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Approaches to the low carbon transition of heavy industries

The role of Circular Economy measures in China and Germany

Carried out under the bilateral energy partnership on behalf of the German Federal Ministry for Economic Affairs and Climate Action

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Content

Executive Summary

This summary encapsulates the core findings of the report titled "Approaches to a Low Carbon Transition of Heavy Industries and the Role of Circular Economy Measures in China and Germany," and contributes to the EnTrans project. The report focuses on leveraging circular economy strategies to facilitate the low carbon transition of heavy industries in these China and Germany.

The report emphasizes the imperative of integrating circular economy principles into the decarbonization efforts of industries. While energy efficiency, renewable sources, and carbon capture technologies are well recognised pillars, the report highlights the importance of resource efficiency and the circular economy concept. Circular economy strategies aim to minimize resource consumption through approaches such as resource-saving design, efficient resource utilization, and product life extension.

Key insights highlight the shift from the traditional linear production model to the circular economy paradigm by reducing waste generation and promoting reuse and recycling. This circular approach not only conserves materials but also enhances energy efficiency in industrial processes.

The report highlights specific industries that are both carbon-intensive and also energy and resource-intensive. The report explores recycling processes for steel, aluminium, glass, cement and paper industries and delves into the potential utilization of secondary raw materials, presenting opportunities and challenges related to implementing circular economy measures. Amongst others, these challenges encompass impurities and availability of secondary materials, accurate sorting methods, and lacking infrastructure for effective recycling.

The report provides an overview of recycling processes of energy intensive raw materials with a focus on metals, paper and glass and describes the current production practices of those energy intensive materials in Germany and China.

For plastics, the report focuses on three circular solutions—mechanical recycling, chemical recycling, and bioplastics. While mechanical recycling is well-established globally, the potential of chemical recycling is anticipated to rise with the chemical industry's shift towards sustainability. Furthermore, the report underscores the significance of material efficiency within the construction sector, given the substantial emissions from cement and concrete production. The recommendations encompass optimizing building design, reducing clinker content, and implementing prefabrication techniques to mitigate emissions.

Based on the challenges and potentials highlighted in the different sections, the report offers a set of political recommendations developed for the Chinese context, evolving from the aforementioned challenges. These recommendations address critical issues:

- **Equitable Raw Material Economics**: Addressing economic imbalances between primary and secondary materials through technology support, potential taxes, and Extended Producer Responsibility systems.
- **Stimulating Circular Demand**: Boosting circular product demand through recycled content quotas and leveraging Public Procurement to endorse circular technologies.
- **Empowering Circular Design**: Introducing an Eco-Design Directive to enhance recyclability and sustainable practices, especially in the construction sector.
- **Establishing Circular Infrastructure**: Constructing a resilient circular infrastructure with recycling quotas, reusable systems, and incentive frameworks for plastic recyclability.

In conclusion, this report underscores the pivotal role of circular economy strategies in steering heavy industries toward a low carbon trajectory. It calls for unified efforts to embrace circularity, curtail emissions, and optimize resource utilization, while the EnTrans project serves as a beacon for sustainable industrial transformation.

1 Introduction

1 Introduction

1.1 The role of energy and carbon intensive industries

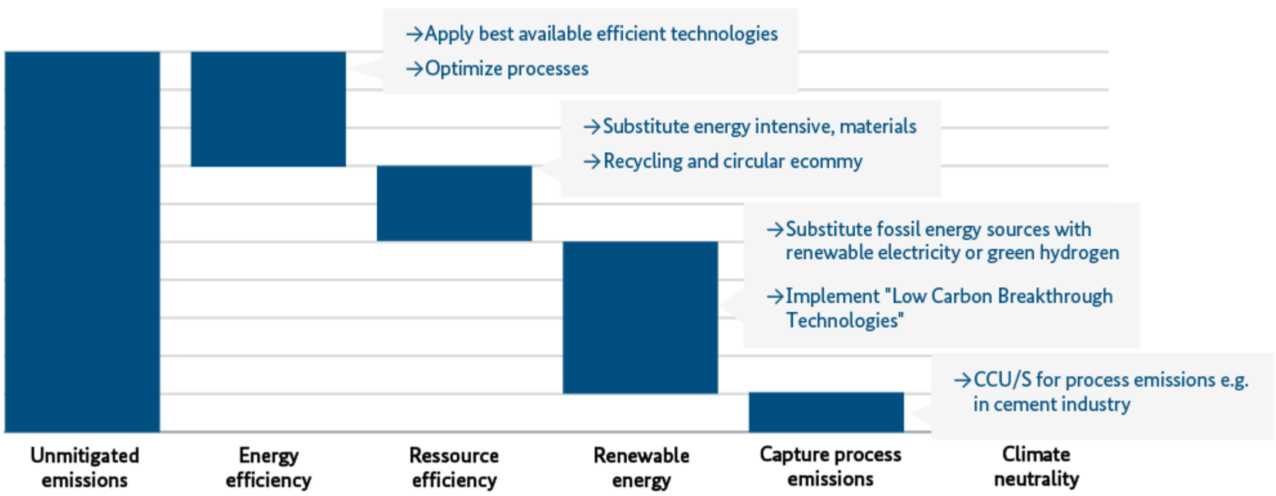
The need to mitigate climate change and create a carbon-neutral future is more urgent today than ever before. After the power sector, heavy industries are the second-largest global source of CO_2 emissions (IEA, 2023). The majority of industry emissions comes from three material groups: Steel, cement, and chemicals. As the global economy and population grow, so will demand for materials and goods, including materials from carbon intensive industries. Even though the population increase will eventually will come to a decline in China, foreign trade as well as improvements in infrastructure developments will continue to create demands for raw materials, including steel, primary aluminium and cement (IEA 2021). Current decarbonization measures related to renewable energy and production efficiency are in danger of being outpaced by increasing emissions from higher production.

On a global scale, emissions attributed to the production of essential materials and chemicals such as steel, plastics, ammonia, and cement are rising. Emissions from these sectors currently constitute a substantial 20% of the overall emissions (Material Economics, 2019 *Industrial Transformation 2050*). Unless substantial changes are embraced, the production of basic materials alone would exhaust the allocated 'carbon budget' intended for achieving the 2°C objective. Consequently, this would render the goal of limiting global warming to a level 'well below' 2°C virtually unattainable.

One challenge lies in the categorization of emissions from these sectors as ‘hard to abate.' The intricate relationship between carbon and prevalent production processes is deeply ingrained. Carbon serves as an elemental building block of the material for example within plastic or plays a pivotal role in the chemical processes utilized for their manufacturing, for instance in the cases of ammonia, cement, and steel production. The materials and chemicals produced by heavy industries are essential inputs to major value chains: transportation, infrastructure, construction, consumer goods, agriculture, and more making industrial emissions one of the main roadblocks to a net-zero economy (Material Economics, 2019, *Industrial Transformation 2050*).

Existing strategies within the industrial realm, aimed at curbing the carbon footprint, have placed considerable emphasis on carbon capture as the primary avenue for achieving notable emissions reductions. However, even within a framework including CCU/S, a considerable amount of emissions is projected to remain.

Figure 1: The role of ressource efficiency on the path to carbon neutrality. Source: dena

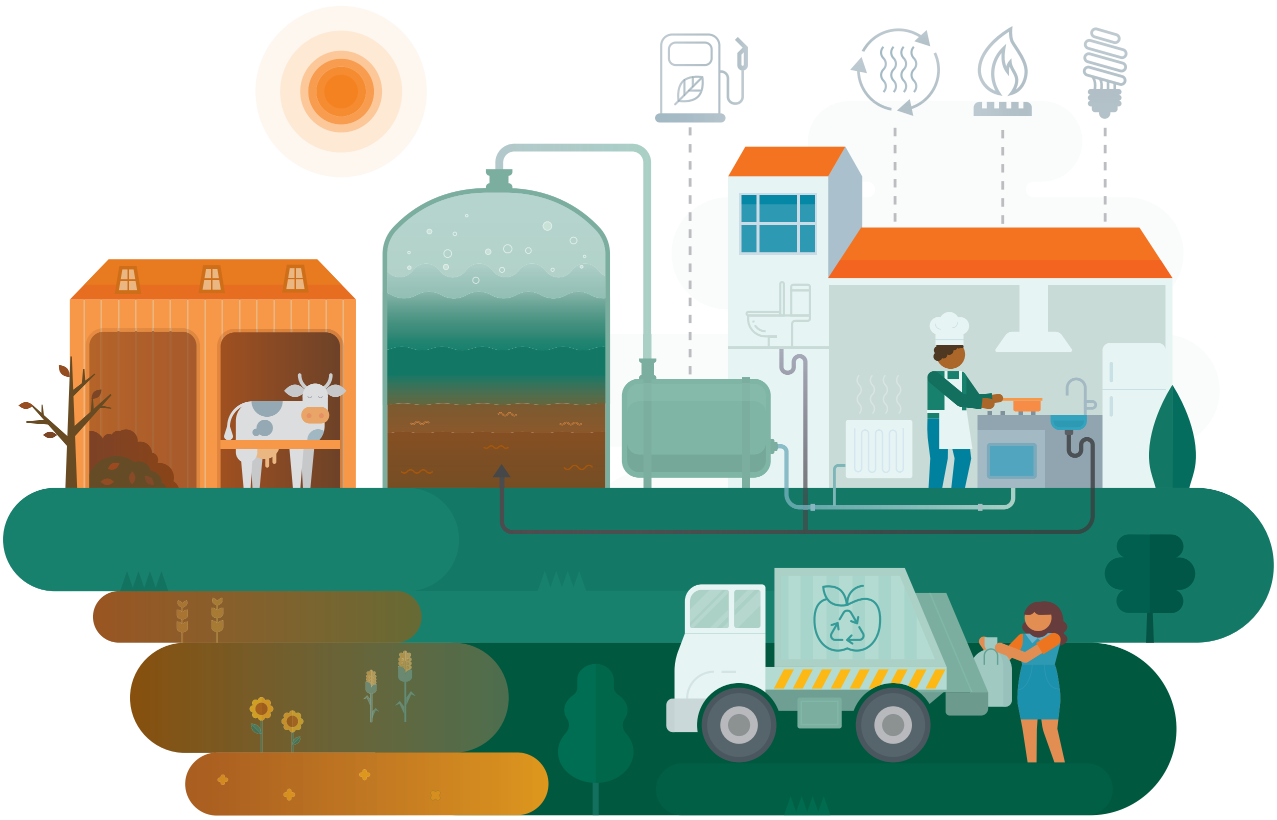


1.2 Circular economy as an essential component of the industrial climate-neutral transition

In the pursuit for decarbonizing heavy industries, the focus is often set on well-established pillars such as energy efficiency, renewable sources, and, more recently, carbon capture technologies. However, one essential aspect that deserves equal attention is resource efficiency. A concept closely linked to this is the circular economy.

The Circular economy strives to use resources more efficiently, minimise waste and avoid emissions. By extending the life of products, promoting repair and reuse, and recycling materials, fewer primary materials and resources are needed. This reduces the need for energy-intensive extraction and production processes and thus reduces greenhouse gas emissions associated with the production of goods, especially in the energy-intensive basic material industries.

The overarching goal of the circular economy is the absolute reduction in resource consumption through various measures including resource-saving design, efficient use of resources, product life extension and the gradual transition to the use of renewable energies. Enhanced recycling and greater material efficiency hold enormous untapped potential for the transition to a fossil free production of energy-intensive materials, in both the short and long run. Circular economy approaches have the potential to save energy. Applying them globally could, according to one estimate, reduce the global demand for Primary Energy (PE) by around 5–9% (Cooper et al. 2017).



2 Circular Economy Framework

2 Circular Economy Framework

2.1 Principles of Circular Economy

Circular economy thinking is founded in recognizing the limits of planetary resources and energy use, and acknowledging the significance of perceiving the world as an interconnected system, where waste and pollution are regarded as undesirable (Kirchherr et al. 2017). The Circular economy approach contrasts with the traditional linear business model of production of take-make-use-dispose by aiming at 'decoupling' resource use from economic growth. In practice, it mostly implies reducing waste to a minimum through different means and to keep materials within the economy wherever possible through reuse or recycling (Fischer-Kowalski, M. et al. 2011).

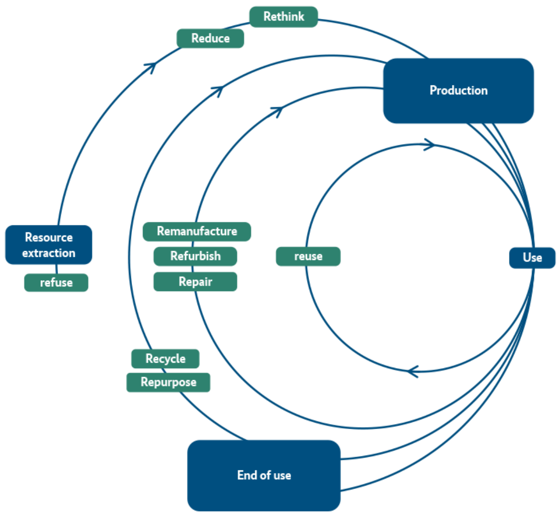
When comparing linear and cyclical approaches for the development of products and systems, it can be distinguished between "cradle-to-grave" flows of materials and cyclical, "cradle-to-cradle" flows. (Bocken et al. 2016). This distinction clearly marks a difference in resource flow patterns that characterize linear and circular models. Since the first use of the concept, the terminology around the "circular economy" has been diverging rather than converging and a multitude of definitions exist in parallel.

Although definitions and frameworks of Circular economy differ between scholars, common consensus exist about the underlying strategies to achieve absolute reduction in resource use (Circle Economy 2023 ; Bocken et al. 2016.) Circular economy strategies in general are aiming to achieve the following:

a) **Slowing resource loops** through the design of long-life goods and product-life extension
b) **Closing resource loops**: The loop between post-use and production is closed through recycling and recovery, resulting in a circular flow of resources.
c) Resource efficiency or **narrowing resource flows**, aimed at using fewer resources per product.
d) **Regenerate** to phase out hazardous or toxic materials and processes, and substitute them with regenerative biomass resources.

Various approaches, known as R-strategies, have been developed to achieve less resource and material consumption in product chains and make the economy more circular. In this report we are using the model of the "9R Framework" consisting of nine different circular economy strategies in a hierarchy complementing each other. In the following, the 9R framework, which is also used predominantly in research as well as UN publications, will be shown (Reike et al. 2018; Alexa Böckel et al. 2022; José Potting, Marko Hekkert, Ernst Worrell and Aldert Hanemaaijer). The graphic below shows how the 9R's complement each other to reduce primary resource consumption, close material cycles, keep products in use and eliminate waste.

Figure 3: R-Strategies of the Circular economy based on the 9R UNEP Framework. Source: UNEP 2023



Refuse: Changing habits to make a product unnecessary or replacing the same function with a radically different (e.g., digital) product or service. Eliminating or reducing the use of raw materials, designing production processes to avoid waste.

Rethink: Develop new business models, conscious material selection for (substitution of substances of concern, material innovations). Intensification of product use (e.g., through product-as-a-service, reuse and sharing models).

Reduce: Design that enables circularity, increasing efficiency in the manufacture or use of products by consuming fewer natural resources and materials as well as energy.

Reuse: Reuse of a product that is still in good condition and fulfilling its function (and is not waste) for the same purpose for which it was designed, possibly after repair or refurbishment.

Repair: Repair and maintenance of a defective product so that it can be used again with its original function.

Refurbish: Recover an old product and bring it up-to-date

Remanufacture: Use of parts of a discarded product in a new product with the same function.

Repurpose: Use of a redundant product or its parts in a new product with a different function.

Recycle: Recovery of materials from waste for reprocessing into new products, materials or substances for the original or another purpose. It includes recycling of organic material, but does not include energy recovery and recycling into materials to be used as fuels or for backfill operations.

Circular economy rebound

Similar to rebound effects observed in energy efficiency, circular economy approaches can lead to unintended consequences, such as increased overall production and use of products. This can lead to higher environmental impacts despite recycling efforts. Circular economy rebound can occur when secondary goods produced are of inferior quality or less desirable to users. This can lead to increased production and consumption of primary goods, offsetting the benefits of circular activities. Another mechanism for circular economy rebound happens when increased secondary production activity impacts prices. Pricing reused products and recycled materials lower to make up for real or perceived technical deficiencies are very likely to produce rebound. Even if secondary products are not discounted, their increased production can depress their own price and that of all substitutes, leading to rebound. Secondary products that compete in either low-end or high-end niches simply grow the "pie" rather than taking slices from primary production and also result in rebound.

To avoid the circular rebound, it is necessary that circular economy activities produce products and materials that truly are substitutes for primary production alternatives.

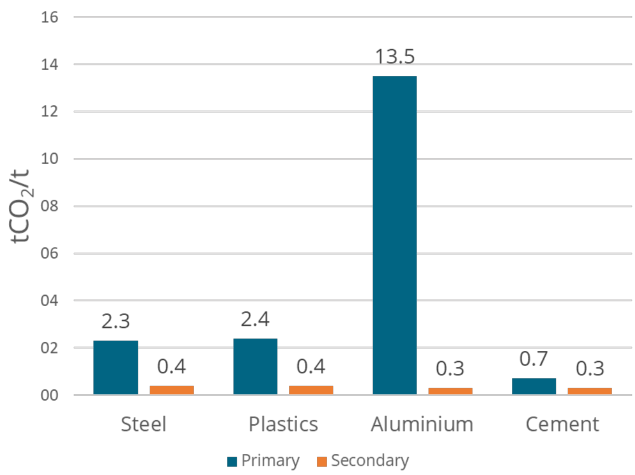
(Zink and Geyer 2017)

2.2 Circular economy for decarbonization

For energy, resource and CO_2-intensive sectors such as steel, aluminium, plastics and cement, a circular economy approach can play an essential part for decarbonisation through more circular and resource-efficient value chains. Moreover, studies argue that achieving climate goals in the industrial and energy sector will not be feasible without significantly increasing the efficiency and reuse of materials (Agora Industry 2022).

