A “Paris Agreement” for recycling the Earth’s resources

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WBCSD and BCG thank the following contributors for their active participation

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At Arcadis, we are committed to placing sustainability at the heart of everything we do and are proud of our involvement with this report. It clearly states what I strongly believe is true; the circular economy and the re-use, recycling and reinvention of materials are critical if we are to limit global warming and met net zero targets. But this won't happen if we stand still and don't act. A concerted effort is needed today, bringing together governing bodies, manufacturers, investors, NGOs and consumers, with the clear ambition to make the circular economy a reality.

Peter Oosterveer
CEO, Arcadis

Creating more value with fewer resources will be the largest challenge for business in the next decade. We need to increase both product circularity and use. Products that have reached end of life will need to be recycled at rates well above 80% - partially starting from 15% - given our finite resources. Those executives who decouple growth from resource extraction will be rewarded with both lasting competitive advantage and a healthier planet.

Christoph Schweizer
CEO, BCG

Circularity is the opportunity of our time. It unlocks economic growth in a way that is climate-friendly, nature-positive and socially-inclusive. My vision for construction is that each new building should be made out of at least 50% of recycled materials, to build more new from the old.

Jan Jenisch
CEO, Holcim

Circular economy will be crucial to meet our net-zero ambitions. At Arçelik we thus strive to play our part in limiting global warming to 1.5°C with our innovative technology. We are proud to be part of this report and support implementing the circular economy through the effort of bringing together various stakeholders.

Hakan Bulgurlu
CEO, Arçelik

Executive summary

The global economy is growing at a rapid pace and with it, the use of natural resources. Resource consumption has more than tripled since 1970, a rate that threatens the renewal capacity of our planet and the availability of finite resources for the next generations. This calls for a formal global plan for material recycling and the creation of higher circularity through technology and innovation.

At our current consumption levels, we would need about 1.8 planets to continue to provide the resources we are consuming. We will need 2.3 planets by 2040 if the global population and demand for materials continue to grow at their present pace.[13] For the Earth to continue regenerating its renewable resources and for finite resources to last several more generations, we will have to lower consumption levels of virgin resources so that they equal the resources of no more than one planet. This will help protect the climate and biosphere and provide greater societal equity.

A formal global plan for material recycling would make this kind of renewal possible, but currently there is no global compact for recycling. This situation needs to change: we need a joint agreement that sets guidelines for conserving materials and resources in the way that the Paris Agreement presents a framework to reduce global warming.

Currently we are recycling 25-35% of the-waste streams that, by value and volume, are the most detrimental to the environment. To bring resource consumption within planetary boundaries by 2040 would require an additional recycling rate of 55%, meaning that 80-90% of all consumed resources are then recycled—measured as recycling input[1] across materials. To reach these ambitious levels and overcome existing technological challenges, industries will need to invest in upgrading their capabilities in four critical areas: design, collection, sorting and recycling itself.

While most companies can identify business cases for responsible resource consumption and recognize the strategic value to be gained, the lack of standards and collaboration across the value chain often leads to disincentives. Businesses need more consistent and clear regulation to discourage landfilling and incineration and encourage recycling.

They often face a lack of financial incentives for recycling, as production with virgin resources can be more economically viable than recycling and businesses don't always factor in the environmental and societal costs of virgin material extraction and waste generation.

Moreover, the technology of sorting and recycling for many materials makes downcycling to lower-value products the only feasible option, due to material contamination and the difficulties in disassembling different materials. So far, we have seen limited investment in improving recycling technologies.

Technology and innovation are key to creating higher circularity, so that products are created from the start with a plan for putting the product or its material components back into the value chain. Some industries require a strong focus on new technology and innovation, while others that are more technologically mature will need to find ways to scale their existing technologies. Whatever the stage of the business, however, capital investment is required for the design of innovative products with a focus on reuse and eventually recycling.

To ensure that the infrastructure is in place to collect all waste and dispose of it correctly, to move away from single stream collection into material specific collection, companies need to invest in building this collection infrastructure. Also crucial is the technological advancement and expansion of sorting equipment so that materials can be broken down into their main components for high-quality recycling. In addition, capital expenditure must go into the technological advancement and expansion of equipment capacity to recycle materials that can be reused in new products, partly replacing the use of virgin materials.

In this report we outline a set of proposed recycling and collection objectives for eight materials that yield high levels of waste in terms of volume, value and/or environmental impact: cement and concrete, metals, biowaste, wood, paper, plastic, electronic waste (e-waste) and electric vehicle (EV) batteries.

An estimated capital expenditure of USD $2.1-2.2 trillion will be needed to reach a recycling rate of 80-90% across these materials globally by 2040. The investment would be split between design (USD $500-530 billion), collection (USD $170-200 billion), sorting (USD $180-210 billion) and recycling (USD $1.2 trillion).

Globally, around 24% of the cost would go into product design innovation. For collection, sorting and recycling, we have broken down the capital estimates into regions based on regional waste volume, collection and recycling rates as of 2020 and the projected rates for 2040, as there are significant differences in regional prerequisites to achieve the 80-90% recycling rate across collection, sorting and recycling. According to these estimates, the Asian Pacific region will need 48% of the regional investment in collection, sorting and recycling. Europe and North America, which have the most mature collection infrastructures and recycling systems, will need 8% each (total 16%).

Latin America, the Middle East and Africa, which have a less mature collection and recycling systems and lower waste generation will need 6% each (total 12%).

These investments often present positive business opportunities. The capital that is needed accounts for less than 1% of the total annual market size (by industry revenues) for the materials covered here. At the same time, demand for recycled products is rapidly increasing.

For example, the investment required to achieve the recycling aspirations for the wood industry is USD $7.5 billion per year, equivalent to only 1.2% of the industry's annual revenue; while the investment needed in the paper industry is USD $11.5 billion, equivalent to a product price increase of only 1.3% on average.

Moreover, achieving a recycling rate of 80-90% across these industries will have a tremendous impact on the climate, as well as biodiversity and societal equity.

Meeting these recycling levels would save 40-50 billion tonnes of carbon dioxide (CO2) emissions between 2021 and 2040. This is equivalent to saving 10-15%2 of the remaining carbon budget as expressed in the terms of the Paris Agreement.1 Put another way, this is equal to a year's worth of emissions from 12,000 coalfired power plants or 10 billion passenger vehicles.[2]

Benefits to the biodiversity of the planet would include more unspoiled territory for endangered species through better forest management, less unsustainable quarrying and mining and less contamination of water and soil due to the reduction of hazardous waste and micro-material pollution. Recycling on this scale would also result in less water consumption and more sustainable management of nature's resources. The extent to which natural resources can be saved will, of course, vary from one industry to another. For example, an 80-90% recycling rate in the paper industry can save 58% of the industry's required input of water resources, while metal recycling can save 40%.

While it will take a strong coordinated effort on the part of governing bodies, manufacturers, investors, industry organizations, NGOs, consumers and recyclers, large scale recycling can also have a positive societal impact.

The transition from informal systems of waste recycling to formal ones has the potential to increase job opportunities and secure better working conditions for people at the margins of society.

Studies show that for every 10,000 tonnes of metals, plastics, paper and cardboard and organic waste, landfilling or incineration can create only two jobs, while recycling the same materials can create more than 100 jobs. Repairing – avoiding the creation of waste – can create even higher numbers of jobs, three to four times higher than those created by recycling. In addition, health and wellbeing will be improved for all as pollution, chemical exposure and disruptive exploitation of local land are decreased.

This report is intended to serve as a starting point for global communities, including the stakeholders noted above, to establish guidelines for the use and recycling of materials in the coming decades.

The report highlights some of the key challenges to circularity on a global, regional and industry level. It provides a technology focused and ambitious lens on what the future of recycling could look like if key actors come together to overcome these challenges. Finally, it breaks down the costs of innovation and equipment that will be needed to meet sustainable recycling objectives and examines the impact of these objectives on the climate, nature and society.

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What you will find in this report:

- A starting point for global communities, including the stakeholders noted above, to establish guidelines for the use and recycling of materials in the coming decades.
- A set of proposed recycling and collection objectives for eight materials that yeild high levels of waste in terms of volume, value and/or environmental impact.
- Highlights of some of the key challenges to circularity on a global, regional and industry level.
- A technology-focused and ambitious lens on what the future of recycling could look like if key actors come together to overcome these challenges.
- A breakdown of the costs of innovation and equipment that will be needed to meet sustainable recycling objectives and examines the impact of these objectives on the climate, nature and society.

① A circular approach to resources

The Earth's resources are key to allow humanity to develop and thrive for generations. Currently, industries and consumers are exploiting those resources beyond the extraction limits of finite resources and replenishment rates of renewable resources, as well as the planetary boundaries[3] that science has established to maintain these favorable conditions (see definition, Box 1).

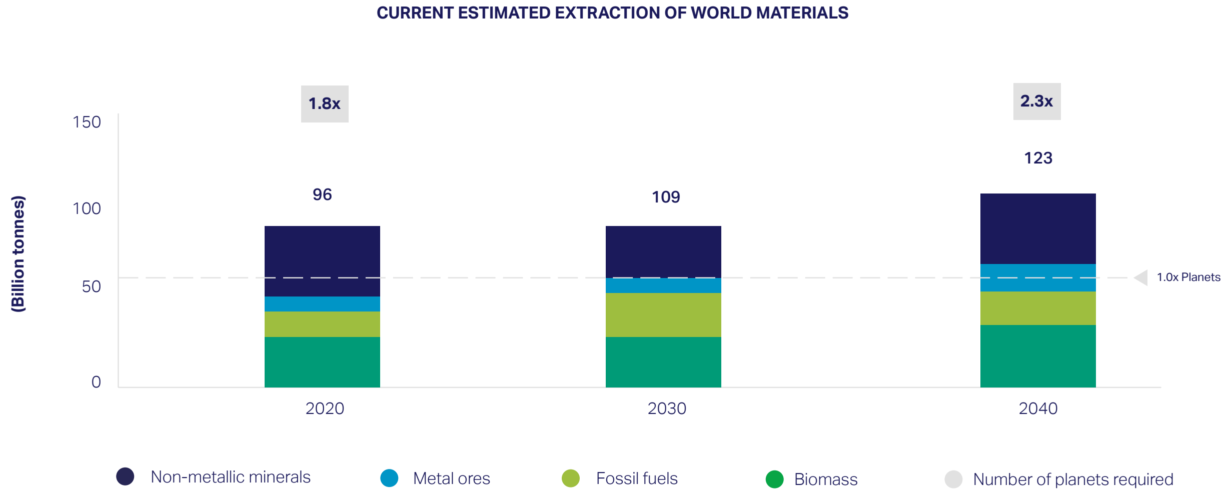
At current consumption levels, we would need 1.8 planets to continue to provide the resources we are consuming and to absorb our waste.

If the population and material demand continue to grow at the present rates, we will need 2.3 planets by 2040 (see Figure 1). Moreover, the numbers are significantly higher in several Western economies; the U.S., would need five planets to make its present-day consumption levels sustainable, while Germany would need three.[3] Since we have only one planet, we must lower this consumption so that the Earth can renew its resources. By consuming less than the planet produces we can protect the climate, stabilize the Earth's biodiversity and improve societal equity.

The rapid pace of global economic growth has increased the demand for resources. Consumption has more than tripled from 1970 and continues to grow.[4] While some high-income countries are becoming more resource-efficient, global material productivity (defined as USD of GDP per kg of material use) has declined since 2000.[5]

The global circularity level was only 8.6% in 2020, down from 9.1% in 2018 (see Table 1: Key Definitions, p.10).[6] Each year we extract and harvest 90 billion tonnes of resources from the planet.[7] Of these, 25% are renewable (biomass), with a 29% expected growth over the next two decades, while 75% are non-renewable resources, including fossil fuels, with a projected 28% growth over the next two decades.

Figure 1: Action areas to achieve transformation



Source: OECD, Global Material Resources Outlook to 2060; Footprint Network, Ecological Footprint: Managing Our Biocapacity Budget

According to the BCG CIRCelligence report, at the current rates of circular improvements it will take more than two centuries to develop a circular economy that designs products with the intent of making them recyclable and regenerative.[8] So far, we are seeing only limited efforts by some countries; Germany, for example, has improved its circularity by 0.1-0.2% per year.

Our economy and society are dependent on continuous growth of wealth. For living standards to keep increasing, however, we need to ensure that future generations have enough resources. Yet at current consumption rates many of the Earth's resources will be scarce by the mid to late 21st century.

There is also a strong political and economic rationale for preserving scarce resources by increasing circularity.

To achieve the circularity that will ensure the preservation of our resources, we need a plan along the lines of the Paris Agreement,[9] with its call to limit global warming by no more than 2 degrees Celsius, preferably 1.5 degrees. There should be a similar global agreement to limit resource utilization. The objective should be no more than 1.0 planet, preferably by 2040. A slower pace will result in a situation in which many resources are no longer available, while nature and society suffer irreparable damage.

BOX 1: Planetary boundaries and resource limit

The planetary boundaries are a set of nine physical and biological limits to human activity. The core boundaries of climate change, loss of biosphere integrity, land-system change and altered phosphorus and nitrogen cycles have already been crossed, partly as a result of resource depletion lack of circular solutions and excessive-waste, which are the focus of this report.

When defining the resource limit in terms of number of planets that are currently being consumed, both the rate of replenishment for renewable resources and the scarcity of finite resources (e.g., ores from metals such as steel, aluminum and those in EV batteries and e-waste) should be considered. For the purpose of this report, we used the renewal capacity as a proxy for finite resources, though it should be understood that they are finite and alternative resources would be needed eventually.

Setting sustainable levels

Designing materials for reuse, repairability and recycling today will cost far less than it would to extract such materials from landfills 50 years from now—but that will be our only option if we don't begin to act now.

In order to preserve life on the planet as we know it, we will need to protect both the climate and the present levels of biodiversity, as well as build a future that ensures greater societal equity. These end results are possible only if we develop ways to extract less than one planet's worth of resources, so that the Earth can renew what its inhabitants have consumed and continue to regenerate.

Since both the global population and material demand are steadily increasing, material recycling will be critical to reversing the current extraction rates. We will need to decouple resource usage levels from economic growth by increasing the circularity of industries that use the Earth's resources.

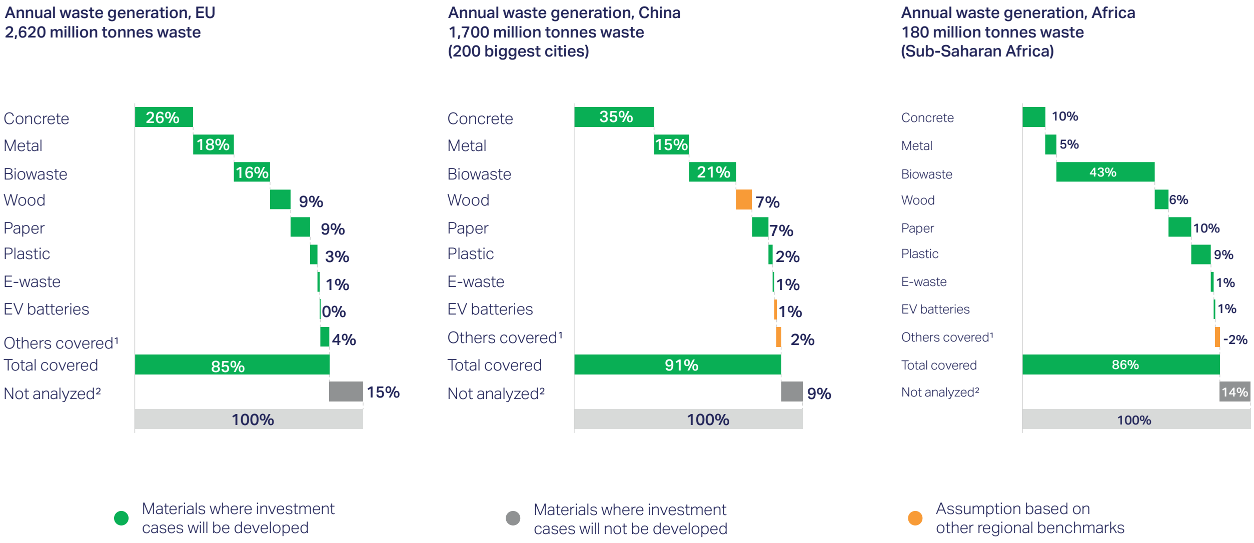
BOX 2: Materials in focus for this report

Throughout this report we will draw on insights from the recycling and recovery of various materials, focusing on waste materials in the following categories:

- Cement waste
- Metals (particularly steel and aluminum)
- Biowaste
- Wood
- Paper
- Plastics
- E-Waste
- EV batteries
- Other covered materials: rubber, glass, nylon

In total, these categories make up 80-90% of annual waste generation (up to 85% of waste in the EU, up to 91% in China and up to 86% in Africa, according to waste volume sources) (see Figure 2).

Figure 2: Annual waste generation from EU, China and Africa



[1] Rubber, packaging glass, nylon
[2] Chemical and medical, non-nylon textiles, fiber and construction glass and sludges

Note: Mineral and solidified waste (except concrete-waste) are excluded; mixed ordinary waste (household, sorting residues, other mixed waste) into other waste categories. Source: Eurostat 2018 w. Concrete-waste data per National and regional waste plans from EU Member States; UNEP; Statista; web research

Table 1: Key definitions used in this report

Circularity: A circular economy is an industrial system that is restorative or regenerative by intention and design. It is a model of production and consumption which involves sharing, reusing and repairing, refurbishing and recycling existing materials and products as long as possible. Relying on system-wide innovation, it aims to redefine products and services to create value and design out waste while minimizing negative environmental and societal impact.

