Aluminium institute, the amount of aluminium exiting use every year is 6.9 million tonnes. Of this, 1.1 million tonnes is not collected. The remaining 5.8 million tonnes are made up of 65% old scrap (scrap at a product's end of life) and 35% new scrap (scrap in manufacturing)[34]. The shares of this that are primary (67%) and secondary (33%) have been multiplied with a price of €1,816 and €1,568 per ton of ingot respectively, to get to the estimate of €12 billion.

Remaining value. 5.8 million tonnes of aluminium scrap is recycled in Europe. Accounting for yield losses during the remelting process, this scrap is remelted into 5.4 milion tonnes ingots. Multiplication with the average price of recycled aluminium ingots and adjusting for reworking costs, yields a remaining value of approximately €7 billion. The value difference between the original and the remaining value, approximately €4 billion, is our estimate of the total value loss in one use cycle.

Collection losses: Currently, approximately 78% of end-of-life aluminium is collected, while the remaining 22% is handled as part of general waste streams, thus ending up in landfills. Looking at both new and old scrap, the corresponding number is 15% for aluminium scrap in total. In value terms, this translates to collection losses of about €2 billion. These losses are mainly due to aluminium not being sorted out of municipal waste. There are several reasons why separating and recovering aluminium from waste streams is difficult: First, unlike steel, aluminium cannot magnetically be sorted out. Second, aluminium is often used in small pieces in many different products. Third, incineration results in large oxidation losses. Finally, extracting remaining aluminium from incineration ashes is often too costly. Additional volume losses come from oxidation of the surface of aluminium that occurs during use; small pieces can lose relatively large shares of the metal due to the high surface-varea-to-weight ratio.

Process yield losses. Aluminium-containing waste called dross is produced as a byproduct of the aluminium remelting process. Approximately 1.1 tonnes of aluminium scrap is needed to make 1 tonne of secondary aluminium, causing losses of around 8%[36] In value terms, we estimate these losses at slightly below €1 billion.

Quality losses. Quality losses are estimated as the residual between the volume losses and the retained value. They amount to just below 10% of the original value, or approximately €1 billion in absolute terms. The key reason, as described above, is the alloy content of secondary aluminium, which in turns limits its applications.

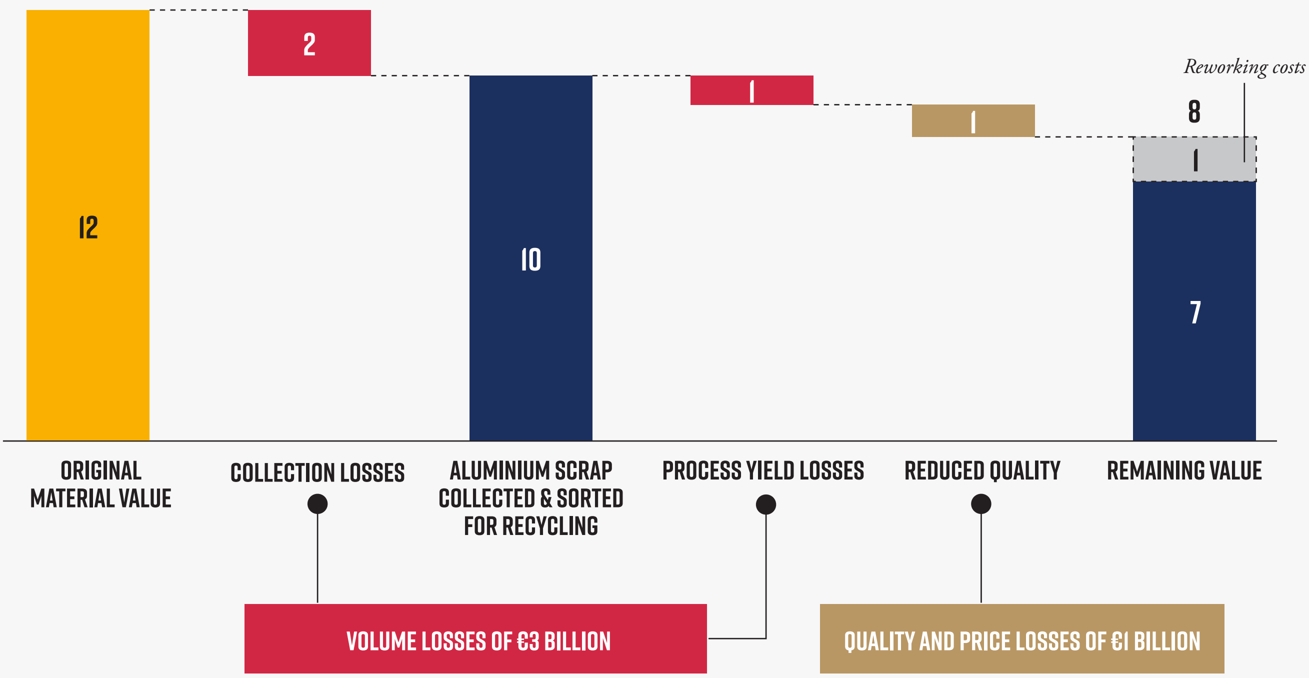
The reworking costs amount to approximately €1 billion. The reworking cost for 'clean' flows on scrap (new scrap and cans) is estimated based on remelting costs of aluminium scrap into ingots, where approximately 5% of the energy required to make primary aluminium is needed to remelt aluminium scrap. Reworking costs for other old scrap is based in price difference between alumimium scrap and secondary aluminium ingots.