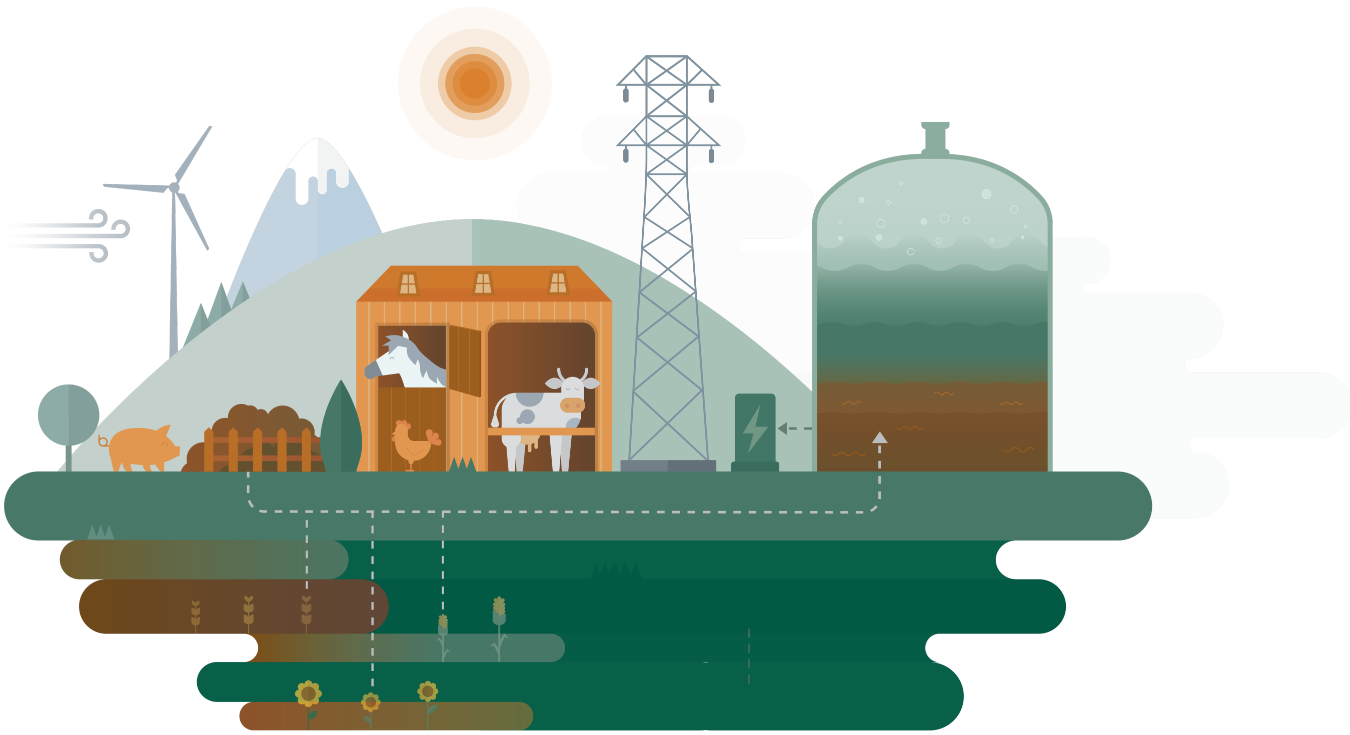
Strategies focusing exclusively on decarbonizing of existing production processes for primary materials involve challenges such as the immense electricity capacity needed for the electrification of all relevant end-usages, infrastructures required to implement new technologies such as CCU/S and the scarcity of certain natural and material resources. Circular economy strategies and measures can complement existing efforts of decarbonisation strategies not exclusively from an energy point of view but through a holistic approach. For instance, recycling solutions can help to reduce the need for the production of virgin material products. Closed material cycles through recycling measures are a major lever for emissions reduction. Above all, secondary materials from the energy-intensively processed basic materials such as steel, aluminium or plastics reduce the energy needed significantly than new production and thus reduce CO_2 emissions. Studies have shown that secondary material production can reduce energy use by up to 5 times (Agora Industry 2022).

Figure 4: CO_2 Intensity Factors of Primary vs. Secondary Production Routes. Source: Agora Industry 2022 based on Material Economics analysis (2021), Wood Mackenzie and S&P Global Platts Analytics

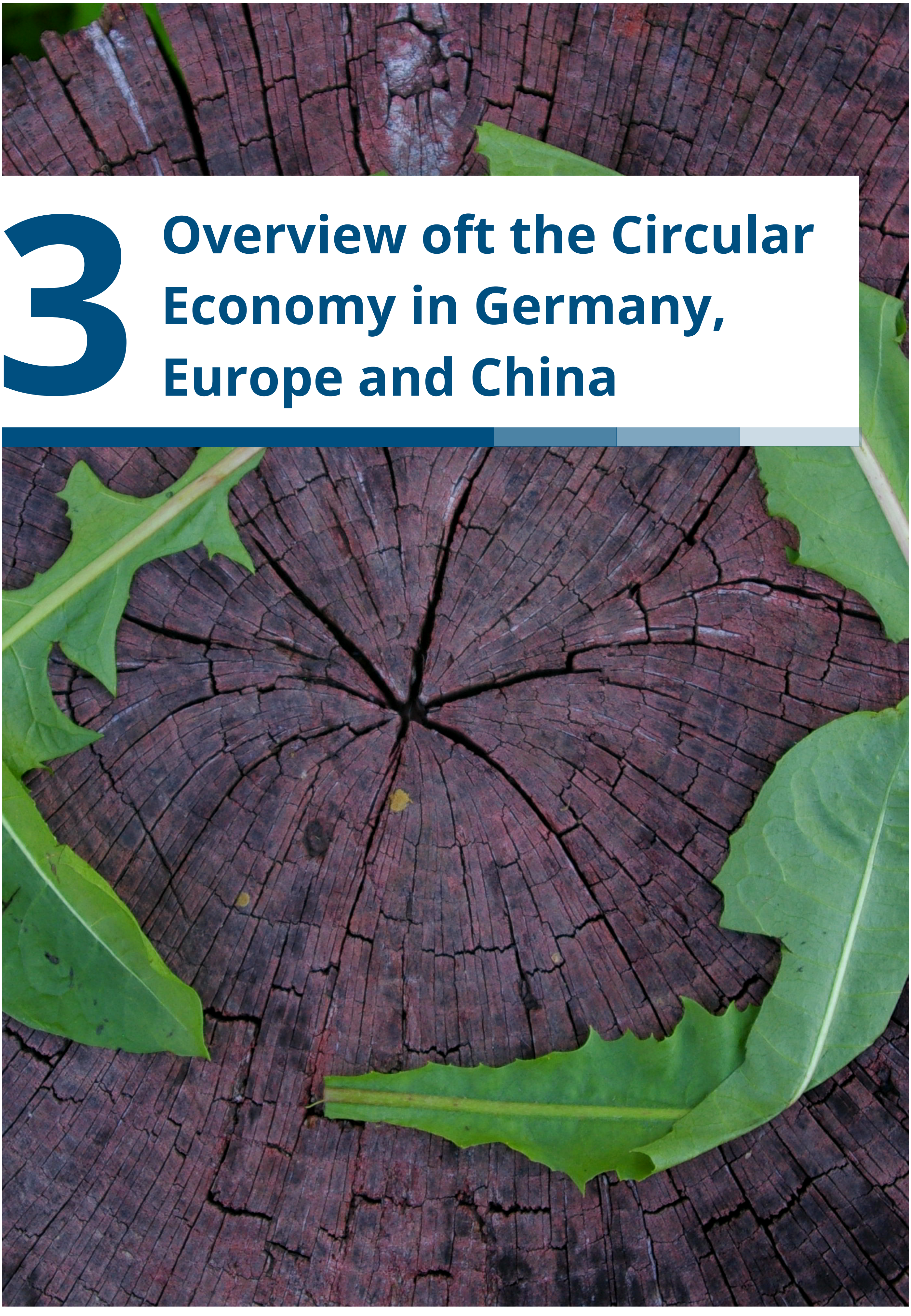


Many circular economy measures at national and EU level are therefore geared towards recycling. For Europe, the CO_2 reduction potential through recycling is estimated at more than 10 Mt CO_2 per year. A large part of the raw materials used could also be covered by reusing materials that have already been produced (Material Economics 2019).

However, not all materials can be recycled. In addition to high-value material recirculation and closed-loop recycling, the second key component of a circular economy is to use less materials per unit of final product. This can be achieved by using materials more efficiently within key products such as vehicles or buildings or packages. Circular economy measures can also include a range of other solutions such as designing products to be less materials intensive while providing the same performance. The extraction and processing of a raw material at the beginning of the value chain has a significant impact on the environment and climate. In Germany, 40% of greenhouse gas emissions are due to the extraction and initial processing of raw materials. As part of a holistic strategy, measures such as recycling should therefore go hand in hand with a drastic reduction in all raw materials used.



3 Overview oft the Circular Economy in Germany, Europe and China

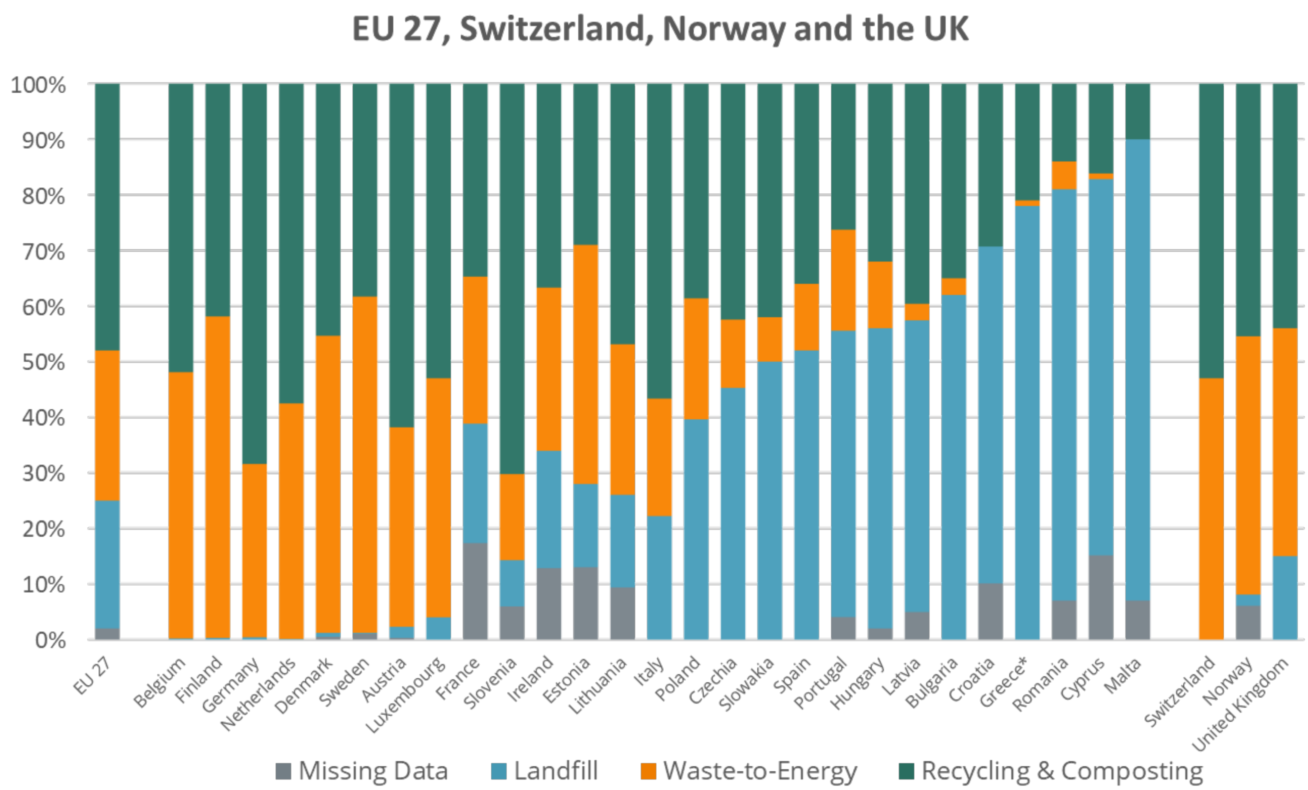


3 Overview of the Circular Economy in Germany, Europe and China

The concept of the circular economy has become increasingly prominent in recent years. As many countries and regions, including China, Europe and Germany have established policies to promote a circular economy and closed material loops. This section provides an overview of the current status quo of waste management and the use of secondary materials within the countries, as well as frameworks and regulations.

3.1 Europe

Figure 5: Municipal Waste Treatment EU27+. Source: CEWEP 2020



3.1.1 Status Quo of Waste Management and Secondary Materials

In the EU, 781 Mt waste excluding major mineral waste were generated in 2020, equivalent to 36% of the total waste generated. When expressed in relation to population size, the EU generated, on average, 1.7 tonnes per inhabitant in 2020, excluding major mineral waste. Germany (401 Mt) and France (310 Mt) contributed most to the total amount of waste produced in the EU. As of 2020, these two countries were responsible for one-third of the EU's waste at 19 and 14% respectively.

In general, the proportion of municipal waste recycled has increased substantially within the past two decades. However, just eight countries having a recycling rate higher than 50%, while countries such as Cyprus, Romania, and Malta have recycling rates lower than 20%. Germany was the top recycler of municipal waste in the European Union in 2020, with an estimated recycling rate of 67%. Analysis of municipal waste management remains undermined by uncertainties about the comparability of national data as countries apply varying definitions of 'municipal solid waste' (EEA 2013). A study by the European Environment Agency (EEA) (EEA 2013) showed substantial variation between different regions, indicating a significant influence of regional and local policies on recycling rates. Thus, while EU targets and national targets are the overall drivers of enhanced municipal waste management, regional and local implementation seems to be crucial for achieving positive results (EEA 2013).

Secondary raw material (SRM) markets are key to delivering a circular economy as they enable recyclables to re-enter the production value chain reducing dependency on primary resources. In 2021, recycled material accounted for 11.7% of material used, an increase of less than 1%age point since 2010. This rather slow progress together with projections for increased material demand in the EU by 2030 suggest that the EU is currently not on track to meet its target of a doubling in the circular material use rate (EEA 2022).

Despite a strong policy push to increase recycling and the steady supply of recyclates that has resulted from this, the supply side of SRM markets is challenged. The main problems are insufficient specifications such as the definition of waste and secondary materials, and the presence of hazardous substances in recycled materials. The demand side, on the other hand, is characterised by a lack of trust in SRMs. There is hesitance to invest in technologies that would integrate SRMs into raw material supply operations (EEA 2022).

3.1.2 Targets, Frameworks and Regulations

In recent years, the European Commission has become a key driving force for Circular economy measures. With the adoption of the **Circular economy Action Plan (CEAP)** in 2015, it has presented an ambitious roadmap for the transformation of the European Union towards circular value creation. The goal of the EU's action plan is to keep materials and resources in use for as long as possible, while minimizing the amount of waste. The specific goals in the framework include

- halving the amount of residual waste by 2030,
- doubling the proportion of recycled materials in industry,
- creating 700,000 new jobs and
- Increasing gross value added by 80 billion euros per year.

In addition to environmental and climate policy, the focus of the CEAP lies primarily on strengthening competition and innovation ability of European industry (European Commission 2020). The CEAP needs to be translated into national law by the individual Member States. It has 35 key measures, including the following (European Commission 2020):

The development of a political framework for circular and sustainable products, e.g. a right to repair and the extension of the Ecodesign Directive to include aspects of product circularity.

- Specific measures for selected value chains such as packaging, vehicles or buildings with specific specifications, e.g. the proportion of recycled materials.
- Improvement of existing waste law instruments, for example the specification of quantitative waste prevention targets in addition to the existing recycling quotas or the adaptation of waste management plans.

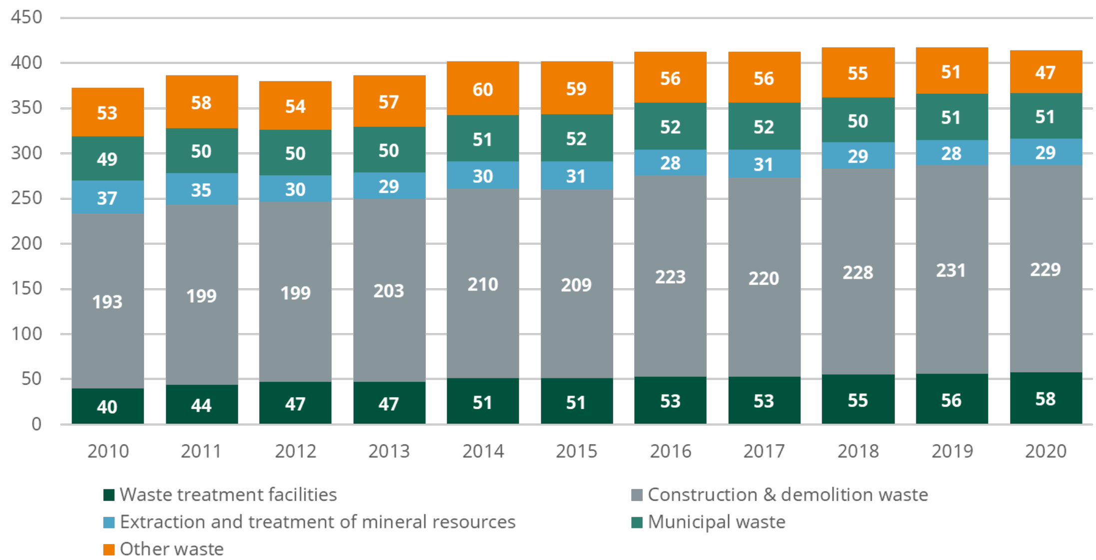
In addition to the CEAP, the **EU Waste Framework Directive** and the **Eco-Design Directive** primarily cover the more than 30 binding targets of EU waste legislation for the period 2015-2030. Some member states already have resource efficiency strategies as well as circular economy frameworks.