Collection: Collection and transport of waste to the place of treatment or discharge.
Our investment case for collection and sorting uses the collection rate.

Recovery: Any operation that produces the primary result of making waste serve a useful purpose by replacing the materials that would have otherwise been used.

Recycling: Any recovery operation by which waste materials from one product are reprocessed into other products, materials or substances whether for the original or other purposes.

Closed-loop recycling: The process by which a material can be used and then turned into a new product or converted back to raw material over and over, without losing its properties during the process. Closed-loop recycling is the preferred method, though there will be acceptable open-loop recycling along the transformation journey.

Composting: A recycling method for biowaste, decomposing organic solid wastes to be used to fertilize or improve soil.

Biogas conversion: Anaerobic digestion to produce biofuel from the decomposition of biowaste. Even though it is a waste-to-energy method, we include it in the investment case, as it is another main treatment method for biowaste in addition to composting.

Waste-to-energy (excluding biogas conversion): The process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source.

Currently we are recycling 25-35% of the-waste streams, based on both value and volume, from the industries covered in this report.

While the properties and renewability factors vary greatly between one material and another, we have determined that to keep from depleting the Earth's resources we will need to recycle an additional 55% of all of the waste streams on average by 2040. Adding the existing rate to the additional recycling that is needed means that we need to achieve a total recycling rate of 80-90% on average for all materials by 2040 (see Figure 3).

This 80-90% recycling rate can be seen as the circularity equivalent of the proposals in the Paris Agrement for limiting global warming.

Figure 3: Global recycling objectives for selected materials

We need to strive towards

80-90%

Global recycling by 2040

This should be the equivalent recycling objective to the 1.5-degree climate goal of the Paris agreement

[1] Rubber, packaging glass, nylon

Defining what is possible

As is the case today, recycling practices are likely to spread differently across regions and materials, but will require significant changes in most industries across the world. While the overall aspiration is to recycle 80-90% of all materials, the potential for each industry will differ due to technical feasibility and other limits. The aspirations are based partly on what is technically feasible today, but also on an informed prediction of innovations that are needed and can be achieved by 2040 (see Figure 4). Industries will need to come together, however, to create guidelines within the art of the possible. Looking at the key materials covered in this report, we find that it is a stretch but technically possible across the board to reach average recycling and collection rates of 80-95% by 2040.

Concrete has a collection rate of 60-70% globally, but only 25-30% of waste products in this category are recycled. Recycling techniques for concrete-waste include reusing the product on site, e.g. for road sub-base, as well as closed-loop recycling, or mixing the concrete with aggregates in clinker or cement production. Closed-loop recycling is the optimal recovery method, as when concrete is reused on site the material will require more extensive recovery practices such as excavation to be reusable a second time. Many European countries (e.g., Switzerland and the Netherlands) have already achieved 95% collection and recycling rates, which we have set as the 2040 objective for the overall waste stream, with closed-loop recycling constituting 75% of all recycling activity. This level is technically feasible considering that some cement production has some requirements on the use of virgin aggregates to achieve the necessary strength performance.

Although **steel and aluminum** products are currently recycled at a rate of 75-80% and collected at a rate of 82%, it is theoretically possible to recycle close to 100% of metals, as recycled pure metal products have similar properties to virgin materials. In practice, however, 100% recycling is not feasible because alloyed metal products are adulterated by the use of other materials, especially copper, making sorting unfeasible. Furthermore, particularly in rural areas the infrastructure setup does not exist to collect all metal wastes. The aspiration for 2040 is a collection rate of 97% and a recycling rate of 95%. Within these rates, it is possible to reach 100% recycling of home scrap and prompt scrap, which make up 18% and 20%, respectively, of total steel scrap. Of the rest—the 62% that is obsolete scrap, 90% needs to be recycled. The last mile recycling must be made economically viable to make obsolete scrap recycling possible. A 95% recycling rate will cover 60% of steel demand; as such, the prerequisite is that 60% of the steel and aluminum the world consumes can be successfully covered by recycled steel, both from a supply and demand perspective.

Data is scarce on the current level of collection and recycling of **biowaste** and can vary widely. Collection rates vary from 10% to 90% for European countries, while globally only 83 million tonnes are recycled out of 665 million tonnes of waste.[10] To cover materials lost in the processes, an additional 5% of biowaste should be collected, bringing the global collection objective for 2040 to 90%. The recycling rate for 2040 should be 85%, with a 70-80% rate for municipal bio-waste and 90-100% for industrial bio waste. These levels are based on the objectives set by countries that currently have the best practices; Bulgaria, for example, is already aiming to recycle 75% of its municipal biowaste by 2025.

Today, 80-85% of **waste wood** is collected, but only ~21% is recycled. Although wood is a renewable material, recycling is necessary to help reduce the use of virgin wood and therefore the forests. The aspiration is to reach a collection rate of 90% and a recycling rate of 80% by 2040. Waste wood is expected to comprise about 20% of total wood demand by 2040. Accounting for yield losses, if we can recycle 80% of wood waste, it will cover 8% to 10% of wood demand at that point. To achieve this objective, it will be necessary to develop significant mechanical recycling capacities and chemical recycling capabilities.

Paper collection and recycling is a relatively mature practice already, with a collection rate of 80% and a recycling rate of 60%. Technological advancement is expected to increase the recycling activity significantly over the next few years.

By 2040 we can expect to see the collection rate reach 95% while the recycling rate should reach 80%. The recycling rate for 2040 is the estimated practical maximum limit for paper recycling. Paper is recycled only five to seven times on average[11] while individual paper fibers can be recycled 25 times or more maintaining paper quality[12] and some paper consumption, such that of hygienic paper products, results in contamination so that recycling is not technologically feasible.

Plastic is recycled at a rate of only ~16% globally, although the collection rate is 75%. It is very difficult to recycle some plastics, primarily because the composites, mixes and certain additives used in polymer products can make the product difficult to break down. Industries will need to look into innovation that would allow them to design plastic products with less complexity and using fewer and more circularity-friendly additives and advance the sorting technology to develop a higher quality of recoverable plastic feedstock. It will be necessary to invest in capacity for mechanical recycling and innovation in chemical recycling to tackle products that cannot be recycled mechanically. Waste reduction is another important initiative—we will need new forms of design that reduce the use of plastics by avoiding overpackaging and increasing re-use options where feasible.

Overall, we recommend a waste volume reduction by 20%, a formal collection rate of 90% and recycling of 80%, by 2040.

A large amount of **e-waste** is collected but then sent to landfills or informally recycled. While the collection rate is estimated to be 70-80%, only 17.4% of e-waste is currently recycled formally. We see the potential to collect 85% and recycle 80% by 2040, factoring in the limitation that 5% of e-waste is non-recyclable or is lost during the collection process. These levels are in accordance with the EU's current guidelines and are technically feasible today. We cannot achieve 100% recycling due to technological limitations. The complex composition of e-waste leads to some elements being lost in the recycling process, for example plastic being lost in the pyrometallurgical process step, or e certain metals being partially lost in slags or in the hydrometallurgical step.

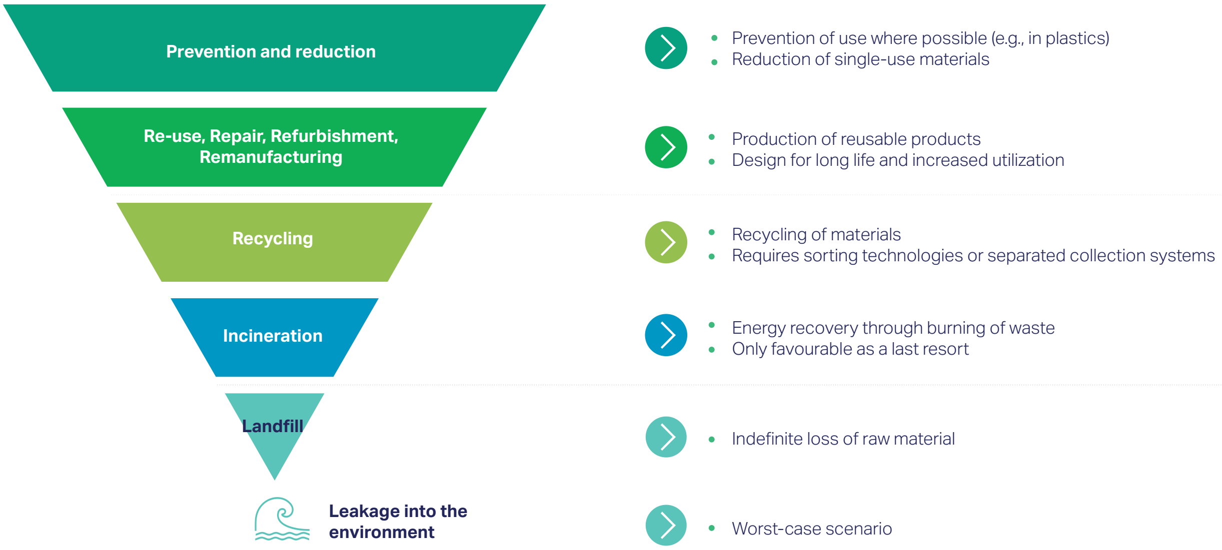
A design for recylability can help to improve the recovery rates.

Today, 85-100% of all **EV batteries** consumed are collected, though only 50% are recycled. However, the current use of EV batteries produces only a small waste stream—estimated to be less than 1 million tonnes per year. The-waste will increase significantly as electric vehicle use grows and by 2040 we should be collecting 95% and recycling 90%.The 90% recycling rate is the current best practice for recycling lithium ion batteries, as exemplified by the U.S. Department of Energy Recycling Prize. For other types of batteries the rate can be even higher.

Figure 4: 2040 collection and recycling ambitions for selected materials

It should be noted that increasing circularity is not just about increasing recycling rates. When it comes to overall waste management there is a clear prioritization, starting with prevention and reduction, followed by re-use and then recycling (see Figure 5). Incineration should be considered only as a last resort. Dumping materials into landfills or leaking them into the environment should be avoided at all times.

Figure 5: Prioritization in waste management



- Prevention of use where possible (e.g., in plastics)
- Reduction of single-use materials

- Production of reusable products
- Design for long life and increased utilization

- Recycling of materials
- Requires sorting technologies or separated collection systems

- Energy recovery through burning of waste
- Only favourable as a last resort

- Indefinite loss of raw material

- Worst-case scenario

② The challenges

Most business leaders know that a circular business model is increasingly necessary in today's world and some industries are starting to move in this direction. However, change is happening at a very slow pace, largely because there are multiple challenges throughout the entire value chain to meeting the objectives outlined in Chapter 1.

Regulatory measures that would help guide the process of material recycling have been historically slow in coming and there is not a great deal of transparency about the impact of recycling to encourage the process. Leading progressive companies are starting to look at ways to develop collaboration along the value chain to encourage the effort, but collaboration is still in a nascent stage. Technological solutions have been difficult to bring to scale and although the degree of recycling-conscientiousness ranges greatly within communities and countries, the global population at large has not established the consumer behavior patterns that are needed. Complicating the picture is the fact that circularity levels also vary greatly from one industry to another, as do the processes, technologies and costs that go into building a circular business model.

Yet linear value chains are simply not sustainable, so all industries need to clearly identify and understand what actions they must take and where they need to direct their investments.

Overcoming the barriers to circularity

Several challenges related to the business value chain are systemic, stemming from intertwined economies and complex value chains across multiple industries. These challenges range in their nature from behavioral to technological to cultural and budgetary.

If a business is to be fully circular, every step of the value cycle needs to play a role. Here we look the strategic considerations that must go into five main phases of a product's value cycle: raw material input, design, use, the collection and sorting process and finally, recycling. These are the steps that make the highest level of impact on an industry's circularity.

Circularity begins with addressing the challenges presented by the raw materials. Products should be made with materials that, as much as possible, come from recycled or renewable input and a design that fosters circularity, thereby reducing the need for raw materials extraction.

However, with some materials, particularly scarce materials such as precious metals, extraction produces adverse effects on nature, the environment and societal equity—for example through high carbon dioxide emissions, human rights abuses such as child labor, or appropriation of land that local communities depend on for their livelihoods.

Businesses must agree to use materials that are regenerative or already recycled and ensure that their raw material extractions are conducted in a sustainable and socially responsible manner while providing transparency about their sourcing.

Products become difficult to recycle if they are designed with a mix of materials. Most existing product business models are linear rather than circular, leading to a lack of economic incentive to design for circularity or longevity. To break down this barrier to change, businesses need to reduce and simplify the use of materials in the design phase and innovate in ways that will make it possible to design products for multiple uses over a long period, with components that can be recycled and reused.

A plan needs to be in place for consumers to use products responsibly and reduce the amount of waste created during the use phase. Right now, value chains are not optimized for product longevity; we need more sharing, renting, leasing, re-selling, or re-using, as well as simpler reparability and less excessive consumption. As wealth grows in many parts of the world, consumers only increase their purchases of disposable products. While they need products that are designed for multiple use, they also need regulations and incentives to encourage them to recycle, re-use and share what they buy.

Businesses also need to develop strategies for collecting waste and sorting it into different categories. Many countries lack the adequate collection systems, however, as well as regulatory incentives and consumer awareness of recycling and collection objectives.

Businesses need to build a value chain that includes the collection of products and materials at the end of each lifecycle to close the loop on disposal and avoid landfilling.

For the recycling phase, the last step before the product or the materials go back as production input for new products, governing bodies need to establish supporting regulations and strong incentives for recycling. Examples include setting minimum required recycled content or recycling rates, establishing extended producer responsibility (EPR) policies that add the environmental costs associated with a product to the market price and levying other costs for low circularity.

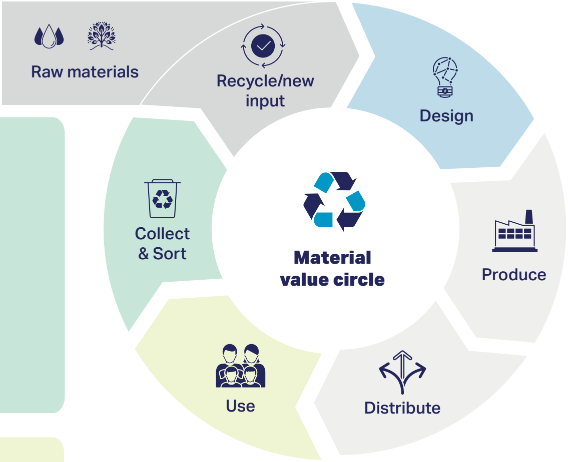
Consideration should also be given to the type of input raw materials when thinking about circularity be it recycled or renewable choice considering the whole life cycle carbon footprint. Businesses need to invest in technologies and innovation that make it possible to avoid using materials that are unrecyclable because of toxicity. Businesses should also build products for the future with recyclable and recycled materials, employing production methods that make it possible to separate materials so that they can be re-used for input, rather than simply downcycled.

These barriers to large-scale recycling vary greatly from one industry to another, which adds to the challenges across the value cycle (see Figure 6).

Businesses that try to build circularity into products made with plastics, for example, will find that few products have been designed for recyclability and re usability. To compound the problem, collection systems are inadequate and there are sorting and technological limitations, especially when it comes to mixed and contaminated products. Demand for recycling is low and with few financial incentives or meaningful regulation and monitoring, the industry faces an uphill battle.

Challenges to achieving circularity in e-waste products include the frequency with which consumers replace their personal electronic devices, such as cell phones and laptops, with little awareness of the environmental impact. In addition, few markets have the level of sophistication that is needed in their collection infrastructure. There is little standardization in the materials used in electronic products and some of the components become hazardous when broken down. Additional challenges include a lack of transparency on trade flows and an inefficient secondhand market, combined with highly complex recycling processes and technologies, plus a shortage of economic and regulatory incentives to recycle in certain geographies. Moreover, reporting procedures related to e-waste recycling lack clear metrics, standards and transparency.

Figure 6: Key challenges to circularity across industries



Steel & Aluminium
Lack of waste collection infrastructure and appropriate sorting technology to avoid downcycling in recycling process.

Paper
Contamination of paper from production (coating of paper), use, and disposal into single-stream waste bins.

Biowaste
High food loss and waste at consumer stage (especially in developed markets).

E-waste
Frequent replacement of personal electronic devices (e.g., cell phone, laptop) due to low awareness of e-waste impact.

Cement
Technical limitations on recycled concrete aggregate; virgin material input is required.

Wood
Challenge to repurposing. Most recycled wood is down cycled and applied in a limited range of wood products.

Plastics
Complexity of products—seven main plastic grades with thousands of polymers—makes it difficult to sort and recycle.

EV Batteries
Technological uncertainty associated with converting batteries for second life usage.

Gauging the consequences

Though there are many hurdles, we cannot afford to continue using and discarding materials at the present rates. If industries don't tackle these challenges to circularity, the impact on climate, nature and societal equity will be disastrous (see Table 2).

About 20-25% of global greenhouse gases are the result of emissions from industry and agriculture materials management, while the remaining are attributable to energy supply, transport and end users of products.[13]

Resource extraction and production—through agriculture or mining, for example—are the main causes of biodiversity loss due to land-use changes, disturbance of land surfaces and overuse of water resources. Conventional patterns of natural resource use are generating 90% of global biodiversity loss and water stress and 11% of global species loss.[14]

When it comes to societal impact, the linear economy has clearly brought prosperity to many segments of the population, but rapid economic growth has also led to excessive levels of material extraction and consumption that present immediate threats to the most vulnerable populations.