Discussion. There are good reasons that the current aluminium use cycle looks the way it does: So far, the downgrading issues have been possible to manage through high demand for cast aluminium products and through dilution with primary aluminium, two pragmatic strategies. But going forward, as described above, recycled aluminium supply will become ever larger compared to total demand and in addition, the demand for cast aluminium products might decrease significantly. This will make the current strategies insufficient, and value losses might further increase. The main sustainability argument of the aluminium industry has always been that aluminium can be recycled almost endlessly, thus motivating the highly energy-intense production of primary aluminium. If the downgrading becomes too pronounced, consumers and policy makers might start to question the validity of this argument.

Exhibit 22

ALUMINIUM LOSES €4 BILLION IN MATERIAL VALUE ANNUALLY

VALUE OF ALUMINIUM FALLING OUT OF THE EUROPEAN ECONOMY ANNUALLY
BILLION €



SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE[35]

4.3 THE PATH FORWARD

We believe there are several good arguments for the aluminium value chain to proactively address the issues mentioned above: There is a strong environmental case for doing so, it provides an interesting industrial and economic opportunity, and there is an increasingly strong geopolitical argument (bauxite is now on the EU's list of critical raw materials).

This report has not looked at the path forward in any detail. Instead, this section highlights a few of the action areas that will be important to move towards an even more circular aluminium use.

ACTION AREA 1: EXPLORE MORE CLOSED ALUMINIUM LOOPS, INCLUDING IMPROVED SORTING

An obvious area to explore is whether it is possible to reduce the alloy-related downgrading effects by introducing more closed aluminium loops. Beverage cans provide an interesting example: They circulate in a separate collection and remelting system in most countries, with much lower value losses. It is possible to create similar loops in other areas. For example, some companies have started recycling wrought aluminium profiles from windows and other building components into products in the same category, achieving a recycled content of 75% or more.

Is it technically and economically viable to create similar loops in other areas? They might not be as 'closed-loop' as beverage cans, but could more sorting fractions and alloy standardisation be introduced to make the alloy metals into an asset for the next user rather than a liability?

This would likely require new product definitions in the aluminium scrap market. Matching multiple categories of scrap with demand would also require both larger geographical markets and better real time information about available scrap fractions. Digitisation would become key for such a market, a significant development from today's system.

It might also be possible to increase standardisation of material design. Today's proliferation of alloys is a product of specification by composition, rather than function. It thus might be possible to reduce the total number of alloy varieties, which would facilitate more closed loops. Of course, this cannot be done at the expense of sacrificing material properties or the advantages of tailor-made materials.

ACTION AREA 2: INVEST IN ADVANCED END-OF-LIFE SORTING AND PROCESSING

Advanced sorting of mixed aluminium flows offers another way forward. Technology has made large strides in the last decade, and technologies such as LIBS (Laser-Induced Breakdown Spectroscopy) now make it possible to quickly and reliably determine the composition of aluminium parts. Sorting mixed flows into many separate fractions is still expensive (up to 500 EUR per tonne), but the automation of this process is moving fast. With a high learning rate and investment, it may well be possible to profitably separate aluminium into more fractions, thus escaping the price penalty that now attaches to mixed metal. Of course, a condition for this is that recycled metal is profitable vs. imports of primary metal, something that has been difficult to achieve in a highly challenged global trade environment that also does not put a price on the often high carbon footprint of primary aluminium.