Within the EU, a main indicator for measuring the share of material recovered and fed back into the economy in overall material use is the circular material use rate (CMU). The CMU rate is defined as the ratio of the circular use of materials to the overall material use. However, only Austria, France and the Netherlands have concrete measures and targets for waste avoidance and absolute reduction of raw material consumption. The goal of the Netherlands is a fully circular economy by 2050. By 2030, the consumption of primary raw materials is to be halved. In Austria, the recycling strategy provides for a reduction in resource consumption to a maximum of 14 t per capita per year by 2030, an increase in resource productivity by 50% and an increase in the circular material use rate to 18%. In France, the Waste and Circular economy Act includes, among other things, measures to reduce resource consumption by 30% in relation to GDP.

According to the CMU, approximately 12% of the total raw materials utilized in Germany consist of secondary raw materials. While several European countries have experienced a significant surge in the adoption of secondary raw materials, Germany has witnessed a mere 1%-point increase since 2010 (from 11% in 2010) (ifeu 2021).

3.2 Germany

Figure 6: Annual waste generation in Germany in Million t. Source: Eurostat, 2020



Year	Waste treatment facilities	Construction & demolition waste	Extraction and treatment of mineral resources	Municipal waste	Other waste
2010	40	193	37	49	53
2011	44	199	35	50	58
2012	47	199	30	50	54
2013	47	203	29	50	57
2014	51	210	30	51	60
2015	51	209	31	52	59
2016	53	223	28	52	56
2017	53	220	31	52	56
2018	55	228	29	50	55
2019	56	231	28	51	51
2020	58	229	29	51	47

3.2.1 Status Quo of Waste Management and Secondary Materials

Germany is considered to be on the forefront in waste management within Europe, largely due to its high recycling rate, well-developed waste-to-energy infrastructure, widespread use of advanced biological treatment for organic waste, and relatively high level of at source-separation. Throughout the years, Germany has demonstrated consistent growth in waste recovery and recycling rates. Additionally, the waste management sector has significantly reduced greenhouse gas emissions trough deviating waste from landfills. Currently, Germany is placing greater emphasis on waste reduction and enhancing recycling efforts, particularly with regard to single-use plastics.

Between 325 and 350 Mt (net) of waste are produced in Germany each year, including construction and demolition waste accounting for 60% of this waste, while municipal waste accounts for 14%, and hazardous waste for 5%. Even though Germany has developed a high functioning waste management system, the total amount of waste has remained at the same level for 20 years (see Figure 6). This can be connected to a focus of waste policies and regulations on waste management rather than waste prevention and reduction.

3.2.2 Targets, Frameworks and Regulations

Germany is currently developing an overarching national circular economy strategy. Until now, various programs and strategies exist for individual aspects of the circular economy on a national as well as on state level, covering a wide range of aspects of circularity and resource efficiency. On a national level, the programmes consist of the following:

- The **German Resource Efficiency Program III** (ProgRess III) contains measures to increase resource efficiency along the value chain, i.e. from raw material extraction, product design, production and consumption to the circular economy.
- The **Waste Prevention Program** describes different waste prevention measures that affect the different life cycle stages of products, including approaches that take production, product design, trade, commerce and use of products into account.
- The **Raw Material Strategy** contains 17 specific measures in the three pillars of raw material supply: local raw materials, imports and recycling
- The **National Program for Sustainable Consumption** contributes to the national implementation of the Sustainable Development Goals (SDGs), in particular measures to achieve Goal 12 "Ensure sustainable consumption and production patterns" are included.
- The **Circular Economy Act** is the regulatory basis for the implementation of the circular economy and implements the requirements of European waste legislation at national level. The law mainly regulates the processing of products after they have become waste, and ensures safe waste disposal.

3.3 China

Figure 7: Disposed MSW in China's cities. Source: Adapted from Lee et al. 2020 with data from Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2019

3.3.1 Status Quo of Waste Management and Secondary Materials

In general, China places a growing emphasis on reducing pollution in the form of soil, air, and water contamination, as well as lowering greenhouse gas (GHG) emissions. To achieve both objectives, waste management is considered an important factor. In addition to implementing waste segregation at the source and introducing various treatments for different waste streams, China has begun to focus on waste reduction and upstream interventions that prevent waste generation in the first place (NAMA 2019).

The primary disposal methods employed for domestic waste management include sanitary landfill, incineration, composting, and co-disposal in cement kilns. Notably, incineration has increased rapidly. From 2003 to 2017, the proportion of waste subjected to incineration has surged from 4.9% to 40.2%. Although more recent data was not available during this research, it can be assumed that the proportion of incinerated waste has increased steadily since 2017. This can be attributed to several factors, including reduced land requirements, controllable pollution levels, high operational efficiency, and the capacity for continuous waste processing. Consequently, incineration technology is progressively replacing sanitary landfill as the predominant technical approach for domestic waste treatment in China (Dr. Xianshan Ma 2023).

Although the amount of waste incinerated is growing, landfill sites remain the predominant waste disposal method in the country. In 2017, of the 210 Mt MSW that were disposed in China's cities, almost 60% were landfilled (Lee et al. 2020). This is associated with diverse problems such as loss of land and economic costs for landfills, emission of landfill gases as well as soil and water contamination (Lee et al. 2020). As part of the new waste management strategy, China is increasingly shifting its waste disposal focus from landfilling to waste incineration. Despite the numerous advantages of waste incineration compared to landfilling, its utilization is nevertheless associated with various challenges and problems including high moisture content of MSW, low efficiency utilisation of waste, and air pollution through particulate matter.

In the 1990s, economic development and the rise in living standards increased China's demand for plastic products. During that time, China lacked raw materials, and the production quality was incapable of meeting the growing needs. To address a shortage of domestic resources caused by a rapidly expanding economy, China turned to importing waste. However, over time, the quality of recyclable materials exported to China gradually declined. Countries were found to be exporting unrecoverable waste in the name of raw material utilisation (Pieter van Beukering, Li Yongjiang, Zhou Xin 1997).

Subsequently, as the volume of imported and domestic waste grew beyond China's recycling and disposal capacity and the quality of imported waste declined, China began to implement stricter waste import policies in line with the quality of imported waste. Starting in early 2018, the government of China banned the import of several types of waste, including plastics. The ban has greatly affected recycling industries worldwide, as China had been the world's largest importer of waste plastics and processed hard-to-recycle plastics.

Secondary Materials

As of the end of 2021, the total volume of recycled resources across ten categories (including scrap steel, non-ferrous metals, waste plastics, paper, tires, discarded electrical and electronic products, scrapped motor vehicles, waste textiles, glass, and batteries) accounted for approximately 381 Mt, reflecting a year-on-year increase of 2.4%. Among these, the growth rates for waste plastics, paper, scrapped motor vehicles, waste textiles, and batteries (excluding lead-acid batteries) all exceeded 10% (Dr. Xianshan Ma 2023). Despite China's efforts over the past two decades to increase recycling rates, reports suggest that the rate only ranges from 5% to 20%, with no dependable statistical data available (Hu et al. 2018b).

Although specific recycling quotas are not currently in place, the government has established overarching targets to guide recycling efforts. For instance, the Guiding Opinions of the National Development and Reform Commission and other relevant departments, titled "Accelerating the Construction of Waste Materials Recycling System", outlines strategic measures to be implemented. These measures aim to establish a robust infrastructure for waste material recycling, including the development of more than 1,000 green sorting centres by 2025. The ultimate objective is to achieve a total recycling volume of nine major recycled resources, namely scrap steel, copper, aluminium, lead, zinc, paper, plastic, rubber, and glass, amounting to 450 Mt. This comprehensive approach demonstrates the government's commitment to building a sustainable waste management system and enhancing resource recovery in China (Dr. Xianshan Ma 2023).

3.3.2 Targets, Frameworks and Regulations

Since the 1980s, China has successively issued a series of laws and regulations, industrial, economic and environmental policies on circular economy. These were initially targeted at reducing industrial pollution. Although policies related to circular economy existed as early as 1995, the national government formally adopted the concept of circular economy in 2002 as a new development strategy which aimed to alleviate the contradiction between rapid economic growth and the impacts on the environment as well as shortage of raw materials. In 2004, the NDRC was appointed to implement circular economy as an integrated strategy rather than an environmental policy (Hu et al. 2018b). Since 2000, various regulations have been in place including regulations to reduce packaging waste by banning disposable plastic tableware, production, retail, and use of plastic shopping bags with a thickness of less than 0.025 mm, and a system of payment for the provision of plastic bags in retail establishments.

Later, regulations such as the **Circular economy Promotion Law (CEPL)** in 2008, the **Circular economy Development Strategy and Near-term Action Plan** in 2013 and the **National Circular economy 14th Five-Year Plan** in 2021 were developed and directly pointed at circular economy. The latter recommends sets of actions such as redesign of key products or increasing waste collection and recycling (EllenMcArthurFoundation 2022).

The **14th Five-Year Plan** lists concrete targets including the following (Bleischwitz et al. 2022):

- Increasing resource productivity by 20% compared to 2020 levels.
- Reducing energy consumption and water consumption per unit of GDP by 13.5% and 16%, respectively, compared to 2020 levels.
- Reaching a utilization rate of 86% for crop stalks, 60% for bulk solid waste, and 60% for construction waste.
- Utilizing 60 Mt waste paper and 320 Mt scrap steel.
- Producing 20 Mt recycled non-ferrous metals.
- Increasing the output value of the resource recycling industry to 5 trillion RMB (773 billion $).
- Deepening the development of the agricultural circular economy and establishing circular agricultural production
- Building a resource recycling industry system and improving resource utilization efficiency. Building a recycling system for waste materials and fostering a recycling-orientated society

The understanding of the CE concept in China is broader compared to the EU: while the EU focusses more on the waste hierarchy and product policies, China has been grappling with a range of issues including water pollution and air pollutants (McDowall et al. 2017). In the Circular economy Promotion Law issued by China in 2008, circular economy refers to the reduction, reuse, and recycling (3R) activities in the production, circulation, and consumption of products.

4 Closing material flows in energy intensice raw materials

4 Closing material flows in energy intensive raw materials

Sectors such as steel, aluminium, glass and paper are not only CO_2 intensive, but also highly energy and resource intensive. This section provides an overview of recycling processes of energy intensive raw materials with a focus on metals, paper and glass and describes the current production practices of those energy intensive materials in Germany and China.

Policymakers are often focused on reducing the carbon footprint of virgin materials such as low-carbon primary steel and cement. However, a crucial aspect is often overlooked: the potential to reduce emissions by adopting more circular and resource-efficient value chains in order to produce less virgin material such as steel, aluminium, cement, and plastics (Agora Industry 2022).

4.1 Metal Recycling

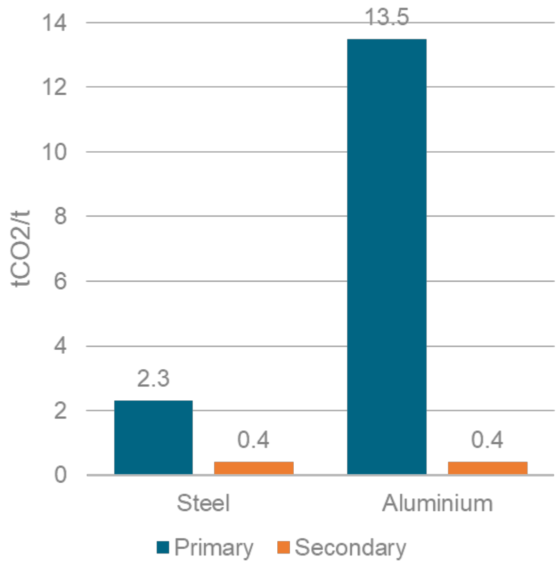
Metals are the largest group of materials in use due to their mechanical strength and elasticity, as well as their electrical and thermal conductivity. While most metals can theoretically be recycled completely and repeatedly due to their physical properties, the large number of alloys and small components make single-variety recycling difficult in practice in many cases.

When metals are recycled, they are molten. Cleaning of molten metals is necessary when there are high impurity contents in the scrap or when alloy components need to be separated. Physical refining processes such as evaporation, distillation, and volatilization processes are used for metals with controllable boiling temperatures, such as cadmium and zinc. Chemical refining processes include selective oxidation.

The cost-effectiveness of the recycling process is determined primarily by the expense of the process, the quality of the final product, and the amount of metal loss during recycling. The cost is also highly dependent on fluctuating metal prices and scrap prices. To ensure effective recycling, a classification of metallic materials into groups based on related properties is crucial. These groups include iron and iron alloys (Fe metals), non-ferrous metals (NF metals), light metals (aluminium, magnesium, titanium), non-ferrous metals (copper, lead, zinc, tin, nickel), and precious and special metals (gold, platinum).

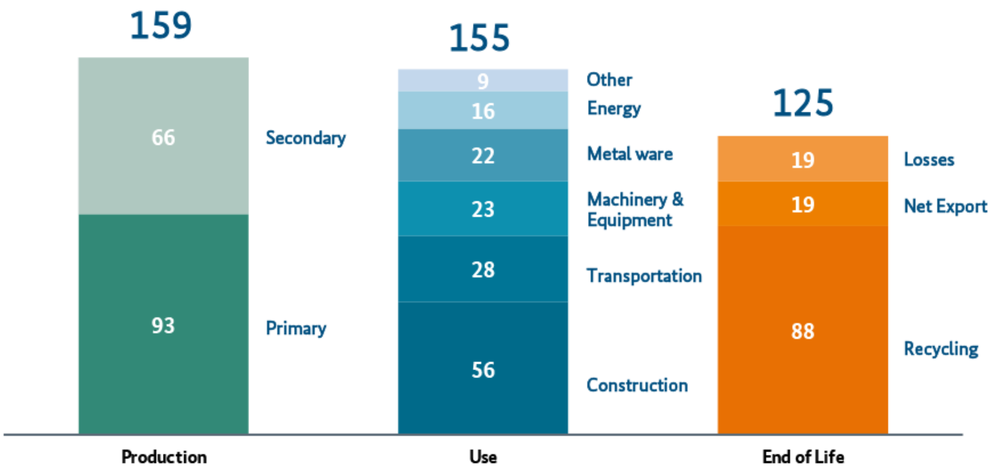
In the following, the focus is on the recycling of steel and aluminium due to the high energy demand during primary production and the significant potential for savings by switching to recycling as well as the production volume. The production of primary steel via the blast furnace route requires an energy demand of 3.5 to 4.2 MWh/t_{CS} and results in approximately 1.8–2.4 tCO_2/t_{CS} in China. In contrast, recycling of scrap steel has an energy demand of 0.83 to 1.67 MWh/t CO_2 crude steel, leading to significant energy savings compared to primary production. Recycling one tonne of steel can approximately save 1.4 tonnes of iron ore, 0.8 tonnes of coal, 0.3 tonnes of limestone and additives, and 1.67 tonnes of CO_2 (EuRIC 2020). As steel recycling is carried out in Electric Arc Furnaces (EAF), which mostly rely on electricity as an energy source, CO_2 emission reductions depend largely on the used electricity mix (Worrell and Carreon 2017).

Figure 8: CO_2 Intensity Factors of Primary vs. Secondary Production Routes (Global Averages). Source: Agora Industry 2022



For the production of aluminium, bauxite is first converted to Al_2O_3 with the supply of thermal energy (6 - 14 MWh/2 t Al_2O_3). To produce 1 tonne of aluminium, about 2 tonnes of Al_2O_3 are required. In the Hall-Héroult

Figure 9: Annual Steel production, use and recycling statistics. Source: EU 2019



process for aluminium production, 13–15 MWh/t_{Al} are needed for electrical energy. As a result, primary aluminium production is one of the most energy-intensive processes.

In contrast, during recycling, only 5–10% of the energy used in the Hall-Héroult process (0.65–1.5 MWh/t_{Al}) is required, and the extraction of bauxite is saved (Lernhelfer 2023; Brunn 2021).

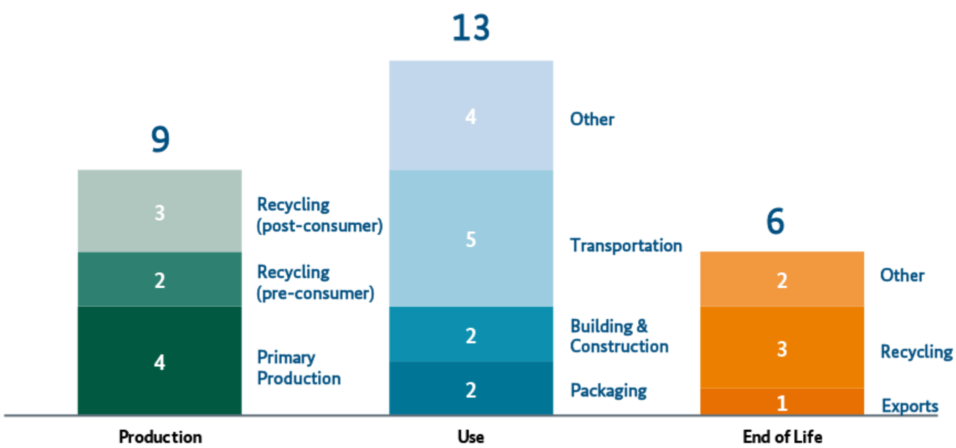
4.1.1 Current production practices of metal recycling in Germany and Europe

Germany has achieved high recycling rates for metal scrap. For instance, in the construction sector, around 88% of steel parts are recycled, with an additional 11% being reused. Additionally, recycling rates of over 90% have been achieved for tinplate packaging, which is made of electrolytically tinned sheet steel. Similarly, recycling rates for stainless steel products range from 60% to 92% (Fraunhofer 2019).