Raw material extraction, for example, has led to human rights abuses as well as over-use of critical resources, such as when water is diverted from local farmers who then have no choice but to abandon their settlements and become migrants.[15] Furthermore, current practices around extraction and handling of materials often expose workers in the informal recycling sector—waste pickers, for example—to serious health hazards.

Table 2: Effects of linear economy on climate, nature and social equity

Cement & Concrete	Cement industry is responsible for 400Mt of annual CO_2 emissions in the US alone, equivalent to 6% of total US emissions
Metals	Bauxite mining for aluminum takes up large areas, often covering land that has significant ecological value and that local communities depend on for their livelihoods[1]
Biowaste	When dumped into landfill, biowaste undergoes anaerobic decomposition; this generates methane, 25 times more potent a greenhouse gas than carbon dioxide
Paper & Wood	When sequestration is considered, net greenhouse gas emissions from the forest products value chain is 467 MT of CO_2 equivalent per year (1% of total CO_2 emissions)
Plastics	Marine plastic pollution is affecting at least 267 animal species, including 86% of marine turtles, 44% of seabirds and 43% of marine mammals[2]
E-waste	Overall, 70% of reported toxic and hazardous chemicals in the environment today come from e-waste[3]
EV Batteries	About 20% of cobalt (used for EV batteries) sourced from the central African nation comes from artisanal mines, where some 40,000 children work in extremely dangerous conditions[4]

[1] Why Car Companies Should Address the Human Rights Impact of Aluminum Production | HRW;
[2] UNEP 2020 "Biodiversity Protection;
[3] Sustainability MDPI "Electronic Waste and Environmental Problem Exported to Developing Countries";
[4] UN News

③ What it takes

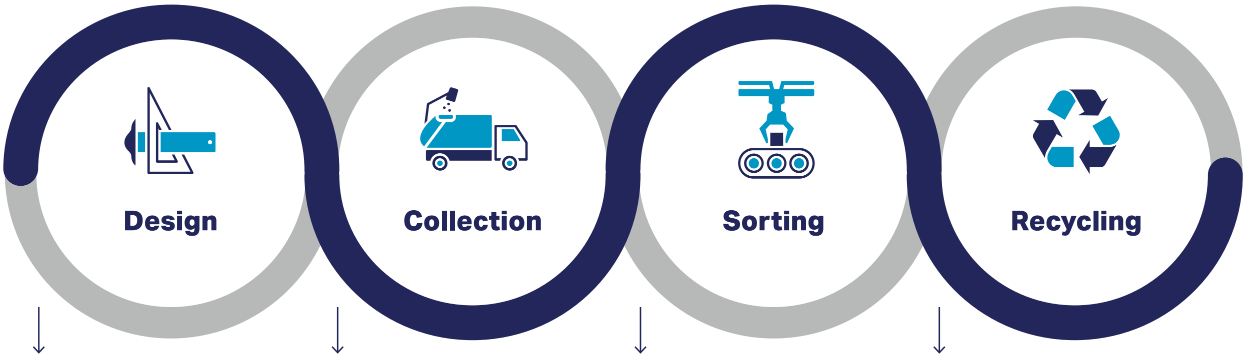
Industries will need to implement a range of actions to achieve the recycling objectives outlined in Chapter 1 and ensure that we stay within resource limits. The actions include developing improved and advanced technologies and creating more extensive financing options for investing in circularity.

Industries should also push for regulatory incentives that encourage circularity, while consumers and industries alike will need to increase the demand for circularity throughout the value chain.

In this chapter we look at “what it takes” in terms of developing technology and innovation and investing in expanding these capabilities.

Businesses have an important role to play in making advanced technologies widely accessible and affordable at each stage of the material process chain (see Figure 7). While we can’t assume that “if you build it they will come” –and all stakeholders should be prepared to build awareness locally and/or globally—any technology that makes circularity easier will help encourage regulatory support and enable responsible consumer behavior.

Figure 7: Technology and investment needs along four steps of the material process



How are products designed and developed for consumption / re-use and recyclability?

Is waste collected for recovery?
How is waste collected (bins, trucks etc.)?

Is waste properly sorted for reuse of materials?
How is waste sorted?

To what extent are materials recycled / recovered?
How are materials recycled / recovered?

What does it take to reach the recovery objectives for each industry?

Innovating with technology

While the needs vary greatly from one industry to another, every business should study how it is currently designing, collecting, sorting and recycling products and how the methods might be enhanced in the name of greater circularity.

In general, in the **design** phase, innovation is needed to improve the product circularity, including reusability, renewability and recyclability.

First, innovation is critical to the effort to reduce material input. As much as possible products should be made from the start with recycled materials. This will help ensure a market for recycled output and ultimately lead to reduced extraction of materials. In addition, businesses should invest in R&D that seeks to design products with less material input.

Second, innovation is needed to improve the lifespan, reusability and reparability of products. The aim should be to turn away from designing any single-use products.

Third, innovation is required to design products with an eye toward where they will go after each use cycle. We need products made from less complex material mixes, as mixes and additives can be difficult to separate and recycle and we need products that reduce the use of chemicals and additives hampering circularity. Plastic products, for example, are still often manufactured with mixes of polymers and chemical additives that are difficult to separate out. Chemical innovation can play a role here, e.g., in enhancing plastic properties to facilitate mechanical or chemical recycling. Further innovation is needed to facilitate disassembly, repair and modularity, so that components can be dismantled or repaired. A smartphone, for example, often contains more than 70 different elements and there is no easy way to disassemble and re-use the multiple metal, plastic and glass parts.

There is significant potential for improvement through innovation at the **collection** step, although there are very different starting points depending on whether we are talking about post-consumer waste, industrial waste, or construction waste.

There are, generally speaking, three levels of collection system maturity for post-consumer scrap. The most sophisticated systems provide source separation, often through a selection of bins clearly marked for such substances as plastics, metals, glass, or biowaste. These systems can be found, for example, in EU member states such as Germany and in certain parts of Canada.

At the next level, curbside or street collection systems have one or several bins to assure that waste is collected, but most of these systems are single-source and therefore require further sorting for higher recyclability. The least mature system is simply no collection at all, a scenario found mostly in rural areas with limited logistics and infrastructure. Here, waste is often openly dumped, burned, or left as litter on the ground and in the oceans. This a serious issue in Southeast Asia and Africa, where in some regions waste is routinely dumped or burned.[16] There have been initiatives that aim to increase source-segregated bin systems via EPR strategies such as Pro Europe (Packaging Recovery Organisation Europe), an industry-financed collection system.

The systems for industrial waste hauling vary greatly depending on the industry, the regulatory climate and the incentive systems. The-waste might be sent to a scrap yard, a waste center, or a recycling center. Some industrial scrap, such as prompt steel scrap, can be re-used on site, with no collection process needed.

The collection system for construction waste is subject to strict regulation in the EU, requiring collection in bulk, while in some African countries construction waste can be left to deteriorate in the ground and in some parts of the U.S. the majority of construction waste goes into landfill.

For product collection, some countries and companies are implementing customer return systems. This is generally done through incentives. Stores might "pay" customers to return bottles and cans; Denmark's "Pant" grading system, for example, sets the refund according to the type of materials in the containers. The incentives might also come in the form of an appeal to consumer responsibility, as in the case of a coffee retailer that uses recyclable aluminum capsules and asks customers to return them when they're empty.

To reach the full potential for circularity, most parts of the world will need to significantly expand their waste collection systems. This is particularly the case for Asia, where high amounts of waste are generated and population is growing, but little of the-waste is collected for recycling compared to the collection rates in Europe. However, North America, Middle East & Africa (MEA) and Latin America are also lagging behind the collection rates of Europe.

Many industries in most of the world also need smarter, more sophisticated and innovative collection systems. For example, countries and municipalities could improve curbside collection with automated systems that use the internet of things and sensors to detect when a commercial site or a public area has a buildup of waste and also track data by location to optimize pickup schedules. Instant payments for return – for example, through e-waste reverse vending machines for used electronics – can help incentivize customers to drop off products. New waste management apps can also support the expansion of dedicated waste pick-ups. TooGoodToGo, for example, is an app that restaurants can use to alert customers of special sales on surplus food, rather than throwing the food out.

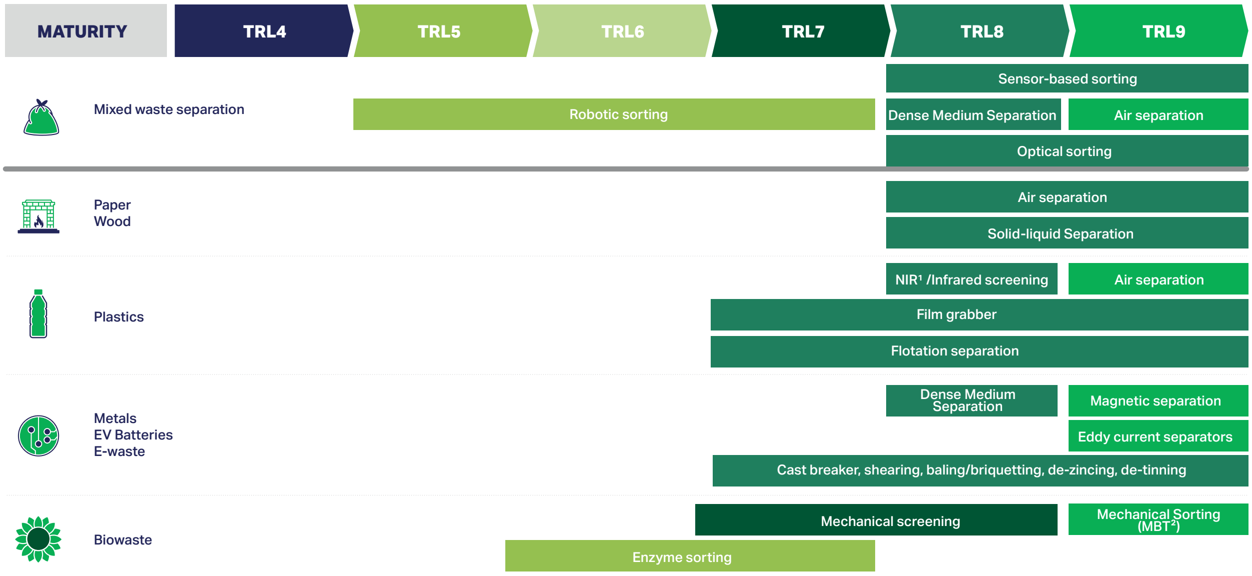
At all times, it is important to ensure that increased collection does not result in a significant increase in GHG emissions, as can happen when waste is transported. Consequently, businesses will need to develop advanced collection technologies alongside a plan for green transport, using hybrid trucks, for example and route optimization.

At the **sorting** stage, circularity depends on the source and nature of the material as well as the way that it has been collected. Pre- and post-industrial scrap is often comprised of relatively pure materials that require little or no sorting to be re-used as material feedstock. Post-consumer scrap, on the other hand, is often contaminated from the materials in the end-product or wastes from the collection process, requiring a much heavier sorting process.

The method of material collection influences the sorting effort and quality. Stream-specific material collection, such as paper collection from paper bins, makes for a much cleaner sorting process than that of paper that has been collected via single-stream sorting, particularly because the paper is often contaminated from food and other waste.

More advanced sorting technologies are needed for mixed waste that has to be broken down into different materials. The technology and innovation required will, of course, depend on the material type and whether there is a need for mixed-waste separation. Existing technology readiness levels (TRLs) for material sorting also vary greatly by scalability and maturity (see Figure 8).

Figure 8: Sorting technology readiness levels (TRLs) vary by material



[1] Near-infrared (NIR);

[2] Mechanical Biological Treatment (MBT)

Source: Expert interviews

A number of mature technologies that are currently in use sort waste that has been collected in a single stream. These include sensor-based sorting, air separation and dense medium separation.

Sensor-based sorting uses color, X-ray or near-infrared sensors to distinguish between colored and colorless PET and HDPE flakes and separate flakes by color. This category includes X-ray sorting technology, which separates the materials based on their specific atomic density. Near infrared (NIR) is used for plastics sorting because it can accurately identify the many different polymers already in use today.

In air separation sorting, fan driven air inlets generate a stream of air above the conveyor belts to facilitate identification of different materials by weight. Air separation sorting is particularly useful for packaging and paper.

Dense medium separation sorts particles based on differences in specific gravity (SG).

Technology with robotic sorting is still nascent, which uses advanced cameras and technology, artificial intelligence (AI) and robotics to recognize specific items such as cans, glass, or plastic containers.

Stream-specific sorting technologies are now in fairly widespread use for waste that has been collected according to its properties. Depending on the materials, the sorting may be done through magnetic separation, eddy current separators, mechanical screening, or film grabber sorting.

Film grabber technology accelerates the separation of plastic waste by moving the materials onto a rotating drum with spikes. The spikes hook plastic film and let other waste materials drop off.

Magnetic separation uses electro-magnets to allow the removal of collected ferrous metals.

Eddy current separators use electrical currents to push non-ferrous metals with magnets into separate collection points, with non-metallic waste falling into another.

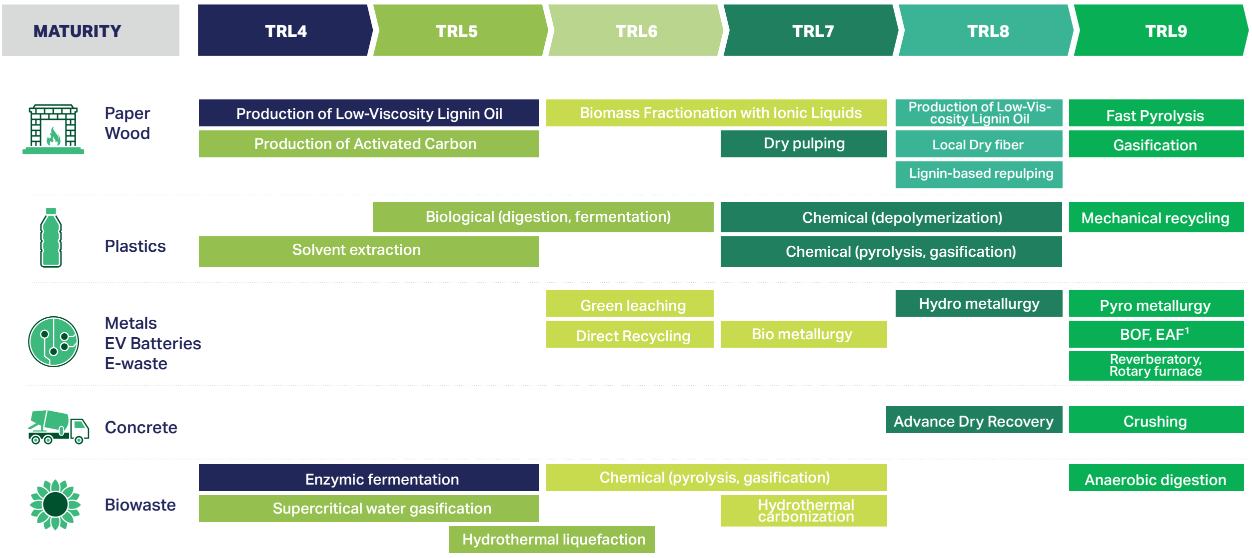
A mechanical screening machine is used mainly to separate materials in the mineral and solid-waste processing industries. Materials are separated by size as undersized materials pass through the screen while oversized materials exit at the other end.

Recycling We define recycling as any recovery operation by which waste materials are reprocessed into products, materials or substances. We include composting and biogas conversion for biowaste, as they are primary recycling methods.

The recycling stage can be either a closed-loop process, in which the product doesn't lose its original properties, thereby ensuring indefinite re-use, or an open-loop one, in which the materials are re purposed into different products, in which case the material may have several more life cycles but will ultimately end up as trash. Closed-loop recycling is clearly the preferred method, though there will be acceptable open-loop recycling along the transformation journey.

When it comes to specific materials, certain industries are far more advanced than others and deployment across regions, countries and even municipalities vary strongly. All industries, however, need to put significant amounts of investment capital into R&D in order to meet the overall recycling objectives of 80-90% (see Figure 9).

Figure 9: Sorting technology readiness levels (TRLs) vary by material



[1] Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF)

Source: Expert interviews

The recycling rate for **paper** is already high, at an average of 60%. As a first step, businesses can in all likelihood increase their paper recycling just through extended use of existing technology. Technological improvements at different steps of the process – contaminant removal, sorting and pulping, for example, might also contribute to greater recycling with more energy-efficient production, especially for contaminated paper.

What the paper sector needs most is technological innovation for the design and recycling stages. In the design stage, we will need more compostable lamination and adhesives for paper packaging to minimize unrecyclable contaminated paper. For recycling, we need advancements in equipment to recycle residual contaminated paper. Stronger capabilities in these areas could potentially increase the practical maximum recyclability to 80%, the level we have set as the objective for 2040. To reach this level and increase overall recyclability, more capital expenditure is needed in the mainly early-stage technologies currently under development for design and recycling.