ACTION AREA 3: DEVELOP TECHNOLOGIES TO PURIFY ALUMINIUM

Several technologies have been proposed to separate alloys from aluminium, for example, reaction with chlorine gas, electrolysis, crystallisation, and filtration. However, these are far from economically viable today, and considerable technological development is required before they can become large-scale solutions. If one of these technologies could be brought down the learning curve, it would be a game changer for the future use of aluminium. This is an interesting technology agenda for the industry to explore.

ACTION AREA 4: REDUCE VOLUME LOSSES

Reducing volume losses is a well-known improvement area, with targets set both at the EU and member state level. We list it here for the sake of completeness, since more than 20% of end of life aluminium still goes uncollected in Europe.

ENDNOTES

INTRODUCTION

[1] Based on Eurostat data and Material Economics analysis of the emissions from steel, aluminium, plastics, and cement. See Material Economics (2018). *The Circular Economy: A Powerful Force for Climate Mitigation.* Stockholm. https://materialeconomics.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1.

[2] The modern term of "circular economy" has various origins, but one of the best-known books on the topic is: McDonough, W. and Braungart, M. (2002). *Cradle to Cradle: Remaking the Way We Make Things.* North Point Press, New York.

STEEL

[3] Steel falling out of use is estimated using a stock-based modelling developed in Material Economics (2018), The Circular Economy. The amount of steel falling out of use is based on assumed lifetimes in each end-use sector: transportation, 20 years; machinery, 30 years; construction, 75 years; products, 15 years. The number presented does not include internal run-around-scrap in BF-BOF production. Model approach and assumed lifetimes are based on: Pauliuk, Rachel L. Milford, Daniel B. Müller and Julian M. Allwood (2013). The Steel Scrap Age. *Environmental Science & Technology*, 47(7). 3448–54. DOI:10.1021/es303149z.

[4] See Material Economics (2019). *Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry.* Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050.

Materials values are calculated based on volumes reported by: EUROFER (2018). *European Steel in Figures 2018.* European Steel Association. http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf. Prices for slabs and steel scrap are based on Eurostat export and import data for stainless steel, other alloyed steel and non-alloyed steel at https://appsso.eurostat.ec.europa.eu. Prices calculated are at the slab level for stainless, other alloyed and non-alloyed €1,812/t, €556/t and €429/t, respectively

[5] EUROFER (2018). *European Steel in Figures 2018*, and Pauliuk et al. (2013), The Steel Scrap Age.

[6] Share of total GHG emissions in Europe calculated based on steel related emissions from Material Economics (2019), *Industrial Transformation 2050*, and total reported GHG emissions in Europe based on Eurostat data at: https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics.

See also: World Steel Association (2020). *Steel's Contribution to a Low Carbon Future and Climate Resilient Societies*. WorldSteel position paper. Brussels. https://www.worldsteel.org/publications/public-policy-papers.html.

The Boston Consulting Group (2013). *Steel's Contribution to a Low-Carbon Europe 2050.* Scientific report. https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050.

[7] Material Economics (2019). *Industrial Transformation 2050.*

[8] EUROFER (2018), European Steel in Figures 2018

[9] Materials values are calculated based on volumes reported by EUROFER (2018), *European Steel in Figures 2018*, and prices for slabs and steel scrap are based on Eurostat export and import data for stainless steel, other alloyed steel and non-alloyed steel at: https://appsso.eurostat.ec.europa.eu. Prices calculated are at the slab level for stainless, other alloyed and non-alloyed steel €1,812/t, €556/t and €429/t, respectively and for steel scrap, €1,056/t, €289/t and €247/t, respectively.

Collection losses are estimated using a stock-based modelling developed in Material Economics (2018), *The Circular Economy*, where steel falling out of use is based on assumed lifetimes in each end-use sector: transportation, 20 years; machinery, 30 years; construction, 75 years; products, 15 years. Model approach and assumed lifetimes are based on Pauliuk et al. (2013), The Steel Scrap Age.

Process yield losses of 4-5% for steel produced in electric arc furnaces, based on Price, D. (2009) Yield improvement in the steel industry. Ironmaking & Steelmaking; London, 36(7). 482-86. and Pauliuk et al. (2013). The Steel Scrap Age.

Value of alloys lost based on difference in price premium for alloyed/stainless steel compared with non-alloyed (reflecting value of alloys) at the slab level compared with steel scrap level, resulting in value of alloys lost of €85/t for non-alloyed scrap and €277/t for stainless steel scrap.