As significantly more metals are used and consumed than metal scrap is available, Germany is still reliant on primary raw material imports for metal production. The potential for increasing production with secondary materials is therefore limited. As long as the stock of buildings and goods in which metals are bound in the long term or which are not sent for waste recycling continues to increase, it is not possible to cover metal demand largely or completely with secondary materials (NABU 2023).

Nevertheless, there is considerable potential for higher recycling rates in individual metals. The Federal Environment Agency in Germany estimates that 67% of the iron and steel produced and 90% of the copper, lead, aluminium and zinc produced could consist of recyclates (NABU 2023). Several challenges remain to increase recycling rates. Firstly, the collection and processing mechanisms for secondary metals need to be improved. Efficient source separation methods need to be implemented to facilitate high quality recycling. Another challenge is the management of impurities during

Figure 10: Annual Aluminium production, use and recycling statistics. Source: EU 2019

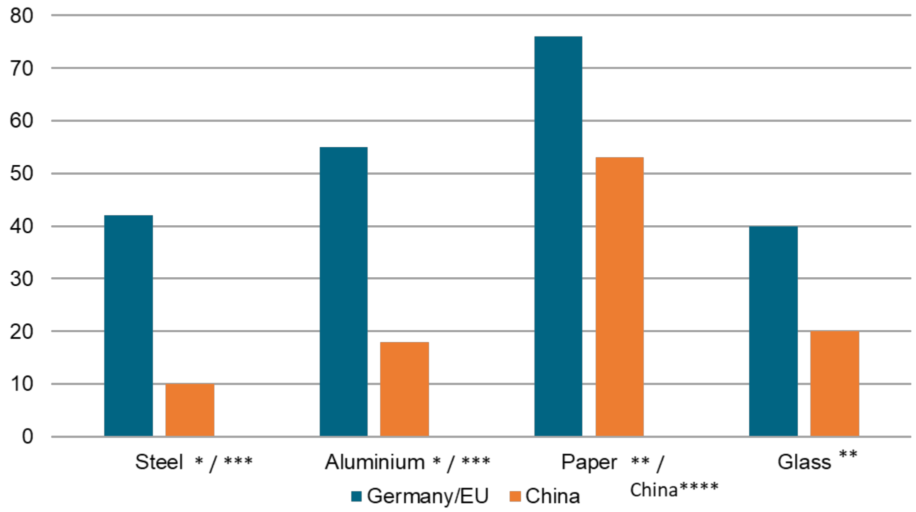


metallurgical processes. Robust strategies have to be developed to effectively sort out pollutants and manage the by-products generated during recycling processes. Additionally, the quality requirements set by end consumers is important to instil confidence in the use of secondary raw materials (Hiebel 2016).

challenges, efforts to improve steel quality are necessary, as the problem of copper contamination is a global issue (Agora Industry 2022).

Over the last two decades, the European Union has shifted from being a self-sufficient producer of aluminium to a significant net importer, with more than 40% of its

Figure 11: Comparison of recycling rates (in %) between Germany, the EU and China. Source: dena



*Values for Europe
**Values for Germany
***Rate of material produced via secondary production
****Recycling rate for recovered paper

The production practices of metal recycling in Germany and Europe are closely linked by shared markets and regulations. In the year 2019, the EU achieved a steel production of 159Mt. Out of this total, 58% constituted primary steel, while 42% was derived from secondary steel production through the EAF route as seen in Figure . Notably, the recycling rate for steel reached an impressive 88% (Agora Industry 2022). Recognizing the significance of mitigating climate change, steel manufacturers are actively pursuing an increased proportion of secondary steel production.

The growing stock of steel scrap in the EU offers the potential to replace primary steel production with secondary steel production (Agora Industry 2022). Agora Industry (2022) suggest that by 2050, 80 to 90% of the EU's steel demand could theoretically be met by recycling scrap flows.

However, a range of challenges exist within the recycling of steel. Contamination with copper and other elements leads to downgrading, thus limiting the range of applications for recycled steel (see Box – Further options for increasing recycling measures). The lack of mini-mills in Europe and the lack of capacity to process recycled steel into both flat and long products constitutes another challenge, which could lead to bottlenecks. In addition, some steel products have different tolerances for copper content, which requires careful consideration in the design phase of a product, as well as in collection and shredding practices (Agora Industry 2022). Despite these

total consumption being imported in 2019. The end-of-life volume of aluminium scrap is constrained due to the long product lifetimes, leading to a limited amount of aluminium being available for recycling.

In 2019, of the 5 Mt of aluminium that reached its end-of-life within the EU, 3 Mt were recycled, while 2 Mt either ended up in landfills, were lost during inefficient recycling processes, or illegally exported. Most of the recycled aluminium is downcycled into cast aluminium products, owing to the high tolerance of these products for impurities (see Figure 10).

Selective deconstruction and de-pollution are deemed necessary by Agora Industry (2022) to increase the recycling potential of aluminium in construction and demolition waste. Raw aluminium is commonly not sold as a pure product, but rather in various metallurgical alloys that serve different applications. The efficient recovery and recycling of end-of-life aluminium is reliant on identifying and sorting these sub-alloys into their respective qualities. Achieving maximum potential for closed-loop aluminium recycling necessitates state-of-the-art technologies for shredding, identifying, and sorting aluminium grades.

4.1.2 Current production practices of metal recycling in China

With the rapid development of industrialization and urbanization, China has been the world's largest steel producer, with 996 Mt and 53% of the global production share in 2019 (Lin et al. 2021). 10% of China's crude steel production is secondary steel produced by EAF, significantly lower than the global average of 29%. This is primarily attributable to the inconsistent quality of domestic scrap steel and the technical complexities involved in the short process electric furnace steelmaking. Present sorting technologies lack standardization, resulting in an inability to effectively regulate the composition of scrap steel.

In 2020, China's aggregate scrap steel resources were approximately 210 Mt, which were predominantly consumed by the steel industry in the form of raw materials for electric furnaces, enhancements for blast furnace production, and maintaining the heat balance of converters. However, due to technical limitations, impurities such as Copper, Zinc, Lead, Phosphorus, Nitrogen, and Hydrogen within steel products cannot be controlled effectively during short process electric furnace steelmaking.

China Iron and Steel Association (CISA) has issued a national standard for the classification of scrap steel stipulating that the carbon content in scrap steel should typically be less than 2.0%, with the content of sulphur and phosphorus generally not exceeding 0.050%. The standard also contains requirements for non-alloy scrap steel. (Dr. Xianshan Ma 2023). This, along with the inconsistent quality of domestic scrap steel, restricts the application of the EAF short process predominantly to low-end products like profiles, wire rods, and a small quantity of stainless steel.

Further, the relatively brief period of industrialization in China has resulted in low accumulation of scrap steel, limiting production of EAF steel. Excess steel production capacity during the initial stages led to iron prices falling below scrap steel prices, making scrap steel less competitive from a pricing perspective. The sorting and categorization processes for scrap steel lack refinement, and the costs and technical prerequisites associated with processing and distribution remain high. Despite the implementation of scrap steel recycling policies and access standards in recent years, the number of enterprises that meet these standards continues to be limited (Dr. Xianshan Ma 2023).

Further options for increasing recycling measures

A central problem with steel recycling is contamination with copper, which cannot be removed through oxidation. Copper leads to a decrease in steel quality and causes brittleness. Additionally, the possibility of recycling is highly dependent on different sectors. For example, automotive scrap has high contamination levels while requiring high purity in its usage.

Various approaches can address this problem. Firstly, product design can be altered to replace copper with other materials. Furthermore, the option of increasing the tolerance for contamination in steel applications until higher steel qualities are available. In construction, a secondary-first approach can be followed. This involves individual testing of the steel quality requirements for each component. According to (Agora Industrie 2023), an increase in the recyclate content up to 50% is possible.

On the technological side, various innovative technologies for removing copper from liquid steel are in an early development stage (< TRL 4). Among them, leaching at ambient temperature and hydrogen embrittlement are considered promising in terms of energy demand and effectiveness.

Another approach offers flexibility in scrap use and blending. In the Direct Reduced Iron (DRI) process, 0 to 100% scrap can be added flexibly. Mixing can allow for higher toleration of impurities.

Regarding material efficiency, reducing manufacturing waste, lightweight construction in automobiles, optimizing building design, and substituting steel with other materials (e.g., wood) can lead to a reduction in primary steel production.

(Agora Industrie and System IQ 2023)

China's primary aluminium production was around 40 Mt of Al in 2022. As the electricity for the production is mostly coming from coal power plants, the emissions were around 670 Mt in 2020. According to the International Aluminium Institute the recycling rate was 17% in 2019 (Liu and Patton 2023; Guoping and Ge 2021).

4.2 Paper and Cardboard

Paper is a material made from plant fibres. The cohesion of the fibres is created by felting and self-adhesion. The plant fibres used are wood pulp, cellulose and waste paper fibres. The pulp, which is obtained by the wet chemical treatment of wood chips at 160°C, is known to have good strength properties and a high degree of whiteness due to the separation of pulp fibres from lignin (Nurdiawati and Urban 2021).

The sorting out of impurities in waste paper involves distinguishing between different paper qualities such as cardboard and paper. Waste paper typically contains various additives and problematic components, such as printing inks. The paper is broken down into individual fibers through wet sorting processes, which allows for the separation of additives and foreign matter. The use of chemicals like NaOH and fatty acids during the dissolution process can detach printing ink from the fibers. However, this process generates large quantities of wastewater, which require treatment and sludge management during paper production.

There are technical limits to how many times fibres can be recycled before their quality is significantly reduced. With each recycling cycle, the length and strength of the fibers decrease, allowing for only five to eight recycling passes before the fibres become too weak for further use. This means that the use of secondary fibres is limited for certain paper grades.

4.2.1 Current production practices of paper and cardboard recycling in Germany and Europe

In Germany, 22 Mt paper and cardboard are produced every year with around 3,000 different types of papers. On average, 40.000 tonnes of waste paper are being produced and processed into new paper every day. For one tonne of paper, an average of 790 kg waste paper is used (Umweltbundesamt 2022a).

Papers made from primary fibres (wood and pulp) and those made from secondary fibres (recovered paper) are two sides of the same coin. Germany's waste paper use rate of 79% is a top value internationally. However, the recovered paper cycle can only be maintained by a constant supply of fresh fibres. This is done either directly via the input of pulp or via primary fibre papers, which strengthen the recycling cycle with their young fibres after use (Umweltbundesamt 2022a).

The energy demand for paper production in Germany is around 2,75 MWh/t_{paper}. The paper industry is making efforts to reduce energy consumption. At the same time, many companies are investing in additional process steps to produce papers with higher brightness levels and smoother surfaces from recycled paper. This requires more energy, as a result, the total energy demand has increased by over 50% from 44 TWh in 1990 to 59 TWh in 2020 (Umweltbundesamt 2022a).

The main advantages of recycling paper and cardboard are conserving forests, reducing energy for production processes and reducing water usage for paper production as recycled paper only requires one-seventh to one-third of the water used in virgin fibre paper.

In 2018, the recovered paper input ratio, i.e. the share of recovered paper in total paper production in Germany, was 76% (Umweltbundesamt 2022a). The recovered paper input ratio for packaging paper and cardboard is 100%. However, it is still comparatively low for graphic paper and sanitary paper, at 51% and 50% respectively. Against the background of these figures, the German Environment Agency sees further technical potential for the use of more recovered paper in the production of paper for magazines, office and administrative use and in the production of hygienic paper production. The potential for improvement is estimated to be just under 80% (Purr et al. 2019).

4.2.2 Current production practices of paper and cardboard in China

According to the China Paper Association, the recycling rate for recovered paper in China was 53.1% in 2022 (Birkners Paper World 2023). In the past, Chinese paper production highly relied on imported recovered paper. However, the imports of recovered paper increasingly contained unsorted and partially contaminated lower quality papers which were leading to environmental pollution in the regions where they were processed (Shi and Zhang 2023). However, since 2017 several policy changes in importation rules, ranging from import bans on unsorted paper waste to repeatedly adjusting import tariffs on intermediate products have been reshuffling global and Chinese pulp and paper industries. Consequently, China has developed from the largest importer of recovered paper to an importer of higher quality pulp products, with imports of recycled paper in 2022 down to 57 kt in from 30 Mt in 2013 (Birkners Paper World 2023). Still, the 14th Five-year Plan on the Development of Circular economy (2021–2025) is planning to increase the processing of domestically recovered paper from 54.9 Mt in 2020 to 60 Mt in 2025 (Umweltbundesamt 2023).

4.3 Glass

Glass is one of the most versatile materials and plays an important role in everyday life, in research and science, in modern architecture as well as in future industries. Glass is primarily composed of amorphous silica, but its exact composition can vary widely depending on the specific type of glass and its intended application (Bundesverband Glas 2022).

In addition to these raw materials, waste glass can also be utilized as a source of raw material in the production of new glass. To process waste glass, it is necessary to first remove any incorrect types of glass, pieces of glass with an undesired colour, and foreign materials. This can be achieved through a combination of manual sorting and mechanical processing techniques such as the use of magnetic or eddy current cutters for separating metals, air classifiers for removing plastic lids and labels, and optical processes for identifying and removing ceramics, stones, and porcelain. Finally, the waste glass is melted at temperatures of up to 1600°C to produce new glass products (Bundesverband Glas 2022).

Glass cullet (i.e. shards) can be subdivided into three main categories: own cullet, foreign cullet, and waste glass cullet.

- **Own cullet** refers to the production waste generated by a glass plant, which typically accounts for about 10–20% of the total production.
- **Foreign cullet** is clean production waste from the glass processing industry, which can also be used as a raw material for glass production.
- **Waste glass cullet** is a category of miscellaneous and unknown glass cullet that may contain interfering admixtures and impurities, and may require additional sorting and treatment processes before it can be used as a raw material.

The process of melting glass involves the combination of cullet with primary raw materials at a high temperature of 1600°C. Incorporating waste glass in the melting process results in energy and raw material savings, as waste glass can melt at lower temperatures than the raw materials required for glass production. In glass production, the energy consumption can be reduced by approximately 3% by replacing 10% of natural raw materials with recycled glass. With a usage of 65% recycled material, a subsequent energy saving of 20% can be achieved. A lower energy consumption also leads to a reduction in CO_2 emissions depending on the energy source. For example, by adding 10% cullet (recycled glass) to the raw material mix, CO_2 emissions in glass production can decrease by 5% (Umweltbundesamt 2022b).

Further circular economy measures

Design for Recycling - Some glass packaging are still heavier than necessary due to their shape or chosen manufacturing processes. There are also instances where glass packaging is too thin for effective recycling. The proportion of very fine glass has increased significantly in recent years, but beyond a certain wall thickness, recyclability is compromised. Some glass packaging undergoes refinement processes such as printing, coating, and gluing. When selecting colours for glass packaging, it is advisable to stick to the three common colours: white, brown, and green, wherever possible. One option would be positive and negative lists for adhesives that allow easy removal of labels to ensure a smooth recycling process. Also mandatory and comprehensive eco-design criteria are advisable to ensure a significant supply of high-quality recycled material.

Remanufacture - Brand manufacturers could be advised to use post-consumer recycled material (PCR).

Reuse - Initiatives for expanding and promoting reusable models could be pursued in collaboration with selected brand manufacturers. Filling processes are limited by certain bottle shapes in vision of an increasing number of custom-designed glass packaging. Regional fillers should be preferred whenever possible. Pooling solutions are a possible option.

Rethink - Glass packaging that is 100% recyclable and designed with resource efficiency should be easily identifiable to consumers. Therefore, a uniform industry-wide assessment of recycling compatibility, transparent to consumers, could be developed. This is achievable through independent packaging evaluations, and a commitment to display the packaging's classification on the bottle. Pool and reusable systems, as well as deposit solutions, should be expanded save resources and emissions, which requires communication with consumers.

Recycle - The glass collection infrastructure should be expanded. The number of glass collection containers in the collection infrastructure (at least for coloured and clear glass) has to be increased as well as collection systems. (WWF Deutschland 2022)

However, the utilization of waste glass is dependent on the production-specific requirements for the purity of the cullet, as the presence of impurities can affect the quality of the glass product. While container glass, which consists of beverage bottles, has a high return rate and constitutes 71% of glass waste, other glass types exist that differ in volumes, compositions and impurities. Flat glass, used for windows, building glazing, and automotive safety glass, has large differences in return rate and impurities. Special glass, with varied compositions, is difficult to recycle at a high level. Flat glass waste is mainly generated by the commercial sector, and only small quantities of flat glass granulate can be used for new flat glass due to high quality requirements. The largest proportion of flat glass waste is used as cullet for the production of container glass. Other uses of recycled glass include cast glass, glass blocks, insulation wool, and glass fibre production. The profitability of glass recycling depends on the mass proportions of different glass types and areas of application.