Only 21% of wood **waste** is recycled (45% if we include energy recovery, i.e., using wood waste as fuel), while much is landfilled. Currently most of the-waste wood that is recycled is grade A or B; we need technology that will make it possible to recycle a greater range, including grade C. However, as most wood recycling technology is mechanical and requires shipping of wood, businesses should make an effort to invest in alternative solutions. These can include collection incentives and infrastructure that would make recycling more convenient, an increase in the use of recycled wood chips in product designs and greater consumer awareness of recycled wood products to boost demand.

At the same time, we do need technological innovation for the design, sorting and recycling processes of wood. Treated wood design should use non-toxic alternatives to treatment to mitigate hazardous wood waste, which currently makes up 5% of waste wood. Advanced wood sorting technology is needed to improve the wood grade separation, which would result in a better quality of output.

New chemical wood recycling technologies are emerging that could potentially increase recovery rates by enabling better recovery of Grade C wood into fibers or carbon; this kind of technology should be a priority for the industry. Chemical recovery of wood is still in a developing stage and significant investment will be required to bring this technology to scale and maturity.

Only 16% of **plastic** is recycled today, due to the complexities in recovering individual polymers in products that contain multiple materials. Significant technology investment will be required for the design, sorting and recycling of plastic. Beyond technology advancements, overconsumption of single-use products and plastic packaging remains a key challenge. This overconsumption is not likely to improve without changes in consumer behavior along with regulatory intervention aimed at decreasing low value and single-use plastic consumption overall.

For plastics the main needs for technological innovation are also in the areas of design, sorting and chemical recycling. We need products that use less complex polymer-compositions to facilitate recyclability. Improved sorting technology of polymers is crucial to achieving valuable recycling feedstock, as well-sorted feedstock is a prerequisite for good recycling and with current mechanical recycling technology only certain types of plastic are applicable. Currently 95% of the plastics recycling market comes from mechanical recycling.

This is a physical process that uses washing, grinding, separation of constituents and re-palletization of polymers, but in many cases it is limited in the types of polymer it can use as feedstock and much of the material yielded from mechanical recycling can be used only for downcycling. It is important, therefore, to develop technology that can increase both the rates and the quality of plastic recycling especially for mechanical.

On top of mechanical, higher-quality sorting and recycling can be realized through advances in chemical recycling, which has the potential to break down plastic waste into virgin-grade material through thermal conversion (pyrolysis, gasification) and depolymerization. However, these promising technologies have not yet reached commercial scale for different types of plastics.

It is possible in theory to sort and recycle **metals** such as scrap steel and aluminum into high quality output with properties similar to those of virgin materials at a rate of 100%. The technologies to recycle pure steel and aluminum already exist. However, the major challenge is that many such products are adulterated by other materials, especially copper. This is one of the main reasons that only 80% of steel and aluminum products are currently recycled.

Technological advancement is needed for the design and sorting stages. It will be important to make improvements in the design for disassembly of metals in construction, automotive and machinery products. And though recycling technology exists for well-sorted metals, we need innovation to sort out contamination in the feedstock and to high quality recovered metals. Otherwise the metals can be re-used only for downcycled applications.

Although we are seeing a degree of advancement in sorting technologies, there is an added challenge to metal recycling in the form of minimal incentives to increase recycling rates from the present 80% for steel and 40% for aluminum to the 95% for both that is needed. This is an industry that needs a strong regulatory push and additional financial incentives to achieve greater circularity.

Most challenges across the recycling value cycle of **e-waste** can be addressed by technology, but it will require several additional advances to unlock the higher recycling rate that is needed. Today a major pain point in e-waste recycling is the low collection rate. Consequently, it is crucial that policy makers introduced additional regulatory measures addressing returning and recycling used products. This is a concern especially when it comes to small IT devices, which comprise 9% of the total e-waste market.

Technology advancement in electronics design can improve product recyclability, reusability and reparability. Innovations such as websites that let consumers mail in small IT devices and reverse vending machines that collect small electronics could raise the rate of collection. Robotics can be used to automate the sorting process. New, sustainable recycling methods such as green leaching are also in development. An important factor to weigh, however, is that increased reusability, reparability would result in a longer product life—which could have a negative impact on electronics producers' revenues.

This concern will need to be balanced against the environmental and societal returns of circularity, but more regulatory incentives and support of financial institutions will presumably be necessary. Investors might, for example, factor higher circularity into their growth outlook by quantifying the percentage of revenue and profits derived from responsible circular offerings. In addition, recyclers and producers should recognize the recovery of valuable materials from e-waste when they calculate the overall costs and benefits.

Although the-waste stream from **EV batteries** is not large today, it is expected to increase significantly from under 1 million tonnes to 23 million in 2040. The current recycling rate for lithium-ion batteries is 50%, with a growing base of batteries installed and room for improvement in recycling.

In general, there are four principal recycling technologies for EV batteries, each presenting its own advantages and challenges. The pyro-metallurgy method is the most advanced but also most energy intensive. The hydro-metallurgy method allows efficient separation but has a long recovery process. Direct recycling uses separation and remains a manual process. Bio-hydrometallurgy is still at research stage and not at scale.

EV battery design already allows for a high recovery rate of 95%, but the key to higher actual recycling lies in collection networks and recycling capacities. Technology can further improve the recycling phase by identifying new sustainable methods for smelting or leaching. Such technology development is already underway, as the recovery of metals from batteries has its own economic incentives.

For batteries there is still a significant need for more R&D to develop recycling technologies. Also, the impact of recycled material quality on the performance of the battery will have a need for further investments, as lower quality material drives need for more battery manufacturing capacity to have the same output.

Concrete waste can be recycled into aggregates via mobile sorters and crushers, but only 25-50% is recycled this way in Europe and the number can be lower in other geographies. The reason is that due to current standards and norms there is practically a 15-30% limitation on usage of concrete aggregates vs. virgin aggregates. Technically for structural concrete based on performance standards, usage of 50% - up to >90% recycled aggregates would be feasible.

For example, Advanced Dry Recovery (ADR) technology, which removes fine-particle contaminants, has the potential to increase this proportion to 79%. Increased use of ADR could, in addition, reduce the need for virgin aggregates and waste-to-landfill. The technology is fairly far along, but more regulatory support is needed to develop it and incentivize more wide-spread use; for example, regulation could help by revising the requirement for a minimum proportion of virgin aggregates to a minimum based on material performance, since it is technologically possible to achieve the required materials performance with a higher level of recycled aggregates.

Although it is not closed-loop recycling, one of the main technologies in use for recycling **biowaste** is valorizing with a substrate-conversion-consumption process. The biogas conversion process includes pre-treatment and anaerobic digestion (AD). Anaerobic digestion for biogas conversion is currently the most competitive recycling method for biowaste. It is used for 47% of the EU's current biowaste recovery, while the remaining 53% is composted.

Future technology innovation can enhance biowaste circularity in additional ways. It might, for example, further reduce-waste by enhancing product utilization and distribution. Innovation might improve sorting by separating biowaste from mixed waste streams and enhance recycling with higher-value recovery methods.

Emerging technologies to manage bio-waste include bioethanol production (liquid biofuel), production of volatile fatty acids (VFAs), production of biohydrogen, recovery of phosphorus, pyrolysis (into high-energy-density biofuels), gasification (as fuel or for chemical production), hydrothermal carbonization (solid fuel or soil improver) and production of fermented animal feed product from food wastes.

Investing in the future

We estimate that it will take USD $2.1-2.2 trillion invested globally over the next 20 years to overcome the key bottlenecks across the value cycle and provide sufficient capacity for recycling.

It is important to note that these numbers reflect the capital expenditures (CAPEX) that will be needed and do not include annual operating expenses. Consequently they are not meant as a comprehensive business case. The numbers include CAPEX investments along the value chain in collection, sorting, recycling and as well as estimations of design investments. They do not include operating or capital expenses for land and infrastructure – roads, for example. The estimate is based on modeling waste material volumes for 2020 against those forecast for 2040, factoring in the reduction objectives discussed in Chapter 2.

What a USD $2.1-2.2 trillion investment means

- The investment case is defined as the capital investment required from 2021 to 2040
- Includes investments across the value cycle, from design to collection, sorting and recycling (based on assumptions on average costs of technologies per vertical)
- In specific cases, it may include additional incentives dedicated to waste reduction or collection
- Excludes operating expenses such as manpower and utilities for recycling
- Excludes primary infrastructure investments such as land purchase or road infrastructure

The largest capital requirement will need to go toward technological innovations in recycling and expanding capacity of the world's facilities, accounting for 57% of the total investment.

A significant portion should go into product design, while smaller investments will be required to improve collection and sorting infrastructures (see Figure 10).

Roughly half of the projected investment – 53% – will be needed to build greater circularity in just three industries: plastics, metals and biowaste. For plastics a significant investment is required for recycling, especially for the costly chemical recycling technologies.

For metals and biowaste, the capital needs are driven by the costs of the heavy machinery required for recycling metals and the-waste reduction investment needed for biowaste. These two materials account for approximately 20% of the total capital requirement.

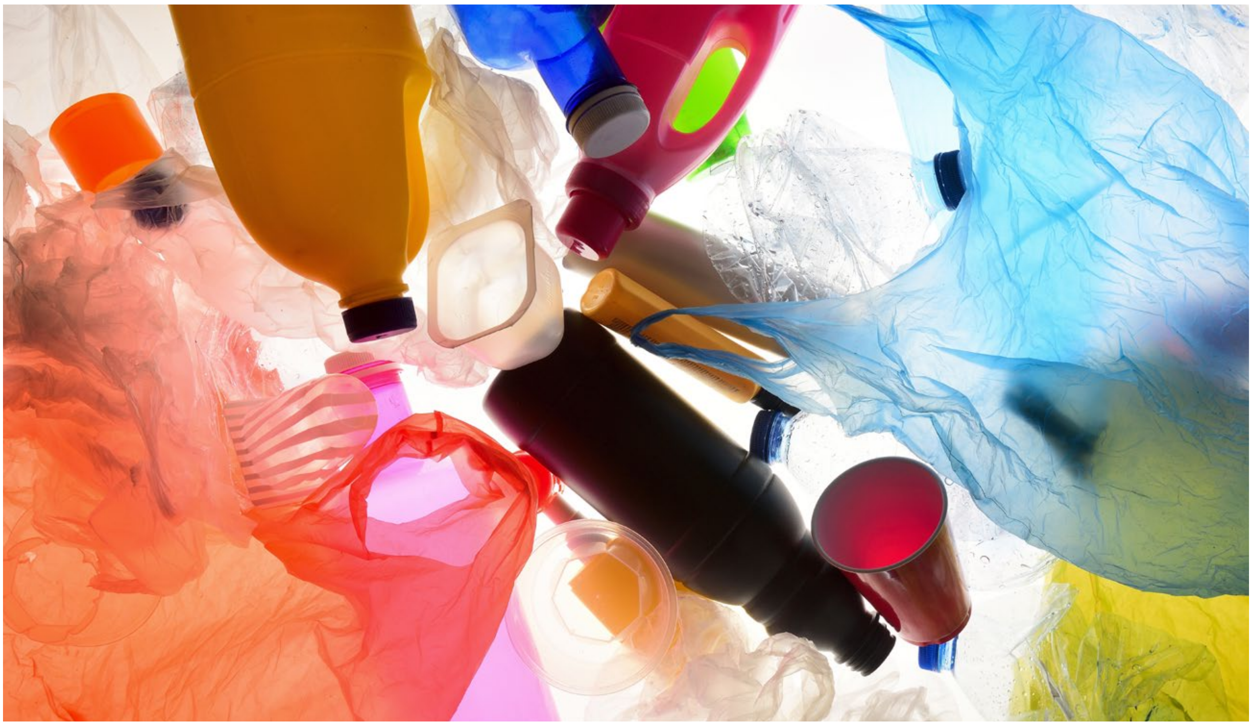


Figure 10: USD $2.1 - 2.2 trillion is needed to recycle 80%-90% across materials

[1] Rubber, glass, nylon

The capital needs are highly uneven across industries, ranging from USD $50 billion to USD $430 billion.

The smallest capital outlay, USD $50-60 billion, should be for **cement & concrete**, which represent a large amount of waste but require less capital to recycle compared to other materials. Construction and demolition are expected to produce about 3.3 billion tonnes of concrete-waste by 2040. About USD $5-10 billion of the investment should be allocated for circularity R&D, aimed at achieving higher recyclability through materials design. Up to USD $5 billion should go into building sorting and deconstruction facilities, while USD $35-45 billion should be invested in mobile and stationary mixed-concrete recycling facilities.

A material requiring large capital outlay is **metals**, with an allocation of USD $320-330 billion to address the massive current volume and the increase in volume of scrap metal expected by 2040.

The investment case is based on steel and aluminum volumes, which cover 95% of all metals and the overall estimated metal waste amount of 1.1 billion tonnes by 2040.

An USD $30-40 billion investment is needed to upgrade product design, mostly of steel for major industries such as construction, automotive and industrial machinery. Of this sum USD $25-30 billion would be dedicated to advancing product design for disassembly and recyclability. The remaining of USD $5-10 billion should go into the development of proper take-back systems for post-consumer scrap, so that there is more economic viability for scrap collection. A smaller investment of USD $10-15 billion should go toward advancing collection systems, while USD $50-60 billion is required for metal sorting, an area in which further technology advancement is critical to increasing the purity of scrap metals.

The sorting needs depend on whether the material is home scrap, prompt scrap, or obsolete scrap. Home scrap and prompt scrap just need to be sorted for de-contamination if they need sorting at all. Obsolete—i.e. post-consumer—scrap general requires more pre-processing. Cast and rail iron must be broken up. Light or mixed automotive scrap needs shredding. Larger scrap, for example from construction, needs shearing. Additionally, a majority of this scrap will need magnetic sorting and decontamination, such as de-zincing or de-tinning,[4] to reach the desired purity levels. We will need technology advancements in the areas of magnetic sorting and decontamination. For aluminum, the main technological advancement required is in sensor-based sorting to increase the output quality. Further, an investment of USD $230-250 billion should go into acquiring more electric arc furnaces (EAFs) for recycling. This is already a mature technology and with additional capital investment it can be scaled to accommodate the large increases in metal volume over the next 20 years.

Expansion of metal collection and sorting is needed across all regions, especially in the Middle East and Africa and the Asian Pacific. While every region is going to need more EAF recycling furnaces, the Asian Pacific is expected to account for 67% of the world's additional metal recycling needs as consumption shifts from developed markets such as Europe and North America to developing countries such as China and India.

Improving **biowaste** circularity requires the second largest investment, at USD $380-390 billion. The-waste volume is very large and innovation is sorely needed to solve the global problem of food waste. We estimate a biowaste volume of 616 million tonnes in 2040. The figure is based on projected population growth from 7.8 billion people in 2021 to 9.2 billion in 2040, the growth in per-capita food consumption from an average 2,942 calories per person per day in 2020 to 2,953 calories in 2040 due to increased wealth and an estimated food waste reduction of 25%. We estimated that food waste represents ~87% of total biowaste amount and this 25% reduction is equivalent to 145 million tonnes.

The bulk of the capital, USD $220 250 billion, is an estimate of what the world will need to tackle the key challenge of food waste and loss reduction. Investment is necessary for waste reduction initiatives such as harvest optimization, product distribution management, refinement and product utilization maximization. We have set a 2040 food loss and waste reduction objective of 25%, which is in line with the World Resource Institute target for 2050 though lower than the UN SDG 12.3 target of 50% food waste reduction by 2030.

The 25% is lower than the avoidable food waste share of the world's total food waste, which ranges from 30% to 60% depending on the country.

An investment of USD $40-50 billion is needed to advance biowaste collection by establishing separate collection networks for biowaste in place of single-stream bins and trucks. Dedicated networks ensure purity for biogas and composting and also prevent food waste from contaminating other materials such as plastic packaging. We do not expect investment to be needed for sorting, as we are excluding non-segregated wastes that are treated in mixed waste plants from the investment case. Recycling capacity, however, needs to be expanded through new biogas plants and composting facilities, for an estimated investment of USD $100-110 billion. Home composting is not part of this estimate, as we have assumed that all composting is done via centralized facilities. Today, composting represents the majority of biowaste recycled, although biogas conversion should be the preferred recovery method from overall sustainability and cost considerations. From our projected 85% recycling rate, we assume that 40%, or about 250 million tonnes will be treated for biogas conversion by 2040, while another 280 million tonnes is likely to be composted in 2040.

An investment of USD $150-160 billion is required for **wood**. Of that, USD $20-30 billion should go into each of the first three stages—design, collection and sorting. About USD $70-80 billion will be needed to upgrade capabilities in recycling lower grade wood.

The estimates are intended to address waste projections of 1.3 million tonnes in 2040.

About USD $20-30 billion of the investment should support R&D of products and construction methods that increase clean recovery and repurposing of waste wood through re-design. A smaller share of USD $2-5 billion should be allocated toward R&D in the chemicals industry to minimize the use of toxic chemicals in wood treatment. Another USD $20-30 billion can go into collection aimed at separating wood from other waste streams, while USD $20-30 billion should be invested in sorting technology that separates wood from other particles and into higher quality wood grades. The largest share, USD $70-80 billion, should be split between building capacity in mechanical recycling for Grade A and B wood (85%) and boosting chemical recycling capabilities for Grade C wood (15%).

For **paper**, a total of USD $230-240 billion should be committed to increasing circularity. Much of the capital should be invested in better sorting to maintain fiber structures and more advanced recycling equipment to increase the quality and yield of the output. The figure is based on an estimated waste amount of 532 million tonnes in 2040.