Reworking costs based on EAF costs of €120/t steel produced (excluding cost of steel scrap, including labour, energy, capital costs, maintenance etc.); see https://www.steelonthenet.com/cost-eaf.html.

Value loss due to reduced quality calculated as a residual between value of steel scrap collected, value retained and other value-losses, reflecting additional value loss due to lower price on scrap-based steel products on average.

[10] Materials values are calculated based on volumes reported in EUROFER (2018), *European Steel in Figures* 2018, and prices for slabs and steel scrap are based on Eurostat export and import data for stainless steel, other alloyed steel and non-alloyed steel at: https://appsso.eurostat.ec.europa.eu. Prices calculated are at the slab level for stainless, other alloyed and non-alloyed €1,812/t, €556/t and €429/t, respectively, and for steel scrap, €1,056/t, €289/t and €247/t, respectively.

[11] Serikov et al. (2015). Metal loss and charge heating in the melt in an electric arc furnace.

[12] Material Economics (2018). *Ett Värdebeständigt Svenskt Materialsystem* [A Value-Stable Swedish Material System]. Stockholm. http://resource-sip.se/content/uploads/2018/01/vardebestmtrlsystemrapport180118.pdf.

[13] Based on a dynamic materials flow model, using the modelling setup described in Pauliuk et al. (2013), The Steel Scrap Age; see Material Economics (2018) – The Circular Economy, a Powerful Force for GHG Mitigation for more details.

[14] Material Economics (2019). *Industrial Transformation 2050.*

[15] Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H. and Pauliuk, S. (2017). Quantifying Recycling and Losses of Cr and Ni in Steel Throughout Multiple Use cycles Using MaTrace-Alloy. *Environmental Science & Technology*, 51(17). 9469–76. DOI:10.1021/acs.est.7b01683.

[16] Plastics Europe (2018). *Plastics – the Facts 2018: An Analysis of European Plastics Production, Demand and Waste Data.* Brussels. https://www.plasticseurope.org/en/resources/publications/619-plastics-facts-2018.

On top of this, there is also substantial trade in plastics products and plastics-packaged goods. There are no reliable estimates of these traded volumes, but the result is a net import of plastics on top of the official demand figures.

[17] European Commission (2019). Circular Economy: Commission welcomes Council final adoption of new rules on single-use plastics to reduce marine plastic litter. Press release, 21 May. https://europa.eu/rapid/press-release_IP-19-2631_en.htm.

BrightVibes (2019). India set to ban 6 single-use plastics on Gandhi's birthday. *EcoWatch,* 5 September. https://www.ecowatch.com/india-ban-single-use-plastics-2640207733.html.

[18] Original materials value is calculated using a weighted average price of virgin polymers of €1,453/t, calculated using the polymer split per market segment of plastics falling out of use each year; the polymer split is from Plastics Europe (2018), Plastics – the Facts 2018, and market volume is from Deloitte and Plastics Recyclers Europe (2015), *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment,* http://www.plasticsrecyclers.eu/sites/default/files/BIO_Deloitte_PRE_Plastics%20Recycling%20Impact_Assesment_Final%20Report.pdf.

The retained value of misclassified or unmanaged waste was zero for the 0.2–0.5 Mt of plastic waste entering the oceans, as for the roughly 7 Mt of landfilled plastics waste. See: European Commission (2018). *A European Strategy for Plastics in a Circular Economy.* Brussels. http://www.europarc.org/wp-content/uploads/2018/01/Eu-plastics-strategy-brochure.pdf.

Of the remaining misclassified waste, 30% was classified as incinerated (of which 86% involved energy recovery), using the share of total EU municipal solid waste incinerated in 2016 (see Eurostat data: https://ec.europa.eu/eurostat/web/products-datasets/-/env_wastrt). No other value recovery for plastics in mixed municipal solid waste was analysed. 98% of plastics waste sent to incineration was estimated to be subject to energy recovery, based on Eurostat (2019a). Plant conversion efficiency for CHP was set to 85% and electricity-only to 44%, based, respectively, on:

IEA Bioenergy (2014). *Waste to Energy: Summary and Conclusions from the IEA Bioenergy ExCo71 Workshop.* Report on workshop held in conjunction with the meeting of the Executive Committee of IEA Bioenergy in Cape Town, South Africa, on 21 May 2013. https://www.ieabioenergy.com/wp-content/uploads/2014/03/ExCo71-Waste-to-Energy-Summary-and-Conclusions-28.03.14.pdf.