Recycling material requirements in flat glass production are significantly higher compared to container glass production. Most glassworks accept a contamination of recycling material from ceramics, stones, and porcelain (known as the KSP content) of a maximum of 5 g/t. As a result, flat glass production does not use recycled glass, for example, from building demolitions. Instead, they primarily rely on transparent cullet and production scrap (also known as in-house scrap) generated during the flat glass production process (Umweltbundesamt 2022b; Bundesverband Glas 2022; BauNetz_Wissen).

4.3.1 Current production practices of secondary glass procution in Germany and Europe

Currently, the share of cullet (recycled glass) in green container glass is 90%, while in white container glass it is 60% (Bundesverband Glas 2022). The potential use of cullet is limited by the requirements of the final product. This is because the exact composition of cullet is unknown, which means that specific requirements for a glass product may not be achieved with the desired target composition. The maximum allowable content of cullet is 95% for green container glass and 70% for white container glass (Bundesverband Glas 2022).

In Germany, waste glass is already recycled to a high percentage. In 2017, 84.4% of the glass from packaging (container glass) was recycled (Umweltbundesamt 2022b). Within glass production, the share of waste glass is currently around 40% across all products. The Federal Environment Agency assumes that the average proportion of broken glass can be increased to 45% in 2030 and 69% in 2050 (Purr et al. 2019).

As the degree of purity of the collected waste glass is decisive for the quality of the recyclate, the collection and transport containers must be clean and the waste glass must not contain any disturbing materials apart from product-related foreign matter (e.g. heating wires and foils in car windscreens). Applications for processed flat glass cullet range from reuse in flat glass production to the manufacture of cast glass, container glass, insulation wool, sandpaper and the production of glass blocks.

Flat glass is mainly produced in the float process and is largely processed into construction and automotive glass. Due to the high quality requirements, e.g. for safety glass or car windows, reuse in the float tanks is currently still facing technical limits (WWF Deutschland 2022).

4.3.2 Current production practices of secondary glass production in China

There is relatively little data available on the recycling of container glass in China. It is estimated that the recycling rate for container glass is currently still below 20%. Various sources report that used glass (cullet) in China has relatively low financial value, and numerous glassworks prefer natural raw materials over recycled glass (Serena 2019; Hu et al. 2018a; Harder 2018b).

While countrywide recycling rates were estimated to be relatively low in the past (Harder 2018a), the current rollout of municipal waste separation schemes in large cities has the potential to increase the quality of waste glass collected. With higher purity waste glass available, recycling becomes economically more viable. The municipal level policies are accompanied by national legislation that mandates to display recycling information on consumer packaging including glass containers starting in 2023 (China State Administration for Market Regulation 11/07/022).

5 Material Efficiency Measure for Construction

5 Material Efficiency Measures for Construction

While operational carbon refers to the carbon released from the ongoing operation of the building, embodied carbon of buildings includes emissions generated throughout various lifecycle stages of buildings. This ranges from material production, transportation and construction activities to demolition. As the superstructure and concrete in particular play a significant role within embodied carbon in buildings, the following section will focus on potentials of reducing embodied carbon of cement and concrete through material efficiency measures.

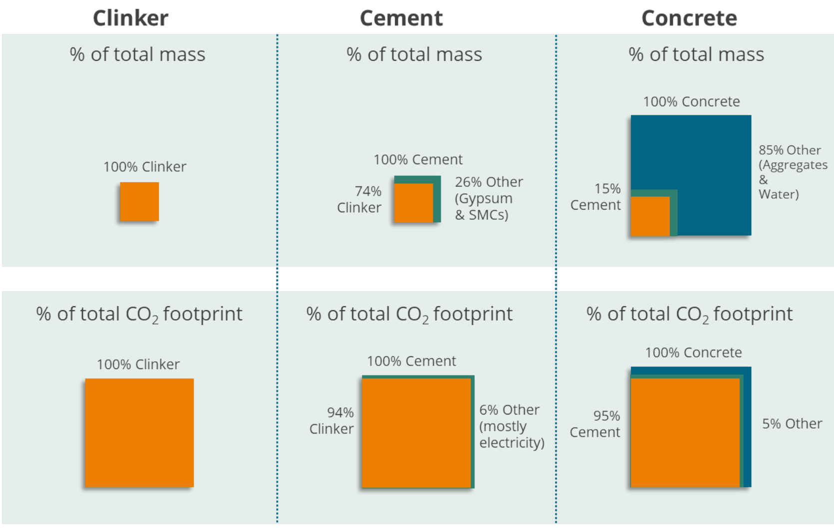
The production of one ton of concrete emits approximately 80 kg CO_2. The majority of emissions from concrete production (95%) arise from the cement production process, particularly the production of cement clinker, the main binder component (Watari et al. 2022). Cement serves as the binding material that, when combined with aggregates and water, forms concrete. On a global scale, cementitious materials account for more than half of all the materials employed in construction (Favier et al. 2018).

Within the production process, the breakdown of limestone (calcium carbonate ($CaCO_3$)) into CO_2 is responsible for over 60% of emissions, while less than 40% of emissions stem from the energy used in cement production. Achieving carbon neutrality poses a significant challenge for the cement sector due to its reliance on limestone, an abundant and widely distributed calcium source used to produce the clinker (Favier et al. 2018).

So far, efforts to decarbonize the concrete and cement industry have primarily centred on strategies such as enhancing energy efficiency, switching to different fuels to reduce process-related carbon emissions (UNEP 2022). However, as the major part of emissions is related to inherently chemical processes and cannot be reduced by energy efficiency measures, the recapture of CO_2 released during cement production has been discussed in political and scientific realms as an option for non avoidable emissions recently.

Carbon capture and storage technologies are currently in development, although certain technical challenges remain to be overcome. These technologies require substantial capital investments and operating costs, in addition to a significant supply of renewable energy for their effectiveness. However, studies as Favier and Wolf show that by considering all the stages in the value chain, reductions of up to 80% of CO_2 emissions are achievable without using carbon capture and storage technologies (Favier et al. 2018). This includes measures of material efficiencies which so far have been underrepresented within the approaches to reduce emissions.

Figure 12: Energy intensities of base materials in concrete production. Source: Agora Industry 2022



5.1 Material Efficiency

While energy efficiency considers sparing use of energy, and ratio of energy use and production, material efficiency is about sparing use of natural material resources, effective management of side-streams, reduction of waste, and reuse and recycling. Allwood et al. (2013) define material efficiency as reducing the amount of material produced, while still providing the same service as another method to decrease CO_2 emissions (Allwood et al. 2013). Material efficiency can be achieved by many different strategies such as maintaining existing products for longer, using them more intensely or designing products with less material. Allwood et al. (2013) define six strategies that are often described in literature:

- **More intensive use**: less product to provide the same service, e.g. through a more space-efficient design of buildings, or use of a product at a higher utilization rate, e.g. through sharing.
- **Lifetime extension** (including through repair, resale, remanufacturing)
- **Light-weight design**: less material and/or lower GHG emissions in the production of a product.
- **Reuse of components**
- **Recycling and upcycling**
- **Improved yield in production**, fabrication, waste processing

More recently, material efficiency has had a surge in interest that was triggered by the popularity of the Circular Economy and environmental concerns. Only recently policymakers have started to consider the potential synergies between Material Efficiency and greenhouse gas mitigation. In the political realm, the term resource efficiency is used in a manner that is synonymous with the use of material efficiency (IEA 2019; Hertwich et al. 2019c).

To date, many material efficiency measures are often poorly understood owing in part to the multitude of material uses and diversity of circumstances and in part to a lack of analytical effort. Material efficiency is not systematically included in most mitigation scenarios or climate policies. Studies of material-related policies often focus on waste management rather than GHG emissions. However, material efficiency has the potential to lead to substantial co-benefits, as resource extraction and waste generation can be reduced (Allwood et al. 2013). In a study by Material Economics from 2019, it was estimated that achieving the same economic benefits while using 121 Mt (65%) less cementitious material per year in 2050 would be feasible for the construction sector (see figure below). (Material Economics 2019).

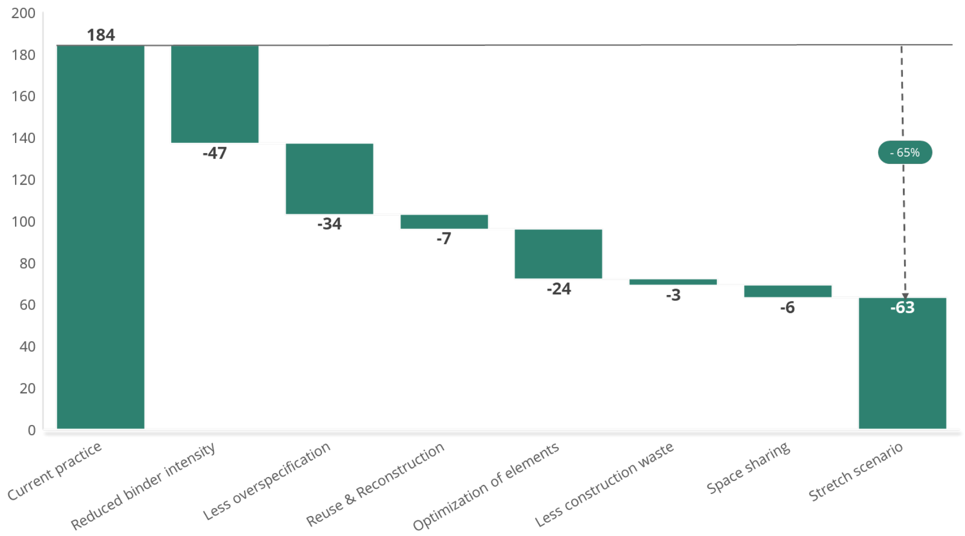
Although an often overlooked lever for reducing emissions, opportunities for material efficiency exist at every stage of the lifecycle, from design and manufacture to use and end-of-life. Pushing these strategies to their practical yet achievable limits could enable considerable reductions in the demand for several key materials (IEA 2019). Applied to the context of the construction sector, the next sections are focussing on structural optimisation and improved engineering design, prefabricated concrete elements, and reduction of clinker content in cement (Substitution), reduction of cement content in concrete, building lifetime extension, as well as recycling and reuse.

5.1.1 Structural optimisation and improved engineering design

Civil engineering structures are often precisely designed, with the shape determined by the load they need to bear. This careful planning helps optimize the amount of concrete used. However, when it comes to buildings, the design phase is often very time restricted, leading to excessive use of materials due to repetitive structures. For example, both concrete slabs and decorative walls are commonly 20 cm thick, and the spacing between columns is usually around 6 meters. These dimensions do not necessarily reflect the building's size or height, but focus more on practical factors like construction site limitations, transportation logistics, and even sound control (Favier et al. 2018). A closer look at concrete usage in buildings from a structural standpoint reveals the potential for significant cost savings as these factors typically correspond to +20% in material use (Pameter and Myers 2021). Although difficult to quantify, the work of De Wolf et al. and Shanks et al. (2019) show that a reduction of 10–20% can be made today without design changes (Shanks et al. 2019).

Efficient structural design aims to achieve the required structural function of an individual element with the minimum necessary volume of material. Many approaches can reduce overdesign of concrete structures. Firstly, there is the appropriate use of safety margins – ensuring that the design is not excessive (or "overly conservative") for the given loading requirements is a technically straightforward way to avoid redundant material use in structures (Favier et al. 2018). Secondly, innovations around the use of concrete can aid material efficiency for particular design constraints, such as the use of steel-concrete composites in prefabricated, lightweight flooring modules (Ahmed and Tsavdaridis 2019). Lastly, in recent years, geometrically optimised structural elements such as honeycomb structures have re-emerged as a more material-efficient alternative to standardised elements (Favier et al. 2018).

Figure 13: Cementitious materials used per year and possible savings options, Scenario 2050, in Mt. Source: Material Economics 2019



To date, most building codes and standards are very specific on the use of concrete and cement to ensure safety within the construction sector. However, revising national building codes to move towards performance-based design in buildings opens potentials for resource and emission mitigations.

5.1.2 Prefabricated concrete elements

Increasing the use of prefabrication, where parts or building components are produced largely in one factory and assembled on-site, can facilitate the adoption of practices and technologies that reduce material use (Hertwich et al. 2019a). The level of prefabrication can range from subassembly of a few small-scale components such as windows to complete modular construction.

Prefabrication of modular building components provide opportunities for material efficiency through standardization and efficiency of off-site production, opportunities for prevention of or increased recovery of production scrap, incorporation of material efficiency-related materials and technologies and the avoidance of scrap generation on construction sites. Other benefits include reduction in transportation impacts, safer working conditions and improved thermal performances of the buildings because of factors such as tighter joints and seams. Prefabrication can also enhance material efficiency by making repair, renovation and reuse more feasible (Hertwich et al. 2019a).

Although building components have long been produced off-site in factories, the size and complexity of the components produced nowadays are new. Precast concrete elements are made in a more controlled environment with greater precision than in-situ concrete, so designers can have greater confidence in thinner parts that use material more efficiently. More complex part such as 'voided' slabs that are significantly lighter and use less material can also be produced (Shanks et al. 2019).

Although studies mention that energy saving potentials can be quite high, reliable data on the possible savings are sparse. Statements about reductions in embodied emissions are often not reliable because they depend on many variables, like the distance from factory to site and the cementitious material content, for example. Estimations differ a lot, for example it was found that compared to non-precast structural element, prefabricated elements can reduce the amount of concrete by around 15–23%. Other studies such as Shanks found precast concrete to be more emitting than in situ concrete (Shanks et al. 2019).

Partial or complete prefabrication is applied in many countries nowadays, mainly with one-way solid or hollow core slabs (Mata-Falcón et al. 2022). China has a history of promoting prefabrication in construction. Jiang et al. (2019) investigate the effectiveness of government incentives for prefabrication, but do not explore the relationship of the incentives to practices or environmental outcomes (Hertwich et al. 2019b).

5.1.3 Reduction of clinker content in cement through substitution

The reduction in clinker (the main component of cement) content through adoption of supplementary cementitious materials (SCMs) and limestone is a key element of the cement industry's roadmaps for decarbonisation (Marsh et al. 2022). The strategy of clinker substitution has proven to be effective in mitigating the environmental impact of production.

Figure 14: Overview of supplementary cementitious materials. Source: dena

Calcium sulfates

- →CSA cements work through a chemical reaction known as hydration, similar to other types of cement
- →When water is added to CSA cement, it initiates a series of chemical reactions that result in the formation of various hydrated compounds. These hydrated compounds contribute to the strength and stability of the cementitious material

Blast Furnace Slag

- →CSA More than 80% is already used in cement or concrete.
- →The availability of BFS is linked to the steel industry and production in Europe is not forecast to increase

Limestone

- →The most widely used SCM, currently, in Europe and worldwide.
- →Limestone is ground without heating, is abundant and is easily accessible to most cement plants.
- →Substitution potential of limestone is relatively low as only small amounts react

Primary synthetic pozzolans

- →Require an "activation" treatment (thermal or mechanical). This means there are some CO_2 emissions associated with their production
- →Today their use is limited in Europe as they have not been economically competitive compared to slag and fly ash
- →However, this situation is likely to change in the future due to the limited availability of slag and fly ash

Primary natural pozzolans

- →Mainly contain volcanic ashes
- →Commonly used in some areas of Europe, where they are available, i.e., Italy, Greece, and Slovenia
- →According to the European standard EN 197-1, various cement types may contain natural pozzolans from 6 to 55 mass %

Fly ash

- →Fly ash is used in significant amounts in concrete worldwide
- →Fly ash comes from the coal power industry and represents the mineral residue once the organic material has been burned

Ordinary Portland cement (OPC) contains 95% clinker. European standards allow other cement types with a clinker to cement ratio varying from 5% to 95%. In those cement types, a part of the clinker has been substituted by waste or by-products from other industries, such as fly ash from coal power plants or blast furnace slag from the iron industry or natural materials, such as natural pozzolans or even just ground limestone. The substitution products do not require the same energy intensive production process and can drastically reduce the CO_2 emissions. Both fly ash (fa), a by-product of coal-fired power plants, and ground granulated blast furnace slag (ggbfs), a by-product of the steel industry, can be utilized for this purpose. While these materials do not affect the process emissions associated with producing clinker, they offer substantially lower embodied emissions compared to clinker. By reducing the reliance on clinker, they can help lower the embodied emissions of the final product (Shanks et al. 2019). Compared to Portland cement, clinker substitution materials can lower the average embodied emissions by about 15%. However, there are limitations in the availability of the materials. International Energy Agency and The World Business Council for Sustainable Development (2009) estimate that globally clinker substitution with these materials can only account for a reduction in emissions of 10% on today's value (Shanks et al. 2019).

Pameter and Myers identify five main non Portland Cementitious material types: **calcium sulfate** (e.g., gypsum), **limestone**, **primary natural pozzolans** (e.g., volcanic ash), **primary synthetic pozzolans** (e.g., calcined clay), and **secondary materials** (e.g., coal fly ash, a coal combustion by-product, and blast furnace slag, a by-product of pig iron production). Limestone, and secondary materials (coal fly ash, blast furnace slag) are currently the most used non Portland cementitious materials in European countries such as Germany and the UK. Besides the substitution of clinker in cement, the cement content in concrete can also be reduced. Concrete mixes commonly used in construction often contain an excess of cement. This is more than is necessary to achieve the required strength. This can be attributed to conventional practices or minimum specifications set by standards organizations (Shanks et al. 2019). By reducing the cementitious content to match the specific requirements, such as compressive strength, significant potential exists for reducing carbon emissions associated with concrete production. This potential becomes even greater when coupled with design changes aimed at minimizing over-specification and overengineering of buildings as described above.