Of the total, up to USD $5 billion should go into improving design and USD $10-15 billion should go into collection, with a focus on decreasing single-stream sourced paper waste and increasing the numbers of paper-specific waste containers and trucks. About USD $50 billion should be invested in advancing sorting equipment to yield more paper-specific sorting and better techniques for shredding, pulping, screening and cleaning.

For the recycling phase, we estimate that USD $165 billion will be needed to improve the scale and maturity of recycling processes and as well advance dry-pulping to make recycling of contaminated waste paper more viable.

Although **plastics** accounted for only 5% of total waste volume in 2020, the complexity of separating and recycling components and mixes means that this material will require the largest allocation of capital, at USD $420-430 billion. The figure is based on an estimated waste amount of almost 450 million tonnes in 2040.

A total of USD $100-110 billion is needed to improve circularity in the design step, particularly to address the two key challenges of overconsumption from unnecessary single-use packaging and the lack of design for recyclability. Innovations in design should aim to eliminate overpackaging, increase multi-use and enable re-fill, all of which could help decrease consumption by about 20%. In addition, producers should be developing products designed with easier sorting in mind, using single polymers when possible.

A smaller but still significant investment of USD $25-30 billion will be needed for the collection phase and there should be regionally determined increases in plastic-specific collection, especially in Central and South Asia, the Middle East and Africa and the Asian Pacific region. Globally, we need to standardize categories for sorting plastics to increase recovery and achieve a higher quality of sorting and recycling.

Capital expenditures in sorting equipment should amount to USD $40-50 billion, which is needed to increase the quality of recycling feedstock. Much of this should go into developing more single-polymer sorting methods such as near-infrared sorting (NIR), which would make it possible to recycle more plastics mechanically, with a smaller carbon footprint . The majority of the capital invested in plastic, however, should go into the recycling step; we estimate that it will take USD $250-260 billion to do what is needed. Plastic recycling technology needs a great deal of innovation to reach advantageous quality and yield outputs. The investment case calls for advancing mechanical recycling as the most optimal type of plastic recycling and it needs to be scaled, rolled out across regions and advanced to optimize quality and yield.

However, further development of chemical recycling technology is also necessary, so that it can be deployed in cases where mechanical recycling reaches its limits.

The basis for these investment cases is an estimated total plastic consumption of 560 million tonnes by 2040. The investment in design alone could lead to a 20% reduction in consumption, bringing the figure down to 450 million tonnes. From these 450 million tonnes the aspiration is that 80%, or 360 million tonnes, will be recycled. Since the reduction in consumption is expected to come mainly from polyethylene-based packaging and single-use products – which are the main input in mechanical recycling feedstock – the amount of mechanical recycled plastics is also reduced. The estimated result would be about 180 million tonnes of plastic waste that is mechanically recycled, while the rest goes into chemical recycling, about 140 million tonnes to be decomposed through pyrolysis and 40 million tonnes to be broken down into small fragments through depolymerized or molecules through monomerization.

Of the plastic that is recycled today, Europe is the world's leader, recycling about 39% of its plastic consumption, while other regions' recycling rates hover between 7% and 17%. By 2040, Europe and North America are both expected to reach a level of 90%, while the other regions are expected to reach 75%. That will mean that on average the world is recycling about 80% of its plastics. With the Asian Pacific expected to produce the largest increase in volume of plastics recycled, more than half of the additional recycling is likely to come from this region, with 20% of the increase coming out of North America and 8-9% from the remaining regions.

E-waste will require an estimated USD $150-160 billion in capital, primarily to create advancements in designing products for recyclability and recycling via smelting or leaching plants. The sum is derived from an estimated waste amount of 100 million tonnes in 2040. About USD $25-35 billion should go toward advancing collection and marketing to expand the formal collection networks to keep up with local waste production. The effort should include customer incentives for e-waste return. An investment of USD $10-20 billion is needed to expand and advance mechanical sorting equipment, including shredding, magnetic sorting and de-contamination of metals. For the recycling stage, USD $55-65 billion should be allocated to building new plants and upgrading existing smelting or leaching plants so that they can be repurposed for e-waste.

EV batteries, as a small market, will need only about USD $90-100 billion. We estimate that the-waste from EV batteries will be about 23 million tonnes by 2040, based on the capacity for 2030 and an assumed average lifespan of 10 years. Of the capital needed, USD $5-15 billion should go into product design that increases recyclability by reducing the presence of undesirable materials such as cobalt and nickel and designs for disassembly to ensure the batteries can be recycled efficiently. About USD $2-5 billion will be required to upgrade collection networks through such acquisitions as as battery testers and both regular trucks and Hot Box trucks to transport hazardous batteries. The remaining USD $75-85 billion should be invested in expanding recycling plant capacity.

These capital expenditures are what is needed globally, but each region is coming at this from a different starting point. As such, collection, sorting and recycling aspirations differ widely from one region to another (see Figure 11).

The 2020 collection rate across materials, for example, averages 70% globally, but is broken down regionally as 86% in Europe, 80% in North America, 77% in the Asian Pacific region, 62% in Latin America and 61% in the Middle East and Africa. The 2020 recycling average across materials is 35% globally, while the regional breakdown is 51% in Europe, 38% in North America, 32% in the Asian Pacific, 18% in Latin America and 175 in the Middle East and Africa.

We have calibrated our overall objectives for the investment cases accordingly, with attention to the need for regional collection, sorting and recycling to mitigate unnecessary trade transportation of waste. This consideration results in higher collection, sorting and recycling rates from Europe and North America and lower rates from Latin America and the Middle East and Africa.

Overall, the largest investment outlay is required in the Asian Pacific, at about USD $1.0-1.1 billion. This is due to expectations of rapid economic growth and with it a dramatic increase in consumption rates.

Although North America and Europe drive a larger relative share of volume, Latin America and the Middle East and Africa have less mature starting points in their collection, sorting and recycling infrastructure. Thus, more capital will be needed for Latin America and the Middle East to achieve their ambitions than for North America and Europe (see Figure 12).

Across all regions, the 20-year total investment case required is less than 0.2% of each region's economy measured as share of annual GDP.[17] The more exact proportions are: Asian Pacific, 0.2%; North America, 0.04%; Europe, 0.04%; Latin America, 0.1%; Middle East and Africa, 0.2%.

Figure 11: Regional split between NAM, LAM, MEA, EU and APAC

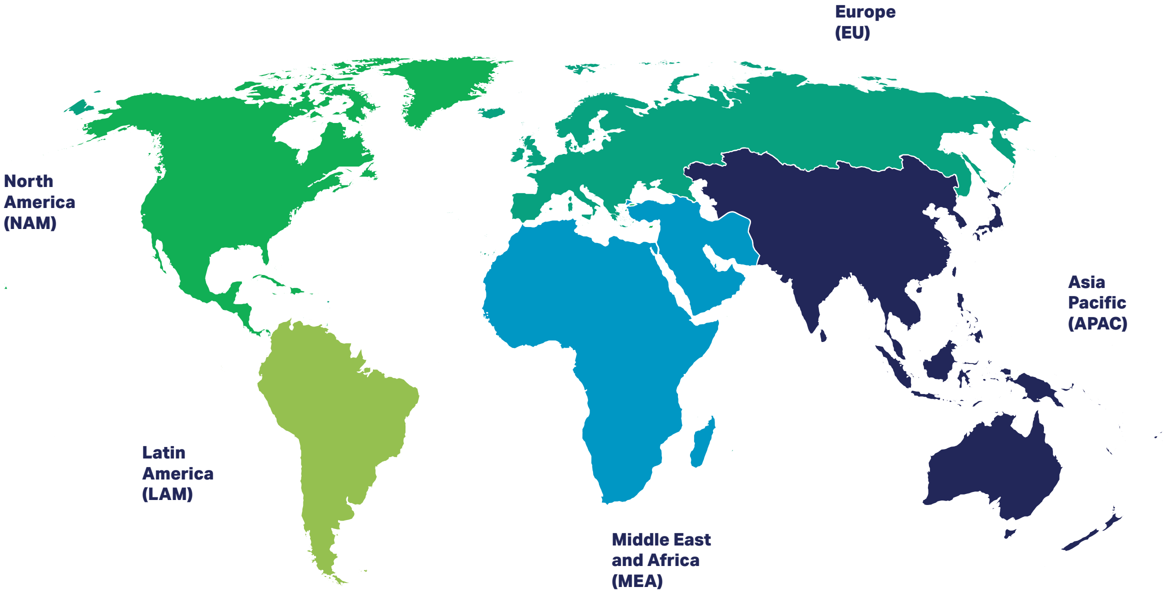
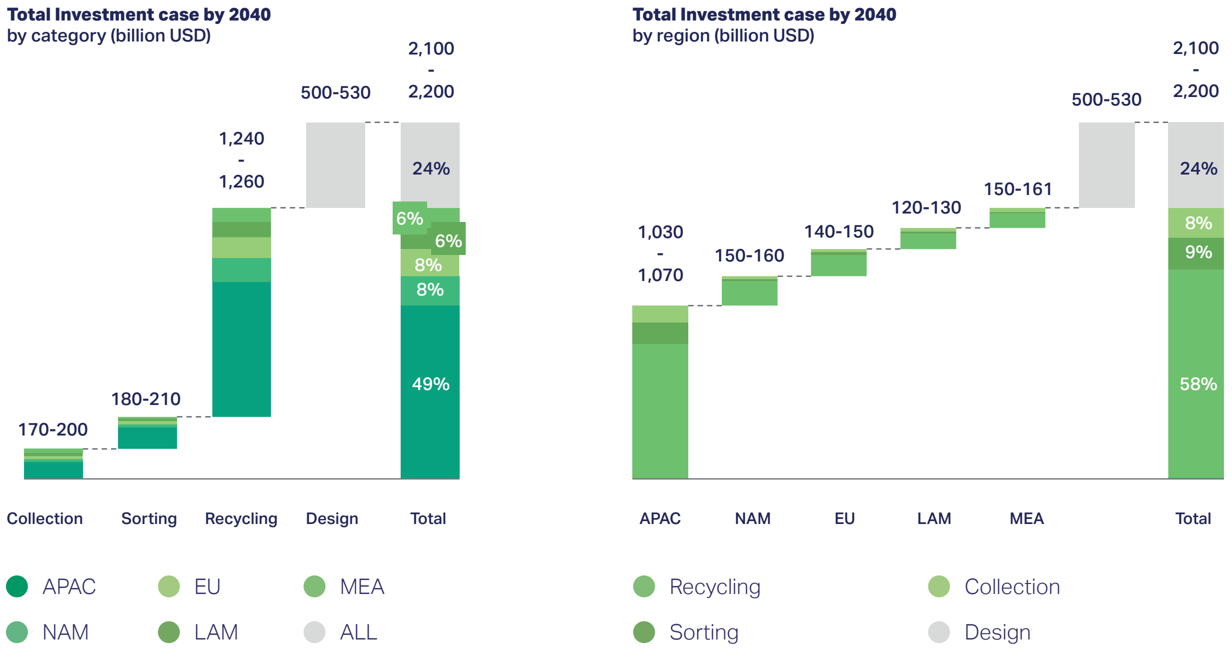
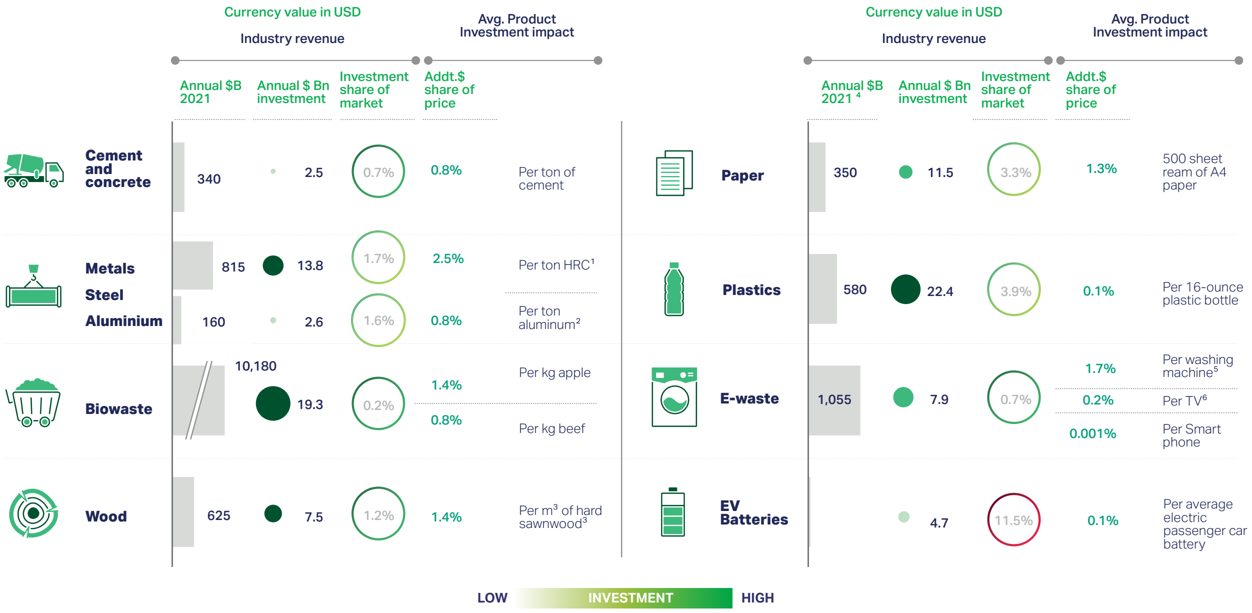


Figure 12: Asia will need the largest share of the total investment



When we compare the total investment needed to market size and product costs, it becomes apparent that the investment over 20 years represents only a small share of market revenue for most materials. The investment required per each of the materials discussed in this report is generally equivalent to 0.5 4% of the relevant industry size on an annual basis (see Figure 13).

Figure 13: Relative financial impact across industries



	Annual $B 2021	Annual $ Bn investment	Investment share of market	Addt.$ share of price	
Cement and concrete	340	2.5	0.7%	0.8%	Per ton of cement
Metals **Steel**	815	13.8	1.7%	2.5%	Per ton HRC[1]
Aluminium	160	2.6	1.6%	0.8%	Per ton aluminum[2]
Biowaste	10,180	19.3	0.2%	1.4%	Per kg apple
				0.8%	Per kg beef
Wood	625	7.5	1.2%	1.4%	Per m³ of hard sawnwood[3]

	Annual $B 2021 [4]	Annual $ Bn investment	Investment share of market	Addt.$ share of price	
Paper	350	11.5	3.3%	1.3%	500 sheet ream of A4 paper
Plastics	580	22.4	3.9%	0.1%	Per 16-ounce plastic bottle
E-waste	1,055	7.9	0.7%	1.7%	Per washing machine[5]
				0.2%	Per TV[6]
				0.001%	Per Smart phone
EV Batteries		4.7	11.5%	0.1%	Per average electric passenger car battery

[1] Hot rolled coil, 3-year avg. China price benchmark
[2] London Metal Exchange, unalloyed primary ingots, high grade, minimum 99.7% purity, 3-year avg 2018-2021
[3] Global 3-year avg.
[4] E-waste: electronics markets, Biowaste: agriculture market
[5] Avg. top-load washer w. >3 cubic feet capacity and multiple cycles
[6] 32-inch flatscreen LCD

Across all materials, the total annual investment as a share of the industries' revenues is 0.8%. These numbers will vary across industries with a few stand-out cases.

Generally, the investment share is between 0.5 and 4% of the industry revenue on an annual basis. This goes for cement and concrete, metals, wood, paper, plastics and e-waste.

The EV battery industry stands out with a high investment share at 11.5% of industry revenue, mostly because of the relatively small size of the market today in relation to where it will be in 20 years and need for significant scaling of recycling in comparison to its current market revenue. At the other end of outliers is the biowaste investment, which represents only 0.2% of agriculture market revenue. Agriculture is a large market and a large percentage of its products are fully consumed and never become-waste. Furthermore, biowaste recycling options (composting and biogas conversion) are relatively low cost compared to other materials.

Generally, investment in circularity adds only about 0.001-2.5% to global product prices. For example, when we apply the investment cost for e-waste recycling to three different types of electronic products – washing machine, flat screen TV and smart phone— the additional cost is 0.001-1.7% per item, if producers are to achieve a higher circularity. Similarly, applying the investment cost for biowaste recycling to apples and beef adds 0.8-1.4% to the cost. The low additional cost on end products underlines the viability of incorporating a circularity strategy.

Globally, the markets in waste collection, solid waste recovery and waste disposal are projected to grow at steady pace over the new few years as population grows and wealth increases. The global waste management market was valued at USD $394 billion in 2020 and is predicted to reach USD $715 billion by 2030, with a compound annual growth rate of 6.1% between 2021 and 2030.[18]

While this report focuses on the CAPEX cases rather than the business case for circularity, a look at the full picture indicates that each material stream needs to be examined closely for an assessment of the potential profitability. The EBITDA margins vary significantly across materials, steps of the value chain, regions and technologies.