Di Maria, F., Contini, S., Bidini, G., Boncompagni, A., Lasagni, M. and Sisani, F. (2016). Energetic Efficiency of an Existing Waste to Energy Power Plant. *Energy Procedia,* 101. 1175–82. DOI:10.1016/j.egypro.2016.11.159.

The share of waste-to-energy capacity by type, including CHP and electricity-only, is from: Scarlat, N., Fahl, F. and Dallemand, J.-F. (2019). Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe. *Waste and Biomass Valorization*, 10(9). 2425–44. DOI:10.1007/s12649-018-0297-7.

Energy content of plastics waste was set to 6 MWh per tonne based on Energimyndigheten (2017). Värmevärden och emissionsfaktorer [Calorific values and emission factors]. Swedish Energy Agency, Stockholm, 19 June. http://www.energimyndigheten.se/statistik/branslen/varmevarden-och-emissionsfaktorer1/

The value of corresponding energy from natural gas was used to estimate the recovered value from plastics incineration, assuming that heat and electricity from plastics incineration replace natural gas. Conversion efficiency for natural gas-powered CHP plant was set to the same as waste incineration CHP plant, and to 55% for a natural gas-fired power plant using the ranges presented in: Andrews, D., Vatopoulos, K., Carlsson, J., Papaioannou, I., Zubi, G. (2012). *Study on the State of Play of Energy Efficiency of Heat and Electricity Production Technologies.* European Commission, Joint Research Centre and Institute for Energy and Transport. Luxembourg. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/study-state-play-energy-efficiency-heat-and-electricity-production-technologies.

Natural gas price of US$7/MBtu is from: IEA (2019). *Gas 2019 – Analysis and Forecasts to 2024*. International Energy Agency, Paris. https://www.iea.org/gas2019/.
Separate analysis of captured value of plastics incineration in cement production was not included in the analysis, but is included in overall energy recovery calculations. Value of (extra-EU) exported plastics waste in 2016 is from Eurostat: https://ec.europa.eu/eurostat/web/waste/data/database. The value of recycled plastics was calculated using the average price of recycled polymers from Deloitte and Plastics Recyclers Europe (2015), *Increased EU Plastics Recycling Targets.*

[19] The most commonly recycled polymer types and market segments are taken from: OECD (2018). *Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses.* Organisation for Economic Co-operation and Development, Paris. http://dx.doi.org/10.1787/9789264301016-en.

[20] European Commission (2019b). Circular Economy Strategy. 7 August. https://ec.europa.eu/environment/circular-economy/index_en.htm
Plastics Europe (2018). *Plastics – the Facts 2018.*

[21] This is pointed out, for example, in the EU Commission Implementing Decision (EU) 2019/1004 of 7 June 2019, laying down rules for the calculation, verification and reporting of data on waste in accordance with Directive 2008/98/EC of the European Parliament and of the Council and repealing Commission Implementing Decision C(2012) 2384. See https://eur-lex.europa.eu/legal-content/GA/TXT/?uri=CELEX:32019D1004.

[22] Production, demand, recycling and waste data taken from Plastics Europe "Plastics the Facts 2018". Recycling yields taken from Deloitte & Plastics Recyclers Europe report "Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment." Recycling capacities for different countries taken from Plastics Recyclers Europe. Export volumes taken from Eurostat.

[23] Scarlat et al. (2019). Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe.

[24] Bishop et al. (2020). Recycling of European plastic is a pathway for plastic debris in the ocean. See https://www.sciencedirect.com/science/article/pii/S0160412020318481#s0125

[25] Sources: Plastics Recyclers Europe (2018a). PET Recycling industry installed capacity reviewed. Press release, 3 July. https://plastics-recyclers-europe.prezly.com/pet-recycling-industry-installed-capacity-reviewed.

Plastics Recyclers Europe (2018b). Plastics recycling grows in Europe. Press release, 13 February. https://plastics-recyclers-europe.prezly.com/plastics-recycling-grows-in-europe.

Plastics Recyclers Europe (2019). Recycling capacity for rigid polyolefins in Europe totals 1.7 M tonnes. Press release, 6 May. https://plastics-recyclers-europe.prezly.com/recycling-capacity-for-rigid-polyolefins-in-europe-totals-17-m-tonnes.