5.1.4 Lifetime extension

The average lifespan of residential buildings in Western Europe often exceeds 80 years, while other developed countries like the United States and Japan tend to have lower lifespans. In rapidly developing and emerging economies such as China, high demolition rates can result in average lifespans as short as 25–30 years (Hertwich et al. 2019c). In the non-residential sector worldwide, buildings typically have lifespans that rarely surpass 50 years, mainly due to frequent changes in commercial activities (IEA 2019). In emerging countries, historically, short building lifetimes have resulted from the inadequacy and inflexibility of buildings constructed during rapid urbanization and industrialization. However, an important question arises: How can we avoid the rapid obsolescence of currently constructed buildings and design new buildings with flexibility and easy modification to meet evolving demands? (Hertwich et al. 2019c)

Since buildings can have relatively long lifespans, the demolition of numerous concrete structures is not primarily driven by their physical deterioration or irreparability. Instead, various factors such as technical, functional, economic, legal, and desirability considerations render them obsolete, thereby dictating the duration of their utility. This circumstance prompts inquiries into the underlying motives and business strategies that favour the demolition of structurally sound buildings, despite the potential for repurposing and reassembling individual concrete components that have not yet reached their physical end-of-life (Marsh et al. 2022). China demolished nearly 10 million m^3 of floor area annually during the late 2000s, which accounted for approximately 15% of the annual construction during that period (IEA 2019).

Approach to extend the lifetime of buildings includes the reuse or adaptive use of buildings. Those approaches could lead to significant savings in materials used and emissions, as no new buildings need to be built. Key measures in life extension include:

- Adaptation and renovation of buildings to avoid demolition and new construction, including energy retrofitting of existing buildings.
- Improved maintenance and servicing to extend the life of key components.
- Design for flexible and/or more intensive use (e.g. sharing or alternative housing) and to enable deep renovation (repurposing-friendly building).

While extending the lifespan of structures may not lead to a drastic reduction in the volume of in-use stocks, it can significantly decrease material flows and waste production over time. This approach offers the potential to minimize environmental impacts while maintaining the same level of functionality (Marsh et al. 2022). Although estimates and scenarios are still limited, the IEA estimates a cumulative reduction of 10 Gt of emissions by 2060 in the buildings sector through reduced materials demand (IEA 2019). Contributing with 90%, this reduction is primarily attributed to the longer lifespans of buildings pursued in conjunction with energy efficiency retrofits.

5.1.5 Recycling

Construction and demolition waste comprises a significant portion of solid waste, accounting for 55% of all waste in Germany, for example. While metals are commonly recycled, concrete and other mineral building materials are predominantly downcycled into coarse aggregates (Hertwich et al. 2019c). During the end-of-life phase of buildings, concrete waste is typically crushed and, at best, reclaimed as recycled aggregate for applications such as road underlay or gravel. This process is energy-intensive and results in a reduction in material properties.

Although recycled concrete reduces construction waste and the extraction of natural aggregates, its production, requiring cement, does not emit fewer greenhouse gas than new concrete. Depending on the application and transport volume (e.g. between construction sites), only about 7% of CO_2 emissions can be saved when using recycling concrete, but in some cases these can even be higher than when using non-recycled concrete. In addition, the preparation process of concrete is very energy intensive, which can cancel out the possible small CO_2 savings (CEWI 2021). Certain studies suggest that the use of low-grade recycled aggregates in concrete production may require additional cement to achieve the same concrete quality. The environmental benefits of mineral recycling are also influenced by the transportation distances involved when comparing virgin and secondary resources (Hertwich et al. 2019c).

For fine particle-size construction and demolition waste, recycling is technologically more challenging. Methods to recycle hydrated cement waste into new cement have been developed but remain on very early stages of development. Unreviewed life cycle assessments suggest substantial reductions in GHG emissions which have yet to be verified (Nusselder et al. 2015).

5.1.6 Reuse of Materials and Buildings

A currently overlooked but promising strategy is the reuse of building materials salvaged from obsolete buildings in new projects. Most recent investigations have focused on the reuse of metal elements. While concrete currently constitutes the largest construction waste stream, there remains a limited understanding of the potentials and issues surrounding the reuse of concrete panels extracted from the walls of pre-fabricated buildings (Hertwich et al. 2019c; Küpfer et al. 2022). Nevertheless, case studies on steel component reuse have demonstrated considerable CO_2 savings compared to recycling and substantial savings compared to virgin steel. A similar, if not more pronounced, potential could be expected for concrete, given its limited current role in construction recycling (Hertwich et al. 2019c).

As modern buildings undergo frequent demolition for reasons unrelated to material degradation or structural safety, their structural components often remain in excellent condition, presenting the potential for an extended service life. Sawing obsolete concrete structures and reusing their blocks in new assemblies therefore appears as a circular and sustainable solution when demolition is unavoidable. To reuse concrete elements, they can be carefully sawn out of soon-to-be-demolished buildings. Elements are then used without other major transformations for another service cycle in a new assembly (Küpfer et al. 2022).

The choice of reused materials needs to include the analysis of multiple technical, aesthetic, economic and social aspects, which often results in a longer and more expensive design and construction process. A similar effect is a consequence of the necessity to conduct material tests and expertise necessary to meet obligatory standards or to obtain certifications and permits. Important barriers are issues associated with quality assurance and risk, the availability of correctly specified components, and costs (Hertwich et al. 2019c).

5.2 Current Situation in Europe and Germany

The construction sector is one of the most resource-intensive sectors of the economy – in Germany alone, the construction sector consumes around 500 Mt of raw materials every year. At 55%, the sector is responsible for the largest share of the total waste produced.

Although the recovery rate of mineral construction waste is about 90%, the share of actually recycled and reused construction waste is significantly lower. Currently, construction waste is neither recycled nor reused to a high standard and ends up in road and earthworks and landfill construction as well as asphalt or concrete aggregate. Officially, about 93.9% of construction waste is recycled, but about 16% of this is used in landfills or backfilled ("other material recycling") and 77.9% is mainly used in civil engineering (earthworks, road and path construction) (Basten 2021). The further processing and subsequent use thus represents downcycling instead of a closed cycle and leads to a dependence on new road construction for the disposal of demolition waste. In view of the condition of German roads and the decrease in material-intensive new road construction observed in recent years, these dependencies should be reduced in the future.

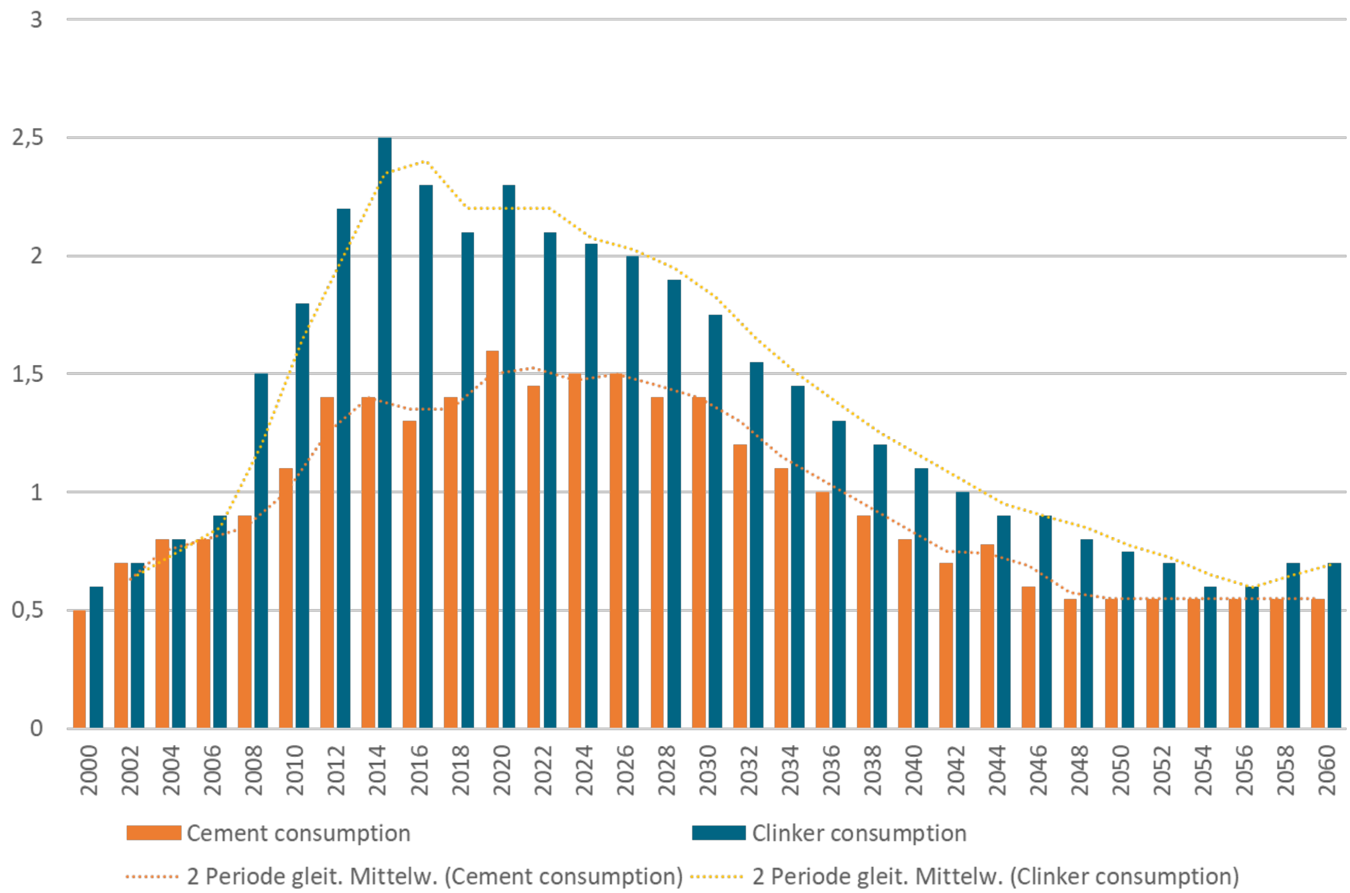
The closure of material flows in the construction sector is limited by a number of factors such as building and licensing regulations, the state of the art or the regional availability of recycled aggregates. For example, for use in building construction, currently only up to 45% by volume of the total aggregate may be contained as recycled material (Deutscher Ausschuss für Stahlbeton e. V. 2021).

In Germany, fine fragments are not yet recycled into cement production, as there is still no technology available for high-quality processing of fine materials of consistent quality. Instead, measures for reuse, extension of the service life and material efficiency must be given greater focus in the future.

Today, material efficiency has no prominent role within regulation of the building sector in Germany or Europe. The current European regulation aligns with the policy targets of promoting and enhancing material efficiency and overall resource efficiency. However, unlike energy performance which is governed by European Directives, material efficiency is relatively unregulated. Additionally, while there are fiscal incentives and instruments for enhancing energy efficiency in building and renovation, no such provisions exist for improving the material efficiency of buildings (Ruuska and Häkkinen 2014).

The Construction Product Regulation (CPR) in Europe mandates that construction products meet basic requirements and be suitable for their intended use throughout their life cycle. Sustainable use of resources is a key requirement, with an emphasis on the reuse/recyclability of materials after demolition, durability, and the use of environmentally-friendly raw and secondary materials. However, even though the Construction Product Regulation emphasizes the importance of material efficiency, it does not give normative rules for it, or dictate mandatory information about material efficiency (Ruuska and Häkkinen 2014).

Figure 15: Scenario for cement and clinker consumption 2060. Source: RMI and China Cement Association 2022



5.3 Current Situation in China

China's cement production and consumption has been the highest in the world. The overall environmental efficiency of China's cement industry is low, and there is still much room for improvement. After power and steel, cement is accounting for about 13% of the country's total emissions (China Cement Association 2022).

At present, carbon reduction in the industry relies mainly on improving equipment and energy efficiency including measures such as switching from coal to low-carbon energy sources, energy efficiency improvement, and development of infrastructures for CO_2 storage and utilization (China Cement Association 2022).

Next to carbon reduction measures, demand reduction will be the main driver of the decarbonisation in the cement and concrete industry. Especially through the slowdown of urbanization and infrastructure build-out. As urbanization and the demand for housing drop in the long run, the scale of new housing development will decline. While China still needs to improve its infrastructure, the scale of infrastructure construction is gradually diminishing. With the slowdown in construction sectors including housing, roads, and railways, a decline in cement demand will be inevitable.

Cement clinker production is forecast to decline to 560 Mt per year by 2050, equivalent to a reduction of approximately 67% of total carbon emissions from the 2020 level. By 2050, China's cement clinker demand is likely to fall by two-thirds from current levels. With the adjustment of China's economic development model, the share of investment in construction engineering has gradually decreased, resulting in a continuous decoupling of GDP growth from cement consumption.

Although these approaches can achieve some emissions reductions in the short and medium term, they are unlikely to attain net-zero emissions using only existing technologies. Even though Chinas demand for concrete is declining, it still remains the world's biggest producer and consumer of cement. The potentials to reduce cement use through material efficiency measures therefore are still significant.

The Ministry of Housing and Urban-Rural development introduced a new national standard called "General Specifications for Building Energy Conservation and Renewable Energy Utilization" in order to improve energy resource utilization efficiency , promote the use of renewable energy, reduce building carbon emissions, create a good building indoor environment, and meet the needs of high-quality economic and social development. In the past, building-related carbon emission standards were more recommendations or suggestions. However, the new standard, coming into effect in April 2022, makes the calculation of building carbon emissions a mandatory requirement.

In 2020, 10 real estate companies, including Vanke and China Jinmao, have publicly promised that 100% of the company's new buildings will meet, green building standards. A number of real estate companies have already added relevant low-carbon energy-saving technology and equipment to their projects. In the context of carbon neutrality, green buildings may become a trend.

Construction Waste

At present, the recycling rate of construction waste in China stands at around 5%, significantly lagging behind developed countries. This deficiency stems from insufficient comprehension of construction waste disposal, inadequate legislative provisions, and limited investment in research and innovation (Dr. Xianshan Ma 2023).

China's construction constituents include waste soil, waste concrete, waste brick, waste steel, waste wood, and waste plastic, among others. The annual production of construction waste in China ranges from 1.55 to 2.4 Gt, representing approximately 40% of the total urban waste generated. Notably, the National Bureau of Statistics' database only accounts for the treatment and utilization of general solid waste, without separate consideration of construction waste disposal and utilization.

Methods for treating and disposing of construction waste encompass open stacking, simple landfilling, comprehensive treatment, and on-site resource utilization. The prevalence of illegal open-air dumping resulting from unauthorized stacking remains relatively common in small towns due to varying levels of government supervision. However, such occurrences have become rare in larger cities. Medium-sized cities primarily rely on simple landfilling as their primary approach, with a recent increase in adoption observed in small cities. Economically developed regions such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Guangdong-Hong Kong-Macao Greater Bay Area have predominantly implemented the comprehensive treatment model. This model emphasizes simple source classification and accounts for approximately 95% of the waste management practices in these regions. Conversely, the on-site resource utilization model is limited in application and primarily observed in a few economically developed areas, constituting a minor share of approximately 5% (Dr. Xianshan Ma 2023).

6 Circular solutions for plastic

6 Circular solutions for plastics

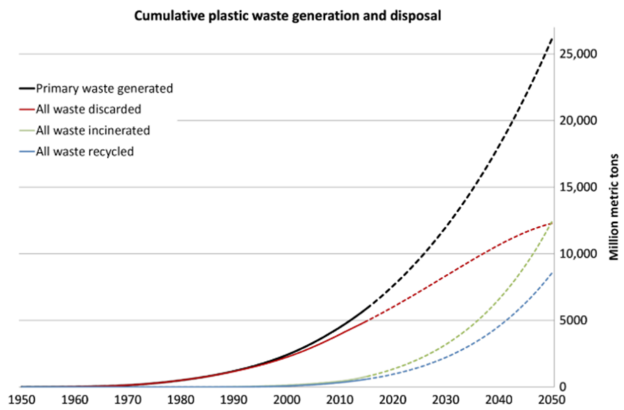
Sustainable management of end-of-life plastic waste is important not only to reduce the need for virgin raw materials (and associated CO_2 emissions), but also to reduce end-of-life CO_2 emissions. Recycling plastics is thus twice as effective and crucial for reducing greenhouse gas emissions from plastics.

The production and management of plastics have significant environmental implications globally. According to Geyer et al. (2017), 8.3 Gt of virgin plastics have been produced to date, and of the 6.3 Gt of plastic waste generated, only 9% is recycled, 12% is incinerated, and 79% is accumulated in landfills or the natural environment. If current production rates continue, an estimated 12 Gt of plastic waste will be in landfills or the natural environment by 2050. In terms of regional distribution, the United States accounted for approximately 18% of the global plastic production. The EU held a share of 15%, while China had the largest share with 32% of the global plastic production (Plastics Europe 2022).

In 2014, the highest recycling rates were recorded in Europe at 30%, followed by China at 25%, and the US at 9%. These numbers highlight the need for urgent and comprehensive action to address the growing plastic waste problem and transition towards a more circular economy approach to plastic production and waste management (Geyer et al. 2017).

One of the main goals in tackling the plastic pollution problem is to reduce the overall amount of plastic produced. This can be achieved through various measures such as promoting sustainable consumption patterns, encouraging the use of alternative materials, and implementing stricter regulations on plastic production and use. Keeping plastic in a circular economy is another crucial aspect of solving the problem. This involves designing products with recyclability in mind, improving waste management systems to facilitate recycling, and promoting the use of recycled plastics in manufacturing processes. By closing the loop and recycling plastic materials, valuable resources can be conserved, and the environmental impact of plastic production can be minimized.