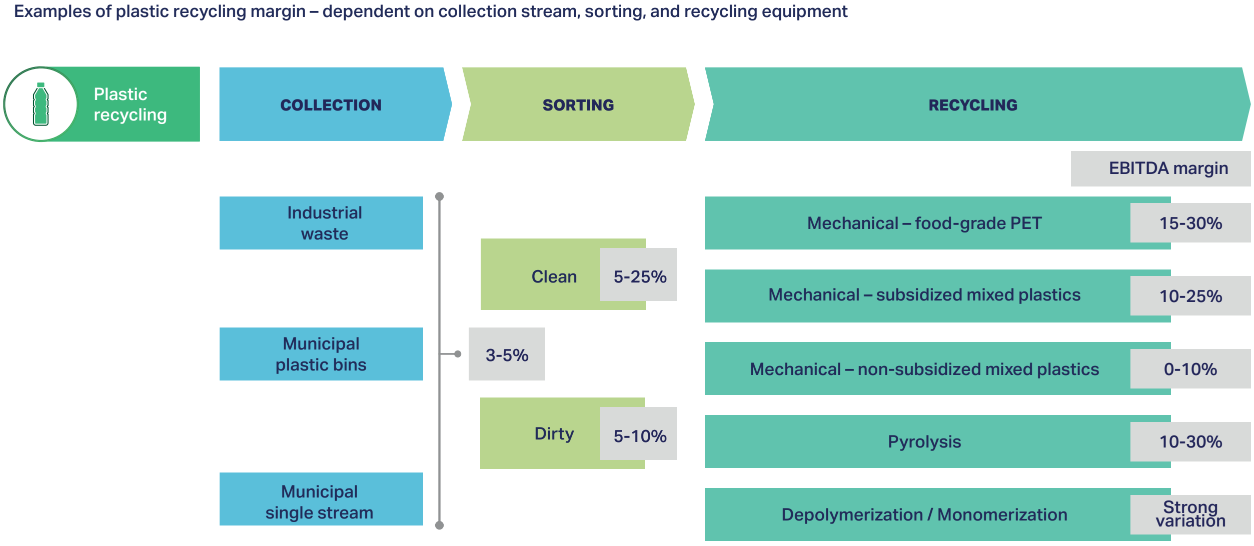
The lowest margins are found in collection and sorting and the highest in the recycling phase. For example, the EBITDA margins in EU municipal mixed waste can be generally split as 3-5% in waste collection, 5-10% in waste sorting and 10-15% in waste recycling, with local spikes possible in every member country.

Incineration and landfilling have higher margins in the EU, ranging from 15% to 40%. These discrepancies between one activity and another make it clear that structural changes are needed in the-waste management space to increase the financial incentive for recycling.

For recycling, the returns on investment vary significantly depending on several factors, including the substances produced from recycling, the technology employed and the regional market. Even within one-waste stream, recycling margins can vary significantly. For some technologies there is a proven and mature business model, while others have yet to prove their economic viability.

Plastic recycling presents a clear example of how wide the variations in margin can be (see Figure 14).

Figure 14: Return on investment in plastic recycling depends on multiple factors



The lowest margins are in the collection phase, at 3-5% depending on waste stream, efficiency of logistics, equipment and regional markets.

Sorting margins can generally be divided into two main groups: dirty (single-stream) and clean (multi-stream). Clean plastic waste streams without contamination from other materials offer higher margins than mixed waste streams with higher contamination, which need a higher level of processing and often provide lower quality output.

The margins in recycling plastic vary greatly with the type of recycling equipment as well as the feedstock quality. Mechanical recycling is by far the most established recycling method for plastics, but margins still depend largely on the feedstock quality. While food-grade PET polymers offer 15-30% margins, non-subsidized mixed plastics offer only 0-10% margins. Within the less mature chemical recycling, pyrolysis and depolymerization/monomerization are two promising technology categories, but ones that are still emerging and have yet to prove their business case. The theoretical margin for pyrolysis at an established state is estimated at 10-30%.

With the more nascent depolymerization technologies, profitability varies by polymer. Polyethylene terephthalate (PET) is the most widely used plastic packaging and the main margin driver for recyclers, while other polymer types offer lower margins. For example, recylers for PET flakes and pellets generally present higher EBITDA margins, at 5-25%, than polyolefin recyclers, which have achieved margins of no more than 2-15% in the EU.

All in all, across materials the recycling markets are growing and becoming increasingly profitable with the maturing of technologies, growing demand and scaling of equipment. However, some recycling methods still need to be further advanced to establish a profitable business model.

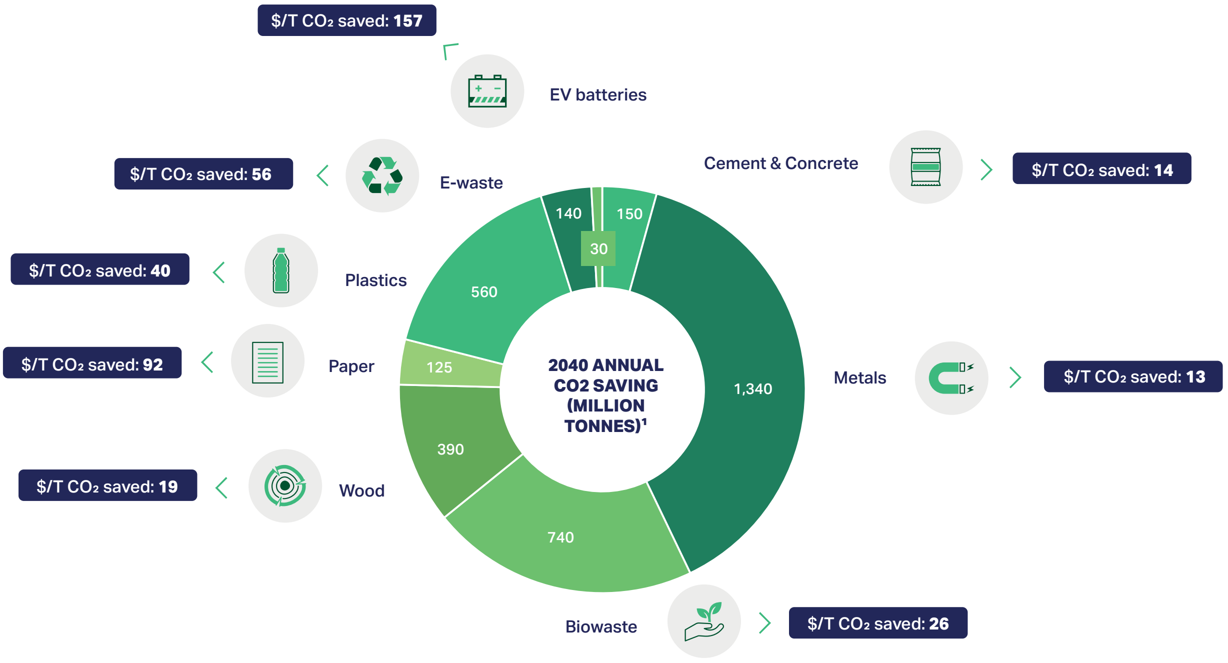
④ The impact

A USD $2.1-2.2 trillion investment in global circularity would not just help limit global warming; it would also have a significant impact on nature through the conservation of water, land, biodiversity and multiple resources and on societal equity through job creation and human rights benefits.

Overall, investment in improving circularity can reduce CO_2 emission by 40-50 billion tonnes over the next 20 years. That is equivalent to saving 10-15% of the carbon budget that would make it possible to limit global warming as per the objectives of the Paris Agreement.[19] Material streams with the highest CO_2 savings potential are metals, biowaste and plastics (see Figure 15).

The costs of emissions abatement per tonne of CO_2 saved – shown in the blue rectangle in Figure 15 – is lower for cement & concrete, metals, biowaste and wood, while paper and EV batteries require the highest capital expenditures. The costs reflect the relative efficiency in achieving an impact on the climate, but there are also impacts on nature and societal equity that must be taken into account. Paper and EV battery recycling yields lower emissions reductions per dollar spent, but both will produce a high degree of impact on nature and society.

Figure 15: Impact on climate by industry



[1] Assumed steady state from 2040

Calculating priceless benefits

Material extraction puts pressure on water, land, biodiversity and all of the Earth's other resources, while handling extracted materials in a responsible and circular way will decrease these pressures.

Increased circularity can reduce the consumption of fresh raw materials and reduce air and water pollution by lessening the need for waste disposal.[20]

The value of biodiversity, calculated as the monetary valuation of ecosystem services, adds up to USD $170-190 trillion annually, a sum equal to roughly twice the world's current GDP.[21] That makes the protection of biodiversity an economic imperative. Circularity produces benefits to the natural environment in many ways, depending on the material (see Table 3.)

It is estimated that 10 million tonnes of plastics waste enter the ocean per year, with toxic effects on the life or food supplies of at least 267 animal species, including 86% of the world's marine turtles, 44% of seabirds and 43% of marine mammals. Plastics have entered the food chain through seafood consumption, presenting threats to human health as well.

Paper circularity can also have a dramatic impact. Recycling 1 tonne of paper saves up to 17 trees, in turn potentially saving natural habitats for birds, insects and wildlife.[22] That one recycled tonne of paper also saves 25,000 litres of water, a critical benefit in the face of increasing water shortages.[23] Paper recycling can save 58% of water inputs,[24] while metal recycling can save 40%.[25]

E-waste represents 70% of reported toxic and hazardous chemicals in the environment today, so massive recycling of this material will significantly improve air and water quality in many parts of the world.[26]

A circular economy can also foster greater societal equity, so that more people can participate in economic growth and reach their full potential.

The positive impact comes through the growth of new technologies and formal recycling systems that can create more jobs in the formal economy, as well as from environmentally—conscious practices that honor human rights, health and safety and living standards.

Less exploration and extraction of raw materials would lead to less forest exploitation, ecosystem fragmentation and chemical contamination of land and water—all of which has forced low income and indigenous populations in many parts of the world to leave their land or suffer serious health consequences. Deploying circular systems instead of incinerating waste, dumping it into landfills, or letting it seep into the soil or water supply would have a positive impact on the health and well-being of populations all over, since dumping sites can cause dangerous emissions of methane, carbon dioxide and other hazardous materials.

Table 3: Impact on nature and societal equity by industry

	NATURE	**SOCIETAL EQUITY**
	Impact on nature, incl. biodiversity	**Impact on equity**
Cement and Concrete	Save 30% input materials, reducing the need for extraction of virgin materials	Up to 5% net job creation
Metals	Decreased mining and processing of ores saves water (40%)	Up to 1-2% net job creation
Biowaste	Save up to 50 billion tonnes of water each year	Improved nourishment for 720–811 million people who face hunger
Wood	Improved recycling saves 500 million trees per year	Up to 1-2% net job creation
Paper	Recycling 1 tonne of paper saves up to 17 trees and 25,000 litres of water (-50%)	Creates 5x as many jobs as virgin paper industry
Plastics	Lower micro-plastic pollution in ocean (today 10million tonnes of plasticwaste are dumped in ocean per year)	Up to 23 jobs per 1,000 tonnes of recycled plastics
E-waste	Reduced hazardous waste (currently 70% of toxic and hazardous chemicals come from e-waste	Up to 30% net job creation
EV Batteries	Reduced hazardous waste (EV battery cells can release problematic toxins, including heavy metals)	Improved to maintain parallel phrasing work conditions by reducing virgin mining (an estimated 40,000 children work in cobalt mining)

Increased recycling would reduce the need to extract virgin materials through mining, thereby reducing health and safety violations related to mining operations. For example, about 20% of cobalt, an important component of EV batteries, comes from artisanal mines in central Africa, where some reports suggest that 40,000 children work in extremely dangerous conditions.

A circular economy will create jobs in such fields as product repair and refurbishment, waste collection and processing and formal waste recycling. Studies show that for every 10,000 tonnes of metals, plastics, paper and cardboard and organic waste that is incinerated or dumped into landfills, only two jobs are created, while recycling can create 100-plus jobs. Repairing products to avoid sending them into waste streams create even higher numbers of jobs, three to four times as many as recycling.[27]

There will be jobs and income sources lost, typically at the low end of the economic ladder; for example the precarious livings earned from informal recycling through waste scavenging as well as jobs associated with landfilling, incineration, virgin mining operations and new production. It is important that regulators and industries make an effort to provide training in the recycling sector to help upskill these workers. Waste-picking is an important informal sector occupation in many regions, such as South and Southeast Asia and South America.

Although they live at the margins of society, waste pickers in Indonesia, India, Chile and Brazil can earn 20% to 110% more than many comparable low-skilled occupations.[28] In Jakarta, scavenging activities recover—for the purpose of recycling—about one third of the total amount of wastes generated by the city.[29]

Even in advanced economies such as the U.S., waste scavenging provides income for many poor and homeless people, for example those who collect empty beverage containers to get the cash refund.[30] Governments should address the needs of this population when recycling is improved. They might, for example, offer them job opportunities in the formal collection and recycling networks. The city of Buenos Aires has been doing this for the past decade. Waste pickers receive training, uniforms, child care services and contracts establishing formal responsibilities and compensation above the minimum wage. They are now officially in charge of the city's collection and management of recyclables.[31]

The net effect on job creation is positive; while a transition to a high recycling rate would lead to fewer jobs in landfill and incineration, 10 to 60 jobs are created for every job lost in disposal.[32] The exact potential for job creation, like all effects of circularity, will differ from one industry to another, though many industries will show positive potential.

An IISD study modelled the employment impact from circular economic interventions in Finland and estimated that there could be a net employment gain of 30% from e-waste circularity, 5% from construction including the use of concrete and 1-2% each for forestry and mining.[33]

Formalized recycling can also have a positive impact on worker health. Take, for example, the serious hazards that can arise from e-waste. Those who earn their living in this sector or live near unregulated e-waste recycling sites might be exposed to toxic soil or fumes from burning wires and cooking circuit boards. Studies have found that the exposure has led to serious health problems, including hearing loss, DNA damage and liver disorders.[34]

Waste reduction initiatives also have a great deal of potential to improve living standards—for example, through a greater effort to reduce biowaste by re-processing food waste and byproducts into food products and nutritional additives that are then distributed in communities that suffer from food insecurity. In 2020, between 720 million and 811 million people faced hunger. Of those most vulnerable to food scarcity, 75% live in rural areas and most of them depend on agriculture for their livelihood. Reducing food waste and loss can lead to better food security and nutrition in the poorest parts of the world.

⑤ A call to action

The USD $2.1-2.2 trillion investment that is needed globally to increase overall recycling to 80-90% by 2040 will not happen by itself. A wide range of actors will need to be involved in enabling the changes and achieving the circularity aspirations discussed in this report. These include governing bodies, producers, investors, industry organizations, NGOs, customers and recyclers.

Governing bodies need to enact regulatory measures and impose sanctions to create stronger incentives for circularity and higher recycling rates. Governments can invest in improved recycling facilities and infrastructure, establish extended producer responsibility (EPR) policies and incentivize both businesses and households through taxes and subsidies designed to encourage recycling. Often harmonization is needed, but it should be done in a way that avoids disruption to otherwise well-functioning systems.

Government policies should discourage, reduce and restrict the transboundary movements of hazardous waste while increasing requirements for industries to extend the lifecycle of materials. Landfill and incineration regulations should be designed to restrict how much waste can be dumped or burned. Regulators should collaborate and establish national, regional and global standards and labeling for the quality and specification of output materials.

The sale of secondary material and usage of recycled material should be incentivized through subsidies. Some governing bodies have successfully piloted "green lanes" that ease the complexity of moving waste to certified recyclers. Governing bodies should also enforce labor rights and enact policies that favor formalized recycling businesses and their workers.

Producers should make a point of investing in R&D aimed at optimizing recycling and designing products with a long lifecycle, as well as using recyclable materials that are easy to dissemble. Those that act as industry leaders in designing recyclable products stand to benefit as consumer demand for such products grows—and rather than waiting for that to happen, producers should be at the forefront of driving demand, for example with marketing campaigns that showcase the value of recycled materials. They should reach out to their customers to explore how circularity can serve the consumer's needs and tie the return and collection of used products to the business model. Producers should be pro-active in creating environment, health and safety (EHS) assurance schemes for secondary materials, with standardized material tracking and traceability platforms for all of the materials they use by defining the business case for recycled content and partnering with recyclers to continue investing in circular innovation, producers can also provide much of the momentum for a new approach to the way we use the Earth's resources.

Investors can make a big difference by considering circularity requirements in their investment decisions and emphasizing the need for high circularity in any analysis of valuation, based on the view that the practice of recycling and re-using lessens a company's exposure to climate crises or raw material access risks. Rather than just evaluating circularity in a single company, investors have the ability to incentivize it in industry ecosystems and encourage collaboration among industry players along the value chain. They can encourage their portfolio companies to adopt close-loop recycling and invest in opportunities to improve collection, sorting and recycling facilities and infrastructure.
In addition, investors should actively seek opportunities to invest in innovations that address challenges to increased circularity, such as cutting-edge collection mechanisms or sorting and recycling technologies.