[26] Value preservation is calculated using figures from Exhibit 2.

[27] Price fluctuations of r-HDPE and r-PET are taken from: Börkey, P. (2019). *Rethinking Plastic Recycling in a Disposable Society.* Webinar, 23 January. OECD Directorate. https://www.oecd.org/env/waste/improving-markets-for-recycled-plastics-9789264301016-en.htm. The share of value compared to primary plastics is calculated using the difference between the average price of recycled polymers and primary polymers, per polymer type, resulting in a span of 53–71%. Recycled and primary polymer prices are from OECD (2018), Improving Markets for Recycled Plastics.

[28] Hahladakis, J. N. and Iacovidou, E. (2018). Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity? *Science of the Total Environment,* 630. 1394–1400. DOI:10.1016/j.scitotenv.2018.02.330.

[29] Virgin polymer prices are taken from OECD (2018), *Improving Markets for Recycled Plastics,* and export value of recyclable plastics waste are taken from Eurostat, https://ec.europa.eu/eurostat/web/waste/data/database. Value loss is calculated using the difference between average price of primary polymers and lowest vs. the highest price of plastics waste exports (€/tonne) between 2016 and 2018, resulting in a span of 83–87%.

[30] See Eurostat, http://appsso.eurostat.ec.europa.eu

[31] EU plastics production and converter demand from Plastics Europe (2018), *Plastics – the Facts 2018,* and net exports are calculated as the difference between production and demand. The stock build-up is calculated as the difference between the converter demand and the estimated end-of-life volumes. The end-of-life volumes have been estimated by developing a stock-based model of plastics demand and average lifetime of the economy for plastics. Demand volumes between 2005 and 2017 are from Plastics Europe (*Plastics – the Facts* for each year, respectively).

Demand volumes between 1981 and 2004 based on interpolation of production volumes for 1976, 1989, 2002, and 2005, assuming constant share of net exports between 1981 and 2004 of 19% (same as the average net export between 2005 and 2017, calculated as difference between production and demand). Data source: Plastics Europe (2013). *Plastics – the Facts 2013.* Brussels. https://www.plasticseurope.org/application/files/7815/1689/9295/2013plastics_the_facts_PubOct2013.pdf

The average lifetime of plastics in the economy, per market segment, is taken from: Geyer, R., Jambeck, J. R. and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances,* 3(7). e1700782. DOI:10.1126/sciadv.1700782.

Missclassified or unmanaged waste is calculated as the difference between end-of-life plastics and the volumes of collected plastics waste. Volumes of plastics waste sent to landfill, incineration, collected for recycling, and shares of plastics waste collected for recycling that is sent to recycling within and outside of the EU from Plastics Europe (2018), *Plastics – the Facts 2018*. Sorting- and yield losses from plastics that are sent to recycling within EU are assumed to be 26%, based on average recycling yield of six waste streams in 2012 (packaging, WEEE, ELV, B&C, Agricultural, and other plastics waste), taken from Deloitte and Plastics Recyclers Europe (2015), *Increased EU Plastics Recycling Targets.*

ALUMINIUM

[32] European Aluminium (2016). EU Aluminium Imports Dependency. https://www.european-aluminium.eu/data/economic-data/eu-aluminium-imports-dependency/

[33] Daniel B. Müller (2017). *The global aluminum cycle: Challenges and solutions options.*

[34] Based on data from International Aluminium (2021) – IAI Material Flow Model

[35] Aluminium prices (primary and secondary ingots) taken from London Metals Exchange website. Import and export volumes taken from Eurostat. Production data and recycling rates taken from International Aluminium. Split between primary and secondary production taken from Cullen et al (2013) *Mapping the Global Flow of Aluminum: From Liquid Aluminum to End-Use Goods.* Yield losses from interviews with industry experts, and other recycling data taken from Material Economics (2018) The Circular Economy: A powerful force for climate mitigation.

[36] Based on interviews with industry experts.

PRESERVING VALUE IN EU INDUSTRIAL MATERIALS

A value perspective on the use of steel, plastics, and aluminium

The report takes an economic value perspective on material flows and assesses Europe's use of steel, plastics, and aluminium in terms of Euros instead of tonnes.

The 'exam questions' we ask ourselves are: If 100 Euros of raw materials is entered into the European economy, how much economic value is retained after one use cycle? What are the main reasons that material value is lost? How could more value be retained? What business opportunities arise as a result?

Disclaimer
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MATERIAL ECONOMICS

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