Figure 16: Cumulative plastic waste generation and disposal (in Mt). Dashed lines show a projection of the historic trend. Source: Figure is derived from Geyer et al. 2017



For the plastic waste that cannot be effectively recycled, incineration can be considered as a last resort. However, it is essential to ensure that incineration processes are conducted using advanced technologies that minimize the release of harmful pollutants into the environment.

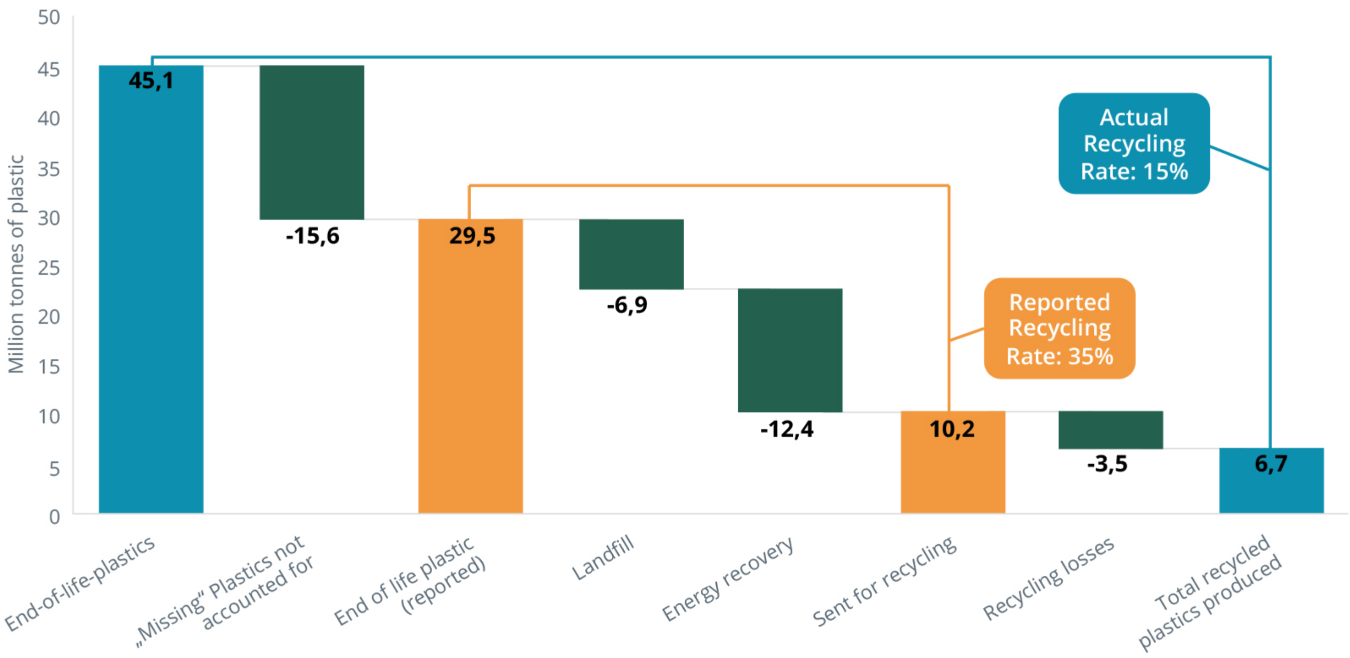
6.1 Current political situation in EU/Germany

The European plastic industry has undergone notable changes in production, demand, and recycling rates in recent years. In 2021, plastic production in Europe amounted to 57.2 Mt. Breaking down the plastic production in 2021 results in:

- fossil-based with 50.1 Mt,
- post-consumer recycled plastics with 5.8 Mt and
- Bio-based with 1.3 Mt.

The packaging sector accounted for the highest share at 39.1%, followed by building and construction at 21.3%. Other sectors accounted for the remaining demand. The use of post-consumer recycled plastics in Europe demonstrated progress, reaching 9.9% in 2021. In 2020, a total of 29.5 Mt of post-consumer plastics waste was collected in the EU27 + 3 countries. Notably, the recycling rates were 13 times higher for separately collected plastics waste compared to mixed waste collection schemes. In contrast, the recycling rates of mixed waste collection were 5%, with 57% undergoing energy recovery and 38% being sent to landfills. These numbers emphasize the importance of efficient waste separation and collection systems to maximize recycling rates and

Figure 17: Comparing Reported & Actual Recycling Rates of Plastics. Treatment of end-of-life plastics in EU + CH + NO, 2020. Source: Agora Industry 2022



promote a circular economy for plastics (Plastics Europe 2022).

The European Green Deal and Circular Economy Action Plan have introduced a range of plastics policies to address the environmental challenges associated with plastic waste. One of the key objectives is to achieve a recycling target of 50% for plastic packaging by the year 2030. To accomplish this goal, the EU has implemented various measures (Agora Industry 2022). Starting in January 2021, the EU has banned the sale of several single-use plastic items, including straws, cutlery, and food and beverage containers made from polystyrene, and cotton bud sticks. Additionally, all oxo-degradable plastics have been prohibited. This ban aims to reduce the consumption of these items and promote sustainable alternatives (Agora Industry 2022).

To control the export of low-grade plastic waste, the EU has restricted its transportation outside EU borders since 2021, following the guidelines set forth in the Basel agreement. This measure ensures that plastic waste management practices meet international standards and prevents the shifting of waste to regions with less stringent regulations (Agora Industry 2022).

In 2021, a tax of 800 €/t was implemented on non-recycled plastic to incentivize manufacturing industries to adopt materials that are recyclable, reusable, or compostable. This tax serves as a financial motivation for companies to shift away from non-recycled plastics and encourages the adoption of more sustainable alternatives (Agora Industry 2022).

Regarding bioplastics, the EU is developing a regulatory framework to determine appropriate applications for their usage. This framework aims to prevent companies from making false sustainability claims about their products and ensures that bioplastics are used in a responsible and environmentally friendly manner (Agora Industry 2022).

The EU's plastics industry currently operates with a linear and fragmented value chain that relies on fossil feedstocks. In Europe, where 78% of the plastic's feedstock is naphtha, the production process begins with oil refining. This is followed by the production of naphtha in oil refineries, the cracking of naphtha into monomers in petrochemical plants, and finally, the synthesis of polymers and transformation of polymers into plastic products. This linear value chain contributes to resource depletion and environmental pollution (Agora Industry 2022). The European Commission has implemented an amendment to the Landfill Directive with the objective of eliminating the disposal of waste that can be recycled or recovered in landfills by the year 2030.

Germany

The treatment of post-consumer plastics waste in Germany has undergone significant evolution in recent years. In 2020, the overall treatment of post-consumer plastics waste in Germany amounted to 5.4 kt. Various methods were employed to manage this waste, including recycling, energy recovery, and landfill. Analysis of the data reveals that recycling played a substantial role, accounting for 42% of the overall post-consumer plastics waste treatment in Germany in 2020. Furthermore, 57%

of the post-consumer plastics waste in Germany underwent energy recovery processes in 2020. Landfilling constituted only 1% of the total post-consumer plastics waste treatment in Germany (Plastics Europe 2022).

When focusing specifically on plastics packaging waste, the treatment methods showed a slightly different distribution. Recycling accounted for 55% of the treatment of plastics packaging waste in Germany, reflecting the significant efforts and investments made to establish efficient recycling infrastructure. Additionally, 45% of plastics packaging waste in Germany underwent energy recovery processes. (Plastics Europe 2022).

6.2 Current situation in China

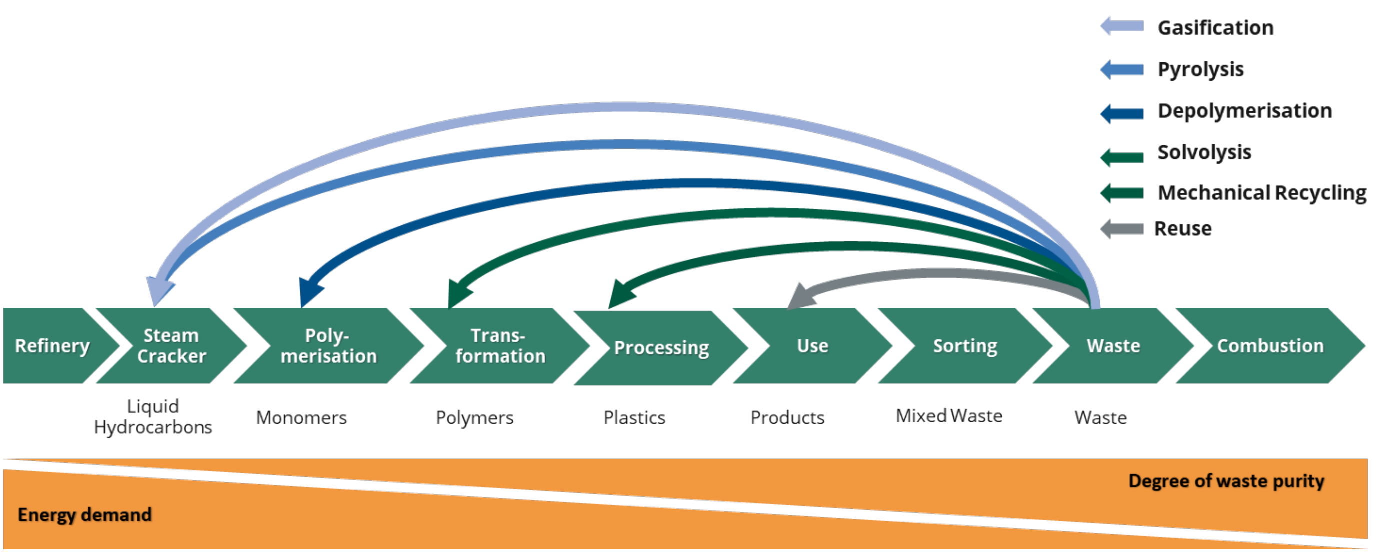
Overall, the trajectory of waste management in China is mainly transitioning to incineration but China is also pursuing a transition of the waste system to resource utilisation. The focus is shifting to resource utilisation pathways, and the entire waste resource industry – encompassing physical and chemical recycling of plastics – is projected to enter a rapid growth phase.

Both physical and chemical recycling methods are anticipated to witness an increase in the tens of millions of tonnes, with chemical recycling potentially becoming a more prominent approach to green plastic development[1]. Furthermore, there is an anticipation that China's plastic recovery rate could reach 45–50% by 2030. However, it is important to consider that achieving this target will require concerted efforts and effective implementation of recycling initiatives.

In China, the issue is already being addressed politically on various levels, which is briefly summarized below. The **14th Five-Year Plan for Circular economy Development** introduces five key projects and six primary actions, including efforts to address plastic pollution and transform express packaging. It emphasizes reducing plastic at the source, banning harmful products like ultra-thin agricultural films, and promoting the evaluation of plastic substitutes' environmental impact throughout their lifecycle. The plan encourages the use of degradable plastics based on conditions, improving standards, testing capabilities, and proper application and disposal. It also focuses on enhancing recycling efficiency, strengthening waste classification and reuse, and developing waste incineration facilities. Measures to reduce plastic waste in landfills, clean up marine litter, and raise public awareness are highlighted.

Since 2020, various government authorities, including the NDRC, have issued policy documents focused on controlling plastic pollution and promoting circular economy development. These policies advocate for comprehensive management systems covering the production, distribution, utilisation, recycling, and disposal of plastic products. They set objectives for 2020, 2022, and 2025, along with specific actions to restrict certain products, encourage recycling, and standardize others. The policies emphasize the importance of green,

Figure 18: Processes and energy demands of recycling. Source: Agora Industry 2022



[1] It is worth noting that these projections are subject to various factors and uncertainties.

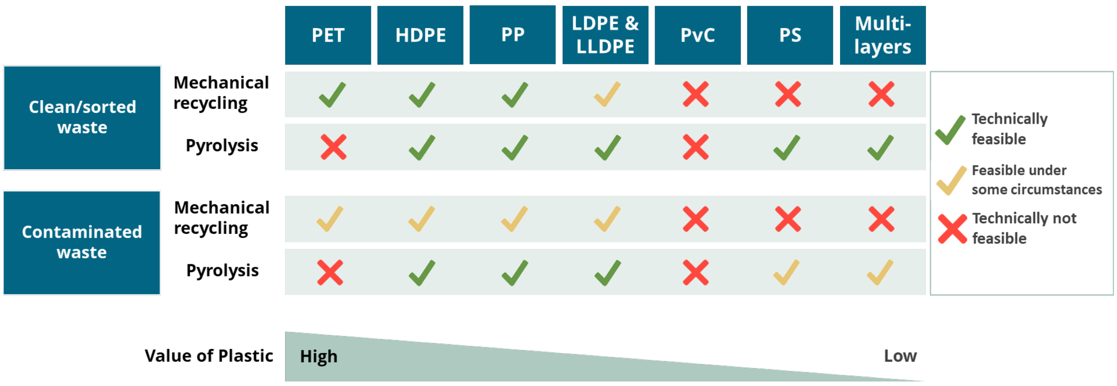
low-carbon, and circular development, promoting sustainable consumption and comprehensive governance of plastic pollution.

So far, the current framework for chemical recycling of waste plastics suffers from a lack of specificity in the "Industrial Classification for National Economic Activities."

The existing regulations and technical standards provide insufficient guidance on the definition and categorisation of chemical recycling technologies. This ambiguity can lead to the classification of such technologies as "high energy consumption and high pollution" projects, complicating approval processes (chem.vogel 2023).

6.3 Recycling Process

Figure 19: Feedstock tolerance comparison for mechanical recycling versus pyrolisis. Chemical coversion expands feedstock tolaerance. Source: PEW and SystemIQ 2020



Recycling is a focal point as it serves as a technical solution to help reduce plastic pollution. Despite efforts to reduce and reuse plastic, there are limits to these strategies, as plastics offer many beneficial properties and are widely used in various applications. Thus, recycling is a necessary component to break the cycle of plastic pollution. The focus on recycling is particularly relevant in the context of industrial production. It involves the collection, sorting, processing, and conversion of plastic waste into new products or materials.

There are three ways of recycling: mechanical closed-loop, mechanical open-loop, and chemical recycling. Primary, or closed-loop, recycling is used for mono-stream plastics and allows plastics to be recovered in the same loop and reused to make products with the same properties as before. Secondary recycling, or open-loop recycling, applies to the majority of post-consumer plastics and involves sorting plastic waste streams, reducing the size of the polymer waste, followed by extrusion. Open-loop means that the plastics are generally used in lower value products, resulting in lower quality (Arena and Ardolino 2022).

6.3.1 Mechanical Recycling

Mechanical recycling is the simplest, cheapest and most common form of recycling and typically involves sorting the plastic waste by polymer type, removing labels, washing, mechanical shredding, melting and remoulding into new shapes (Rosenboom et al. 2022). Through the various steps, a recyclate is created that can be used again to make plastic. In the process, the structure of the plastic is not changed. This is only possible for certain plastics, as different plastics change their properties when exposed to changing temperatures and other factors, and are not suitable for mechanical recycling. There are three main processes for mechanical recycling:

- **Regrind** – Product resulting from shredding and grinding
- **Regranulate** – Plastic recyclate manufactured using extrusion without changing the chemical composition of the input stream
- **Recompund and regenerate** – Plastic recyclate with a modified chemical composition compared to the input stream

The quality of recycled plastics can be significantly impacted by contaminations in the polymer waste, including trace elements such as small degradation products and additives like flame retardants, volatile organic compounds, phthalates, stabilizers, paints, and coatings. Multilayer materials that cannot be separated further add to the challenge. Additionally, plastics that are sensitive to temperature and do not flow at elevated temperatures can pose limitations to the recycling process.

However, there are a few plastic types such as PET, polyethylenes, and PP, primarily from the packaging

Figure 20: Overview of recycling processes and challenges. Source: dena

Process		Challenges	Range of treatable polymer types	Sensitivity to Feedstock	TRL	Complexity of required technology	Costs
Mechanical Recycling	Involves sorting the plastic waste by polymer type, removing labels, washing, mechanical shredding, melting and remoulding into new shapes.	Contamination, multilayer packaging leading to downcycling	Limited (not-contaminated PE, PET, PP, PS/HIPS, ABS)	High	High (9)	Low	Low
Solvent based purification	Chemical recycling process that aims to dissolve or liquefy plastic waste without damaging the polymeric structure.	The choice of solvent must be highly specific to a strictly homogeneous feedstock. No cyclic process as some degradation in product quality occurs. Residual toxic contaminants may remain in the product (Rollinson and Oladejo 2020).	Limited	Very high	Low (3-4) hydrolysis and 4-5 glycolysis	High	High
Solvent-based depolymerisation	Process involves dissolving plastic waste in liquid baths to produce oligomers and monomers. There are various depolymerisation processes used in this method.	There are remaining knowledge gaps regarding product quality and energy expenditure, (Rollinson and Oladejo 2020).	Very limited	Very high	Low – Medium (3 – 6), depending on process and target polymer	High	High
Pyrolysis	Process involves thermal cracking of plastic waste in the absence of oxygen. Resulting products from this process are gas, char, and liquid oil, with pyrolytic oil being the desired product in most cases (Solis and Silveira 2020). *Requires temperatures of 300 to 700°C*	Pyrolysis is not suitable for treating mixed waste since pyrolysis oils are contaminated with heteroatomic elements. This contamination results in acidic, non-stable oils that are immiscible with oil and thus unusable as fuel without downstream reforming (Porshnov 2022).	Wide	Very Low	Medium (6-7)	High	High
Gasification	Solid waste is converted into a mixture of hydrocarbons and synthesis gas. It requires a high level of waste separation and very large amounts of energy. Autothermal gasification uses approximately 28% of the energy of carbon in the feedstock to conserve the remaining 72% of gas (Porshnov 2022). *Requires temperatures of 700° and 1200°C depending on the gasifying agent*	The use of catalysts for Fischer-Tropsch and methanol synthesis is limited by their sensitivity to impurities such as oxygen, bromine, chlorine, and sulfur, requiring gas cleaning for waste-to-methanol processes to be effective (Porshnov 2022). Impurities in the plastic result in a syngas that would require energy-intensive purification before it can be used for the production of other chemicals.	Wide	Very Low	Medium – high (6-8)	High	High

sector, that are commonly treated and recovered through mechanical recycling methods (Arena and Ardolino 2022; PEW and SystemIQ 2020). Figure 19 shows some of the main plastics and their ability to be recycled mechanically or by pyrolysis. As can be seen from the figure, not all types of plastics are suitable for the recycling processes, especially contaminated waste.