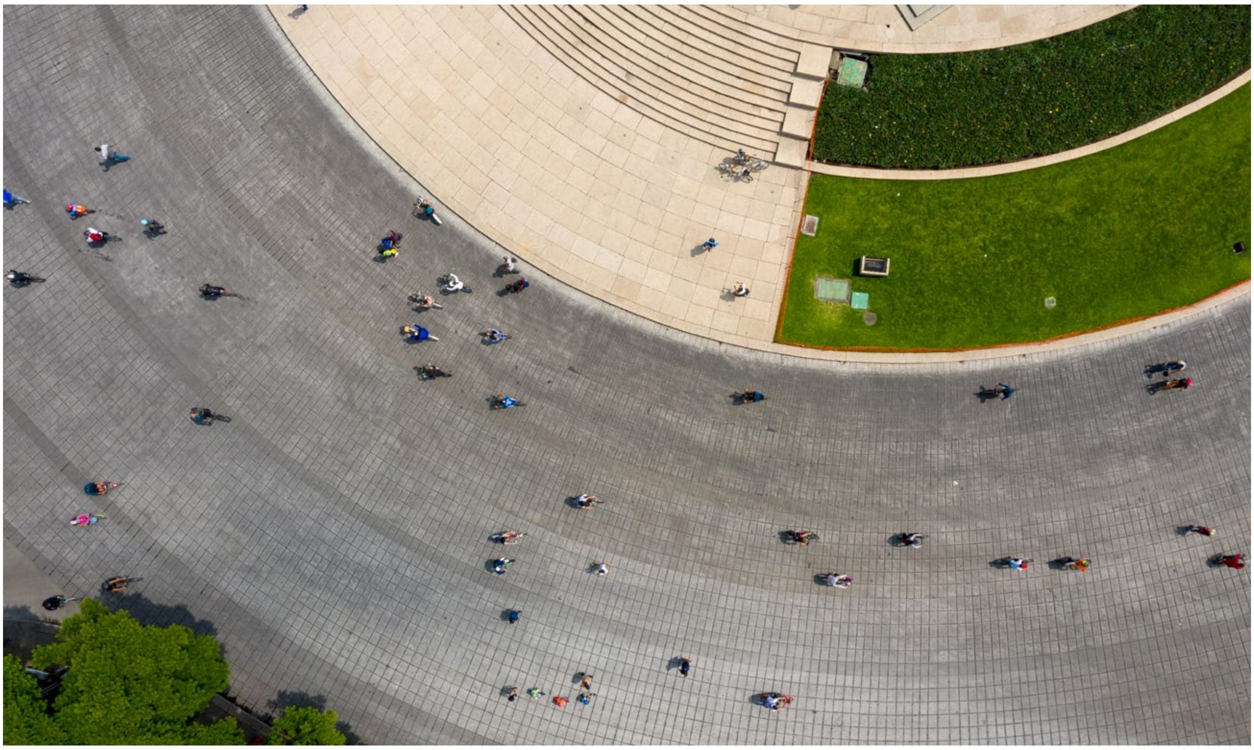
Industry organizations can be powerful advocates for sustainable industry practices. They can, for example, develop guidance for circular product procurement and encourage collaboration across the value chain. They should develop harmonized definitions and reporting standards for waste take-back and collection.
They can also be influential as proponents for increased governance of takeback and collection at the global level and improved classification of waste at borders through trade facilitation programs and capacity building.

NGOs have an important role to play in building awareness of the need for circularity and lobbying to support sustainable progress. They should also turn their sights to facilitating the sale of circular products and services, developing training and promote knowledge and consistent application of circular procurement. NGOs can encourage reporting on circular procurement at the global scale and build the kind of awareness that is needed to stimulate circular procurement of products globally.

Customers, whether they are retail shoppers or businesses, should educate themselves about circular products—and as informed customers participate actively in takeback and collection programs, avoid informal recycling and follow at-source-waste separation. They should promote and support businesses that produce sustainable and circular products and make it a habit to choose repair over recycling.

Recyclers should take a leading role in supporting the formalization of their industry and an increase in transparency. They can build the industry and its impact by increasing public-private cooperation in the development of effective extended producer responsibility (EPR) regulation and engaging informal actors as participants in the process, supporting their transition to formalized entrepreneurs. Recyclers should also focus on the development of sorting, pre-processing and recycling operations at the regional and global level and increase transparency on the secondary material demand and supply.

Since there is no Paris Agreement for material recycling, it is important that we begin to address the way we consume and dispose of materials and establish a set of recycling aspirations that, if realized, will help prevent irreparable damage to the planet. The objective of this report is to create a starting point for global communities, including all of the stakeholders highlighted in this chapter, to develop a plan for materials use in the next decades. By doing so, we can contribute to a global economy that will use the Earth's materials responsibly, staying within the resource limits and preserving its resources for future generations.



Appendix

Assumptions for the material verticals.

1. CONCRETE

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Concrete-waste quantity: 900 million tonnes are generated per year in Europe, the US and Japan alone. China generates estimated 638 million tonnes of concrete-waste in 2020. Data is limited for the rest of the world – we assume 2,200 million tonnes of concrete-waste worldwide per year (assuming rest of the world equivalent to China's amount; 2,200 represents 22% of 10 billion tonnes of concrete produced each year). • Assuming concrete-waste grows by 50% by 2040, to 3,300 million tonnes per year (World Bank forecasts Global Waste to Grow by 70 percent by 2050)
Waste Collection and Recycling Ambition	• Many EU countries already achieved EU ambition for 2020 of 70%, including both closed-loop recycling and reuse on site • Per 2016 data, UK was the highest at 95%; This dataset shows Switzerland / Netherlands also achieves 95-100% recovery • The ambition we set for 2040 is 95% recovery of concrete-waste. This ambition includes 75% ambition of closed-loop recycling of recycled concrete aggregates (79% currently achieved: Source 1, Source 2)
Design Investments (2021-2040, USD $ billion)	• The industry market size is projected to be USD $326.8 billion in 2021 • Industry current R&D as % of revenue is est. to be 0.5% • Assuming 20% increase in R&D for circularity, additional R&D = USD $327 * 0.5% * 20% * 20 years = USD $6 billion
Sorting Investments (2021-2040, USD $ billion)	• Assume some CAPEX requirement (USD $0-5 billion) for improvement on deconstruction and sorting • Example companies include Rotor Deconstruction, AMP Robotics (fund raised to date: USD $74.5 million), Globechain (fund raised to date: <USD $15 million)
Recycling Investments (2021-2040, USD $ billion)	• EU estimate of concrete-waste infrastructure investment of €1 billion for 735 million tonnes per year • Currently, 45-95% of concrete-waste is recycled in developed countries and <10% are recycled in developing countries (e.g. India, China) (assuming 28% globally); 28% recovery today means ~610M in 2020 (CMRA estimate 140 million tonnes in the US) • 95% recovery in 2040 means 3,140 million tonnes in 2040, an addition of ~2,530 million tonnes per year; CAPEX required: 2,530 / 73 = €34.7 billion = USD $40 billion

2. METAL

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Steel scrap: 750 million tonnes in 2020 and 1,100 million tonnes in 2040 • Source: BCG steel & alu model
Waste Collection and Recycling Ambition	• Current recycling at 80% needs to get to 95% - theoretical limit 100% if all metals sorted correctly without contamination • Collection to increase from 82% to 97% recycling (expecting ~2% loss expected in conversion) -> ~450 million tonnes addt. collection
Design Investments (2021-2040, USD $ billion)	• A key challenge in steel recycling is the contamination from other metals, e.g. copper, due to difficulty in disassembling metal-products into different metals. This lowers the purity of the feedstock and thus the quality of the recovered metal. To mitigate this challenge, investments must be focused in the product design phase to make disassembly feasible . Further, the producers must invest in take-back systems that allows for convenient collection of their used steel-products at end of life • The construction, automotive and industrial machinery industries are the main producers of metal products with assumed market sizes of USD $12.5, USD $3.6 and USD $0.6 trillion in 2021 respectively and spend 2%, 3% and 3% on R&D respectively • Assuming 2% of annual R&D spend for each industry for take-back infrastructure for steel and 3-5% of annual R&D spend used redesign for disassembly in construction (7%), automotive (7%) and industrial machinery (5%) • (USD $12.5 trillion * 2% + 3.6 trillion*3% + 0.6 trillion*3%)*2% take-back spend = ~7 billion Take back spend • USD $12.5 trillion*2%*7% + USD $3.6 trillion *3%*7% + USD $0.6 trillion * 3% * 7% = ~USD $24 billion R&D spend for redesign for disassembly ~USD $31 billion total • Adjustment to include 100% metals market: USD $31 billion/95% = ~USD $33 billion
Collection Investments (2021-2040, USD $ billion)	Trucks and containers are the two main investments to ensure scrap is collected according to growth in scrap volume. Trucks and containers should be deployed regionally with focus on areas w. poor recycling infrastructure. • Truck: avg. global capacity of 24.5K tonnes per year(provided 8.5 m^3 space, 8 tonnes steel per m^3 and 1 daily load), avg. lifespan of 10 years and avg. price of USD $120K • Containers: 4 m3 avg. volume 8 tonnes steel per m^3 32 tonnes per week assuming collection once per week * 52 weeks, 1,664 tonnes/year and avg. investment cost of USD $500 • Trucks: 410 million tonnes addt. scrap steel/ 24.5K tonnes annual capacity *USD $120K per truck * 20 years / 10 year life span = ~USD $7 billion • Containers: 450 million tonnes addt. scrap steel / 1,664 tonnes annual capacity * USD $500 = ~USD $0.5 billion • Adjustment to include 100% metals market: USD $5.5 billion/95% = ~USD $8 billion

Sorting Investments (2021-2040, USD $ billion)	• Various initial mechanical processing methods are needed for different types of steel waste: Of the 450 million tonnes addt. Steel recycled, assume split of home scrap, prompt scrap and obsolete scrap according to BCG model 2040 forecast: • 18% home scrap - needs no sorting - USD $0 billion • 20% prompt scrap of which 30% needs de-zincing/de-tinning (15% from construction and 15% form automotive and consumer) • 62% obsolete (post-consumer) scrap of which all needs pre-processing, divided in the following manner: • Cast/rail breaking for 10% of waste steel (iron cast and rail) at ~23 USD $/tonne • Shredding for light/mixed/automotive scrap for 30% of recycled waste steel at ~95 USD $/tonne • Shearing for remaining 60% middle to larger sized scrap, mainly from construction at ~43 USD $/tonne • Additionally, for 15% of the total shredded waste, further baling/briquetting is assumed at ~11 USD $/tonne • Further processing to avoid contamination includes Magnetic sorting and de-zincing/de-tinning primarily. • Assuming magnetic sorting installed for 80% of recycled obsolete-waste steel at avg. ~3.5 USD $/tonne • Assuming de-contamination for 50% of recycled obsolete-waste steel (at avg. ~90 USD $/tonne) • Sorting – prompt scrap: 450 million tonnes addt. Steel * 20% prompt scrap * 30% de-zincing/de-tinning * USD $90 = USD $2.5 billion • Sorting – obsolete (post-consumer) scrap: 450 million tonnes addt. steel * 62% obsolete scrap = ~280 million tonnes scrap • Cast/rail breakers: 280 million tonnes * 10% iron cast and rail * USD $23 = USD $0.6 billion • Shredding: 280 million tonnes * 30% shredding * USD $95 = USD $7.9 billion • Shearing: 280 million tonnes * 60% shearing * USD $43 = USD $7.2 billion • Baling/briquetting: 280 million tonnes * 30% shredding * 50% for baling/briquetting * USD $11 = USD $0.5 billion • Magnetic separation: 280 million tonnes * 80% magnetic separation * USD $4 = USD $0.8 billion • De-zincing/de-tinning: 280 million tonnes * 50% de zincing /de tinning * USD $90 = USD $12.5 billion • Total sorting cost = 2.5 + 0.6 + 7.9 + 7.2 + 0.5 + 0.8 + 12.5 = ~USD $32.3 billion * 20% technological advancement = $38.8 billion • Adjustment to include 100% metals market: USD $38.8 billion/95% = ~USD $41 billion
Recycling Investments (2021-2040, USD $ billion)	• Mature and efficient equipment for steel recycling already established w. Direct Reduced Iron (DRI) and Electric Arc Furnaces (EAFs) • DRI-EAF investment cost of average USD $1,000 per tonne and avg. annual capacity of 1 million tonnes • EAF w/o DRI investment cost of average USD $300 per tonne and avg. annual capacity of 1 million tonnes • Assuming 10% of current recycling across APAC and MEA expected to be idle EAF capacity = 50 million tonnes idle capacity • Assuming 80% will be recycled via EAF and 20% via DRI-EAF • DRI-EAF recycling investment: (450 million tonnes addt. recycled steel – 50 million tonnes existing idle capacity) * 20% * USD $1,000 = ~USD $84 billion • EAF recycling investment: (450 million tonnes addt. recycled steel – 50 million tonnes existing idle capacity) * 80% * USD $300 = ~USD $101 billion • Adjustment to include 100% metals market: USD $185 billion/95% = ~USD $195 billion

3. BIOWASTE

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Global population is expected to grow from 7.8 billion in 2021 to 9.2 billion in 2040, an 18% increase; • World per-capita food consumption is expected to increase from 2,942 kcal/person/day in 2020 to 2,953 kcal/person/day in 2040, 0.4% increase, due to changes in food mix and demographics • We set a 2040 food loss and waste reduction ambition of 25%, in line with World Resource Institute ambition for 2050, though lower than UN SDG 12.3 ambition of 50% food waste reduction by 2030 • This 25% is lower than avoidable food waste share of total food waste (30-60% depending on country) • Given vegetal, animal and mixed food waste represents ~87% of total biowaste amount, this 25% is equivalent to 25% * 87% * 665 million tonnes = 145 million tonnes • Therefore, biowaste by 2040 is: (665 million tonnes – 145 million tonnes) * (1 + 18%) * (1 + 0.4%) = 616 million tonnes
Waste Collection and Recycling Ambition	• We set 85% ambition for biowaste recycling (biogas and composting) in 2040, assuming 70-80% recycling in municipal bio-waste and 90-100% recycling in industrial bio-waste by 2040 (based on best-practice countries - e.g., 75% for municipal biowaste 2025 ambition in Bulgaria; 65% for overall municipal waste recycling in EU by 2035) • Home composting is not part of this recycling ambition or investment case, assuming all composting is done via centralized composting • To achieve 85% recovery, 616 million tonnes * 85% = 524 million tonnes should be recycled; Currently, 83 million tonnes is recycled; therefore, an increase of 524 million tonnes – 83 million tonnes = 441 million tonnes recycling per year is required by 2040 • To cover process loss, additional 5% biowaste should be collected (i.e., 90% collection ambition)
Design Investments (2021-2040, USD $ billion)	• FAO (2020) estimated that investment globally for food loss reduction is $8,580 million annually for 10% reduction by 2030 (using the IMPACT model). Therefore for 20 years at 25% reduction, we estimate that USD $8.58 billion * 10 / 10% * 25% = USD $215 billion • US ReFED 2030 roadmap estimated the investment need in food loss and waste reduction in the United States. Harvest optimization, product distribution enhancement, product management refinement and product utilization maximization initiatives in total cost USD $80 billion for 45 million tonnes food waste reduction (excluding public sector and philanthropic investments) • Given global waste reduction ambition of 145 million tonnes, the total investment need for reducing food loss and waste globally from this approach will be USD $80 billion / 45 million tonnes * 145 million tonnes = USD $255 billion, which is ~19% higher than the estimate extrapolated from FAO projection • Overall, we will set the investment need at USD $220-250 billion range
Collection Investments (2021-2040, USD $ billion)	• A dedicated network for biowaste (e.g., dedicated bins and trucks) can be established, on top of the existing waste separation and collection infrastructure • Data is scarce on the current level of collection of biowaste globally,and can vary widely from 10% to 90% (European countries examples). Assuming current level of collection is at 50% • Assuming 8 tonnes/day for collection and USD $120,000 for a truck, operating 300 days a year at 80% capacity, with product life of 7 years (based on benchmarking for biowaste collection), the additional CAPEX = 616 million tonnes * (90% – 50%) / (8 tonnes * 300 * 80%) * USD $120,000 * 20 years / 7 years = USD $44 billion • Note: This amount is only the estimate for capital investment and does not include operating expenses
Recycling Investments (2021-2040, USD $ billion)	• Per CCAC Waste Initiative for EU-27 countries, CAPEX per tonne for biogas plant (anaerobic digestion) is USD $400-500 per tonne (assumed at USD $400, considering lower Capex in developing countries) and CAPEX per tonne for composting is USD $100-200 per tonne (assumed at USD $100, considering lower CAPEX in developing countries) • In the EU, biogas conversion (anaerobic digestion) accounts for 47 % of the bio-waste treatment capacity; no data are available on the volume of home composting. • We set the ambition of 40% for biogas conversion and 45% for composting (split similar to the EU current status), equivalent to 207 million tonnes increase in biogas conversion and 234 million tonnes increase in composting, compared to the current treatment amount • Total investment required = 207 million tonnes * USD $400/tonne + 234 million tonnes * USD $100/tonne = USD $105 billion

4. WOOD

ITEMS	KEY ASSUMPTIONS

Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Volume calculated based on FAO wood production report using 1990 and 1970 global consumption rates as benchmarks and avg. expected lifespan of wood types:
	  > Wood-fuel: 0% waste wood expected = 0 m3
	  > Industrial roundwood: 30-50 year expected life w. 40 ppt directly repurposed/lost/deteriorated= 0.75 billion m3
	  > Sawnwood: ~35 year expected life w. 40 ppt directly repurposed/ lost/deteriorated =0.15 billion m3
	  > Wood-based panels: ~25 year expected life w. ~40 ppt directly repurposed/ lost/ deteriorated = 0.15 billion m3
	• Total: 0.75 billion +0.15 billion + 0.15 billion = 1.02 billion m3 and expected to grow w. avg. consumption growth at 2.9% CAGR to 1.8 billion m3 in 2040
	• Conversion m3/tonnes = 1.8 * 0.714 and 1.02 * 0.714 = 1.29 -0.73 = 0.56 billion tonnes addt. wood consumption

Waste Collection and Recycling Ambition	• 90% collection and 80% recycling rate of waste wood • Collection: 1.29 * 90% - 0.73 * 83% (2020) = 560 million tonnes addt. collected wood • Recycling: 1.29 * 80% - 0.73 * 21% = 900 million tonnes addt. recycled wood • 83% collection rate today and 21% recycling. Europe leads wood recycling at ~46%, APAC, NAM, LAM recycle ~15% and MEA 10% • Regional recycling to reach 80% recycling impacted by current collection rate and consumption growth expectations
Design Investments (2021-2040, USD $ billion)	• Design for non-toxic alternatives to treatments for wood. Ambition: grade D wood – from 5% to 2% of total wood consumption • Investment need: annual 0.25% of chemical industry R&D spend USD $3.94 trillion global market * 2% R&D spend * 0.25% * 20 years of R&D spend = ~USD $4 billion • Design for re-reuse and repurposing of wood form construction and furniture industries: • Investment need: annual 4% of R&D spend of construction and furniture industry 12.5 + 0.5 trillion global market * 2% R&D spend * 4% * 20 years = ~USD $21 billion
Collection Investments (2021-2040, USD $ billion)	• Wood containers to be installed for wood waste collection in municipal waste areas and wood-waste trucks to be installed in industry, construction sights and municipal areas. Assuming 25% idle capacity in 2020 of trucks and containers today = 610 million tonnes * 20% = 120 million tonnes • (560-120 million tonnes wood collected) / ~3,675 tonne truck annual capacity USD $120K per truck * 20 years/10-year lifespan = ~USD $28 billion • (560-120 million tonnes wood) / 500 tonnes annual container capacity * USD $600 average container price at 5-tonne weekly limit and average price of USD $300 = ~USD $1 billion
Sorting Investments (2021-2040, USD $ billion)	• 560 billion tonnes / 500k capacity per facility = ~1,100 addt. wood sorting facilities at w. average price USD $17.5 million • Focus on advancing wood sorting technology to improve the wood grade separation between grade A-D • 560 billion tonnes wood recycled * USD $35 per tonne sorting capacity = ~USD $20 billion
Recycling Investments (2021-2040, USD $ billion)	• Of the 100% waste wood, 94% is to be recycled: 79% Grade A and B wood and 15% grade C wood. • Expecting 85% of recycling to come from mechanical recycling, chemical recycling of lower grade wood to account for 15% • 21% recycling in 2020 almost entirely mechanical recycling 21% * 730 million tonnes waste wood in 2020 = ~150 million tonnes mechanical recycling in 2021 • Mechanical recycling for 100% of Grade A wood and 90% of Grade B wood (equivalent to 79% of total wood = 1.3 billion tonnes * 79% (79% + 15%) - 150 million tonnes in 2021= 810 million tonnes • 760 billion tonnes / 155k capacity of recycling facility = ~ 5.3K plants and USD $7.5 million per plant =~USD $40-45 billion • Chemical 85% grade C wood (equivalent to 15% of total waste wood = 560 million tonnes addt. recycling * 15% / (79% + 15%) = 90 million tonnes • 90 million tonnes wood / 160k capacity = 560 facilities at USD $37 million investment = ~USD $21 billion • Expected 20% addt. investment in advancing recycling emerging technologies, especially within chemical recycling • = (USD $40 – USD $21 billion) * 1,2 = ~USD $73 billion • Remaining 6% wood is hazardous or lost in conversion and thus not recycled

5. PAPER

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• According to RISI (2020), ~400 million tonnes of waste paper generated annually in 2020 expected to grow to ~530 million by 2040
Waste Collection and Recycling Ambition	• Objective of 95% collection (450 million tonnes) due to feasibility of material collection • Objective of 80% overall recycling (425 million tonnes) of wastepaper is the maximum practical rate given limited recovery of fibers to 5-7x, some contaminated paper impossible to recover (10-20%) . 80% feasible in light of already high collection rates of 73% in EU and potential in non-recycled paper
Design Investments (2021-2040, USD $ billion)	• Some design investments (USD $5 billion) needed to reduce chemical use, e.g. laminated paper turned into biodegradable coatings. Investments already taking place in this market
Collection Investments (2021-2040, USD $ billion)	• Collection: 530 million tonnes * 95% (2040) – 400 million tonnes * 80% (2020) = ~185 million tonnes addt. paper and board collected • Collection rate: 185 million tonnes addt. recycling + 30 million tonnes of current collection converted from single stream to paper/board specific collection = 215 million tonnes • Trucks: Average truck capacity 14 tonnes/day operating 365 days a year and average truck price of USD $120,000 and lifespan of 10 years. Truck investment: 215 million tonnes addt. paper collected / 5,100 tonnes capacity * USD $120,000 * 20 years / 10 year lifespan = USD $10-11 billion • Bins: 100 litres bins avg. paper volume 50 kg per day and avg. investment cost of USD $15 215 addt. paper / 1,5 tonnes annual capacity * USD $15 = USD $2-3 billion
Sorting Investments (2021-2040, USD $ billion)	• Recycling: 530 million tonnes * 80% - 400 million tonnes * 59% = 190 million tonnes addt. paper and board sorted and recycled • Sorting distributed regionally according to consumption with 90% going through paper specific waste streams and 10% through single stream • USD $245 investment per tonne of capacity for wastepaper sorting equipment • USD $80 investment per tonne of capacity for single stream sorting (assuming 20% cost and investment of larger single stream facility directed to paper) • Sorting cost: USD $245 * 90% * 215 million tonnes addt. paper specific sorting + USD $80 * 10% * 190 million tonnes addt. single stream sorting =USD $45-55 billion
Recycling Investments (2021-2040, USD $ billion)	• Recycling distributed regionally according to consumption w. 10% idle capacity utilization of existing equipment • By 2040, 80% of global paper consumed is recycled, of which 75% of recycling stems from regular paper recycling and 5% from difficult to recycle paper. • Regular recycling: USD $250 investment cost per tonne capacity of pulp mill machinery and USD $750 investment cost per tonne capacity of paper mill (De-inking system included in paper recycling mill). Average capacity of large pulp and paper machinery: 295,000 tonnes annually • Difficulty to recycle paper machinery: Dry-pulping scalable with main base in Europe. USD $500 investment per tonne and capacity of 10,000 tonnes annually • 190 million tonnes * 90% * (75/80) * (USD $250+USD $750 per tonne regular recycling) = ~USD $160 billion for regular recycling • 190 million tonnes * 90% * (5/80) * USD $500 per tonne dry pulping = USD $5 billion for dry pulping

6. PLASTICS

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Currently, ~270 million tonnes plastic waste is generated globally per year. This figure is expected to grow ~4% annually, leading to ~560 million tonnes plastic waste generated by 2040
Waste Collection and Recycling Ambition	• Consumption expectation by 2040 (560 million tonnes) to be reduced 20% mainly from packaging due to major potential within re-use and re-fill CPG products: 270 million tonnes consumption (2020) increased to 450 million tonnes consumption by 2040 • Addt. collection: 450 million tonnes * 90% = 405 million tonnes (2040) – 270 millon tonnes * 75% = 205 million tonnes (2020) = 200 million tonnes plastic for addt. collection • Recycling: 450 million tonnes * 80% = 360 million tonnes – 270 million tonnes * 16% = 44 million tonnes = 315 million tonnes addt. plastic recycling - lead by technological development and plastic recycling infrastructure. Chemical recycling will play larger part, accounting for half of future plastic recovery. Recycling distributed regionally according to consumption
Design Investments (2021-2040, USD $ billion)	• The CPG industry is assumed to invest in re-use and recyclability of products. market size is projected to be USD $1.9 trillion in 2021 • Industry current R&D as % of revenue estimated 2% • Assuming 5% of annual R&D spend use reducing overpackaging and increasing re-use and 5% of annual R&D spend used to increase recyclability of plastic w. a focus on single-polymer design, additional R&D = USD $1.9 billion * 2% * 10% * 20 years = USD $100-110 billion
Collection Investments (2021-2040, USD $ billion)	• Truck: avg. global capacity of 5 tonnes per day (1,825 tonnes per year), avg. lifespan of 10 years and avg. price of 120K • Bins: 100 l bins avg. plastic volume 20 kg per day and avg. investment cost of USD $15 • Higher uncollected waste share in regions with rural areas and lower waste development • Trucks: 200 million tonnes plastic / 1,825 tonnes capacity *USD $120 K per truck * 20 years /10-year life span = ~USD $26 billion • Bins: 200 million tonnes plastic / 1.04 tonnes annual capacity * USD $15 = ~USD $2.9 billion
Sorting Investments (2021-2040, USD $ billion)	Plastic need to be recycled mainly via magnetic – and sensor-based sorting at a specialized plastic sorting facility. • Assuming USD $240 avg investment per tonne of capacity for sensor-based plastic sorting equipment • Avg. capacity of large sorting plant is 100,000 tonnes/year and Current facilities at full capacity, 20% of landfill/incineration fill redirected for recycling • Sorting facilities: 200 million tonnes plastic / 100.000 tonnes = ~2,000, sorting investment: 200 million tonnes plastic * USD $240 per tonne = ~USD $48 billion
Recycling Investments (2021-2040, USD $ billion)	• 80% of plastic waste recycled – 60% from mechanical recycling (driven by increased collection and sorting). Chemical recycling share up from <5% to 40% - 30% from pyrolysis (driven by mixed and difficult to recycle plastic) and 10% depolymerization (driven by more difficult PE plastics). Utilization at capacity of existing recycling equipment. • Mechanical recycling avg cost of $600 per tonne and avg. annual capacity of 20.000 tonnes capacity recycling capacity need 2040 minus existing capacity 2020 = [360 million tonnes * 60% - 44 million tonnes recycling = 170 million tonnes capacity] * USD $600 = ~USD $100 billion • Pyrolysis and Depolymerization/monomerization avg. cost at $1,000 per tonne and avg. annual capacity of 20.000 tonnes: • 360 million tonnes recycling in 2040 * (30% pyrolysis+10% depolymerization)= 145 million tonnes tonnes * USD $1,000 = ~USD $150 billion

7. E-WASTE

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Currently, ~54 million tonnes e-waste is generated globally per year. This figure is expected to grow ~3% annually, leading to ~100 million tonnes e-waste generated by 2040
Waste Collection and Recycling Ambition	• The investment case assumes that, by 2040, 85% e-waste is collected for recovery while 80% is recycled (i.e., 5% is non-recyclable or lost during collection process), including the recycling of reused/refurbished products. • The recycling ambition is developed based on the best practice region (EU) and is feasible technically: EU recovery ambition for e-waste as of 2018 are in the range of 75-85% and ambition for recycling/preprepared for reuse is 55-80% • This is achieved in conjunction with 20% ambition for reuse / refurbish rate (which should eventually be recycled) and 50% increase in product lifetime.
Design Investments (2021-2040, USD $ billion)	• Global electronics industry estimated at USD $1,099 billion in 2020, grows at 4.9% CAGR, to USD $2,862 billion in 2040 • R&D represents 12.5% of the industry revenue each year , eq. cumulative ~USD $5,000 billion over 2020-2040 • Recycling-related R&D investment assumed as 1% of annual industry R&D , representing ~USD $50 billion over 20 years
Collection Investments (2021-2040, USD $ billion)	• Currently, we assume that ~40 million tonnes of e-waste are collected per year (including informal collection and those collected for landfilling, equivalent to ~70-80%), while 85% collection in 2040 is equivalent to ~85 million tonnes; therefore, an increase of 85 million – 40 million = 45 million tonnes collection is required • USD $7 billion is required to incentivize customers to return e-waste, equivalent to 1% of annual industry marketing spend over 20 years • USD $25 billion is needed to build formal collection networks, including collection yards, dedicated drop-off locations, mail in services and pickup schemes
Sorting Investments (2021-2040, USD $ billion)	• Various initial mechanical processing methods are needed to separate e-waste into different material fractions: Shredding at ~USD $95/tonne, Magnetic sorting at avg. ~USD $3.5/tonne and de contamination at avg. ~ USD $90/tonne
Recycling Investments (2021-2040, USD $ billion)	• Currently, 9.3 million tonnes are recycled, therefore an increase of 80 million – 9.3 million = 71 million tonnes are required • Assuming 15% e-waste which represents plastics is covered in plastics document separately, the remaining capacity increase is 71 million * (1 – 15%) = 60 million • Assuming average recycling plant capacity of 2,000 t which costs capital expenditure of USD $2 million , USD $60 billion in recycling capacity is required • Assuming new technologies used for improving material recovery efficiency are priced into the CAPEX assumption

8. EV BATTERIES

ITEMS	KEY ASSUMPTIONS
Waste Amount Basis and Projection (2020 and 2040, in million tonnes)	• Total batteries market volume is estimated to be 2,897 GWh in 2030, where EV batteries (incl. hybrid) represent 82% (the focus of the investment assumptions). Assuming average battery life of 10 years and battery weight of 440kg per 60 KWh pack, retired batteries by 2040 would be 2,897,000,000 kWh / 60 kWh * 440kg = 21 million tonnes waste. Assuming waste from industrial manufacturing process represents an additional 10% (BMW Benchmark), total waste by 2040 = 21 million * (1 + 10%) = 23 million tonnes
Waste Collection and Recycling Ambition	• 90% ambition as best practice for Li-ion batteries (higher for others) • For 2040, we set a 90% recycling ambition and 95% collection rate: 21 million tonnes out of the 23 million tonne-waste volume in 2040 are recycled; 22 million should be collected • Today, ~50% batteries are recycled and ~85-100% batteries are collected (90% assumption). Today's batteries waste is a small waste stream (<1m): we assume an additional 18 million collection capacity (excluding 10% from manufacturing process doesn't require additional collection capacity) and 21 million recycling capacity
Design Investments (2021-2040, USD $ billion)	• Assuming batteries prices of $70/kWh by 2040, the batteries market in 2030 = USD $200 billion • Assume 5% of industry revenue goes into R&D, (Samsung SDI 8.2%, LG Chem 4%, SK Innovation 0.7%), 2030 R&D = $10 billion; assuming 2030 R&D would be the average of 2021-2040 annual R&D, total R&D over 20 years = USD $200 billion • Assume 5% of batteries R&D can be attributed to circularity (e.g., Designing for disassembly, Reducing use of undesirable materials), the Design Investment relevant for circularity over 2021-2040 = USD $10 billion
Collection Investments (2021-2040, USD $ billion)	• Average price of $12,000 battery tester that checks 20 batteries a day for 250 days, with average life of 7 years, for checking batteries state of health => CAPEX over 2021-2040 = 2,897,000,000 kWh / (60 kWh * 20 * 250) * USD $12,000 * 20 years / 7 years = USD $0.3 billion • For majority of batteries (~95%), assume average truck capacity 15 tonnes/day (2 trips of ~18 batteries each) operating 250 days a year with 80% utilization => 18 million * 95% / (15 * 250 * 80%) = 5,700 trucks • Average price of $120,000 truck with average life of 7 years => CAPEX over 2021-2040 = 5,700 * USD $120K * 20 years / 7 years = USD $2.0 billion • For small percentage of batteries (5%) that have safety concerns (e.g., fire hazard), specialized Hot Box Trucks are required, which can hold 1-2 tonnes a day (2 trips of 1-2 batteries each) operating 250 days a year with 80% utilization => 18 million * 5% / (1.5 * 250 * 80%) = 3,000 trucks • Average price is 35% more expensive (Daimler Benchmark), with avg. life of 7 years => CAPEX over 2021-2040 = 3,000 * USD $120K * (1 + 35%) * 20 years / 7 years = USD $1.4 billion • Total CAPEX = USD $0.3 billion + USD $2 billion + USD $1.4 billion = ~USD $4 billion
Recycling Investments (2021-2040, USD $ billion)	• USD $38 million plant and equipment for 10,000 tonnes/year recycling plant (based on BCG project experience & expert interview) • 2,100 such plants required (21 million / 10k tonnes) => 2,100 * USD $38 million = USD $80 billion investment in recycling CAPEX

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This report has been developed in the name of WBCSD. Like other WBCSD publications, it is the result of a collaborative effort by members of the secretariat and senior executives from member companies. A wide range of members reviewed drafts, thereby ensuring that the document broadly represents the perspective of the WBCSD membership. Input and feedback from stakeholders listed above was incorporated in a balanced way. This does not mean, however, that every member company or stakeholder agrees with every word.

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ABOUT WBCSD

WBCSD is the premier global, CEO-led community of over 200 of the world's leading sustainable businesses working collectively to accelerate the system transformations needed for a net zero, nature positive, and more equitable future.

We do this by engaging executives and sustainability leaders from business and elsewhere to share practical insights on the obstacles and opportunities we currently face in tackling the integrated climate, nature and inequality sustainability challenge; by co-developing "how-to" CEO-guides from these insights; by providing science-based target guidance including standards and protocols; and by developing tools and platforms to help leading businesses in sustainability drive integrated actions to tackle climate, nature and inequality challenges across sectors and geographical regions.

Our member companies come from all business sectors and all major economies, representing a combined revenue of more than USD $8.5 trillion and 19 million employees. Our global network of almost 70 national business councils gives our members unparalleled reach across the globe. Since 1995, WBCSD has been uniquely positioned to work with member companies along and across value chains to deliver impactful business solutions to the most challenging sustainability issues.

Together, we are the leading voice of business for sustainability, united by our vision of a world in which 9+ billion people are living well, within planetary boundaries, by mid-century.

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