The purity of the plastic stream has a significant impact on the possibility of recycling. Accordingly, in the case of household waste, a necessary prerequisite is the collection and sorting of the waste to enable recycling of the plastics it contains (Shamsuyeva and Endres 2021, Umweltbundesamt 2016).

6.3.2 Chemical Recycling

Chemical recycling refers to a range of processes that involve breaking down plastic waste into its chemical building blocks, which can then be used to produce new plastic products. These processes are divided into two main groups: thermolysis and solvolysis. Thermolysis involves various decomposition reactions that occur through different thermal treatment methods and result in hydrogen-carbon mixtures of different compositions. Solvolysis involves chemically induced depolymerisation reactions that take place in a solvent, leading to depolymerisation products or monomers that can be polymerized with virgin raw materials and further processed into new plastics (Shamsuyeva and Endres 2021). Feedstock recycling involves converting plastic waste into feedstock for the production of chemicals and fuels (Rollinson and Oladejo 2020).

State of the art

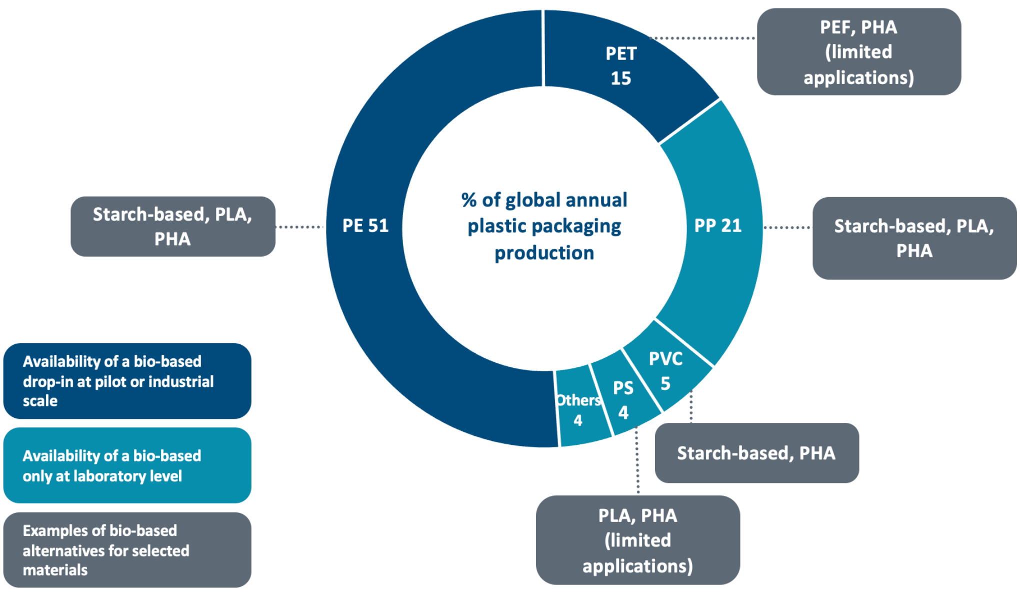
As described above, a range of processes for chemical recycling exist. In the following sections, some of these approaches will be explained. There are four main processes: gasification, pyrolysis, solvent-based purification and solvent-based depolymerisation (Arena and Ardolino 2022).

Challenges

The main challenge of gasification and pyrolysis processes is the generation of a mixture of strongly toxic and highly explosive gases, which requires even higher safety standards than incineration-based approaches. The facilities are technically complex, costly, and capital-intensive, and the unpredictable nature of municipal solid waste feedstock makes it a problematic feedstock, requiring pre-sorting of waste (Porshnov 2022).

Chemical recycling currently does not play a significant role worldwide. However, with the defossilization of the chemical industry, its role is expected to increase. Various technical challenges will need to be overcome. Similar to mechanical recycling, the establishment of pure material streams achieved through product design and appropriate collection and processing infrastructure will be necessary. Without these elements in place, chemical recycling will also have limited impact and only partially support mechanical recycling.

Figure 21: Overview of bio-based drop-ins and new material alternatives for major resin types. Source: Rosenboom et al. 2022; Brizga et al. 2020



6.4 Biogenic Plastics

The production of plastics from biomass offers another option to produce plastics in a GHG-neutral manner. It can be considered as "biogenic recycling" when sustainably grown biomass is used, as these do not generate more CO_2 at the end of their life cycle than was absorbed through photosynthesis.

Biogenic plastics are a type of plastic that can be made from renewable resources or biodegradable materials, or produced through biological processes. Due to various factors such as the energy-intensive processes involved in their production, potential land-use impacts, and the overall environmental footprint associated with their life cycle, biogenic plastics are not necessarily more sustainable than fossil-based plastics. Therefore, a comprehensive life cycle assessment (LCA) is necessary to accurately evaluate the sustainability of biogenic plastics and their potential environmental benefits (Brizga et al. 2020; Rosenboom et al. 2022).

The primary challenge in the production of bioplastics lies in the origin of the biomass used as feedstock, as it determines various restrictions, such as potential competition with food security and land management. To address this issue, the production of bioplastics can be categorized into different generations which allows for a more comprehensive understanding of the sources used and their potential impacts on food security, land management, and resource availability (Brizga et al. 2020).

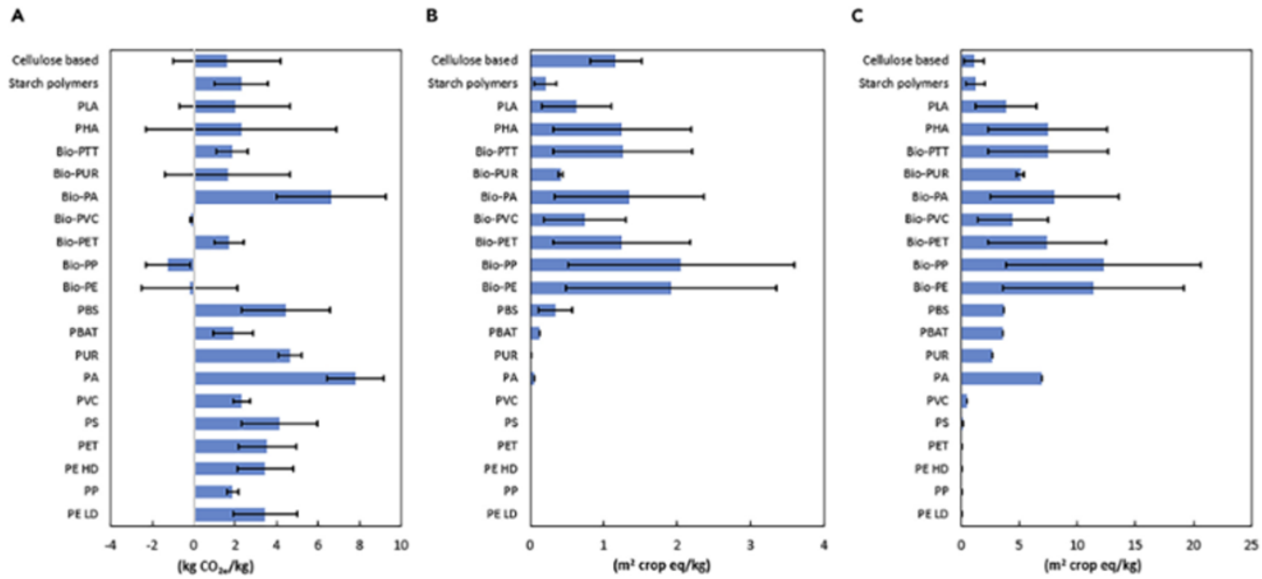
First generation – The first generation involves the use of readily fermentable sugars derived from edible polysaccharide sources, such as corn, sugarcane, and edible vegetable oils. This generation has raised concerns regarding the potential conflict with food production and its impact on land usage.

Second generation – The second generation of bioplastics production utilizes biological waste as feedstock as well as lignocellulosic biomass, which helps address some of the concerns associated with the first generation. Using waste materials reduces the competition with food production and maximizes resource utilization. The utilization of lignocellulosic biomass enables the use of waste wood as well as the utilization of products derived from agricultural practices, such as short rotation plantations. The advantage is that these do not need to compete with food production, as it can be grown on land that is not suitable for food crops.

Third generation – The third generation of bioplastics production focuses on biomass derived from algae.

Currently, only a small portion, approximately 0.02%, of global agricultural land is dedicated to producing precursors for bioplastics. This indicates that the total replacement of fossil feedstocks with biomass for bioplastics production is highly unlikely, considering the limited potential of available biomass resources. The production of 100% bio-based bioplastics is at a scale of around 2 Mt per year (Rosenboom et al. 2022).

Figure 22: Global warming potential, land use and water use for plastic production. Source: Brizga et al. 2020



(A) Global warming potential.
(B) Land use.
(C) Water use.
Full bars show means and error bars show maximum and minimum levels. For more details on the calculations of maximum and minimum land and water use of bioplastics, see Experimental Procedures.

Possible role for biogenic plastics

There are two approaches to the production of bioplastics: **Drop-Ins** and **new materials**.

Drop-Ins – The concept of "drop-ins" refers to identical counterparts of fossil-based plastics that are currently in use, but are instead sourced from renewable materials. These drop-ins, such as bio-based PE as a substitute for PE and bio-based polyethylene terephthalate (PET) as a substitute for PET, possess the exact same chemical and physical properties as their fossil-based counterparts.

New materials – Certain new materials, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), have different chemical and physical properties compared to conventional fossil-based plastics. However, they can still be utilized in a wide range of packaging applications. For example, standard PLA is commonly used in single-use food service packaging and other disposable items due to its biodegradability and compatibility with food contact.

Similarly, PHA offers biodegradability and versatility, but its mechanical and processing properties may not always align with those of fossil-based plastics.To address these barriers, additives can be incorporated into bio-based plastics to enhance their mechanical properties, processing behaviour, and other characteristics (Brizga et al. 2020).

In Figure 21 an overview of the most commercially relevant polymers for bioplastic manufacturing is given. While bioplastics offer various benefits, such as reduced dependence on fossil resources and potential biodegradability, the overall sustainability of the process can be counterbalanced by the side effects of feedstock farming. Increased fertilizer and pesticide use in agriculture can contribute to issues such as acidification potential and eutrophication, which can negatively impact ecosystems. Addressing these challenges requires comprehensive consideration of the entire life cycle of bioplastics, from feedstock cultivation to end-of-life management. Sustainable farming practices, efficient pretreatment technologies, and optimized process designs are being explored to mitigate the environmental impacts associated with bioplastics production and enhance its overall sustainability (Brizga et al. 2020; Rosenboom et al. 2022). For this reason, a brief overview of a LCA for bioplastics is provided below.

The literature on LCAs of bioplastics is limited, and mainly focuses on energy consumption and global warming potential. However, studies have shown that bioplastics can lead to savings in non-renewable energy use and greenhouse gas emissions compared to conventional materials (Brizga et al. 2020).

Recycling of bioplastics

The recycling of bioplastics is less established than traditional plastics, and sorting mixed plastic waste becomes even more challenging with novel bioplastics. Mechanical recycling of PLA and PHA often leads to a reduction in quality, resulting in downcycling due to the inability to remove contaminants and additives from polymer waste. Coloured or low-density materials and medical contaminants can further complicate recycling. Biodegradation rates are highly dependent on various factors, and compostable plastics may not be suitable for typical composting processes. (Rosenboom et al. 2022).

The biorecycling of condensation polymers into monomers can be achieved using microorganisms and their hydrolyzing enzymes. Although this approach is still underexplored, it shows promise as a cleaner alternative to the chemical approach. A better understanding of enzymatic activity and gene editing could potentially enhance the biorecycling of polyurethanes (Rosenboom et al. 2022).

6.5 Challenges of the recycling approaches

The utilization of bioplastics, mechanical and chemical recycling present several challenges that must be addressed for their effective implementation as a sustainable solution:

Need for an overarching Strategy – To maximize the use of these for various sectors, a comprehensive and overarching strategy is necessary. This strategy should demonstrate how the carbon demand can be met in the future, considering both the technical possibilities and the measures that need to be socially and politically supported. This includes addressing behavioural changes among the population, as they play a crucial role.

Cost considerations – The production of plastics through these three processes can be associated with significantly higher costs. The price of crude oil plays a crucial role as it determines the costs of primary production. Therefore, exploring cost reduction potentials is of considerable importance.

Current developments in Germany

In Germany, the necessity of a network of recycling technologies is recognized with mechanical recycling being expanded as far as possible first, and later complemented by chemical recycling. However, the current regulatory framework poses challenges as laws are mostly geared towards mechanical recycling and still need to be opened up for chemical recycling. This leads to legal and implementation obstacles, as secondary raw materials from chemical recycling are not recognized as recyclates.

Another challenge lies in the waste status determination - "End of Waste." When does the waste regulation apply, and when are streams considered secondary raw materials? At present, there are no harmonisation measures in Germany or in the EU. This lack of harmonisation in Germany discourages investment in chemical recycling. Recycling faces an economic deficit compared to incineration. Therefore, additional incentives are needed to for chemical recycling. In addition to the economic deficit in recycling compared to incineration, the production of virgin plastics is about half as expensive as recycled plastics on average in the EU. Therefore, a mineral oil tax exemption is being considered by the German Environment Agency.

Another consideration is a fund for all plastic producers, where every producer contributes and certain behaviours are rewarded. The advancement of mechanical recycling (separation, extrusion, and pretreatment) presents another challenge.

7 Energy saving potentials through Circular Economy measures

7 Energy saving potentials through Circular Economy measures

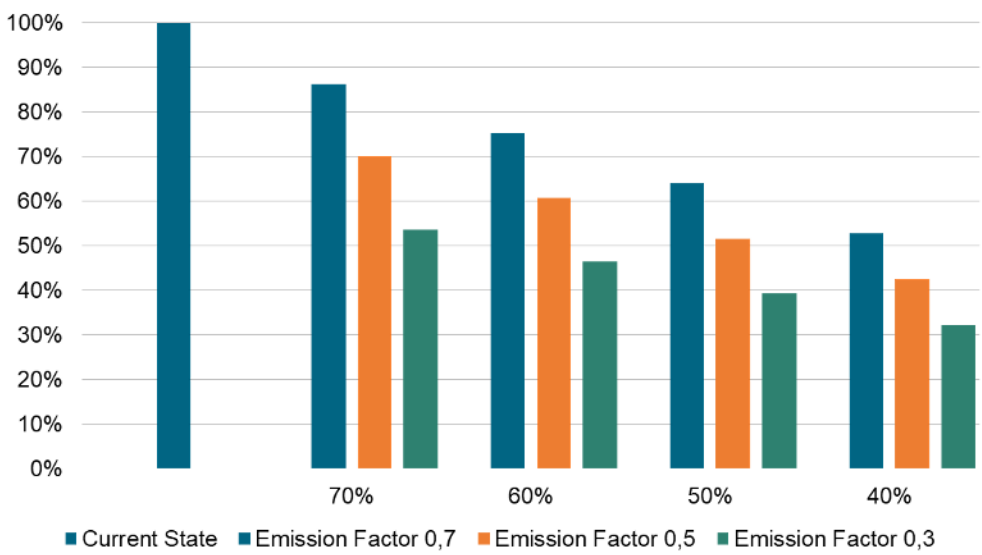
The materials described in this report, including steel, plastics and cement are among the most energy-intensive processes in the industry and result in significant emissions in China and Germany. For instance, the steel industry accounts for approximately 10% of the total Chinese emissions. By transitioning to processes for the production of secondary materials, emissions can be significantly reduced. The following section will provide an overview of the relevant potentials and summarize the factors on which the reduction potentials depend, as described in the previous chapters.

A circular economy enables more efficient use of energy. Many technologies for decarbonising primary industrial production rely on large amounts of renewable electricity or green hydrogen. Examples are the direct reduction of iron with hydrogen, use of green hydrogen for combustion or feedstock use or the electrification of steam crackers. As a result, in an industrial transformation without a circular strategy, the electricity consumption of the steel, cement and chemical sector would increase significantly.

7.1 Potential Emissions & Energy Savings through Recycling

As already described in chapter 4, the secondary production of steel, aluminium, glass and paper as well as for other materials leads to energy savings in comparison to the primary production. These energy savings have a high impact as Agora Industry (2022) demonstrate that circular measures can reduce the energy demand in the European industry by 400 TWh in 2050, from approximately 1400 TWh to around 1000 TWh. These savings primarily result from higher recycling rates enabled through different circular economy measures. As presented in Figure 24, secondary production of steel, plastic, aluminium, and cement require significantly less energy, which is reflected in a significant decrease of CO_2 emissions. For example, the energy and therefore the CO_2 emission intensities of primary and secondary production differ significantly: while conventional primary aluminium production globally typically emits 13–16 tCO_2/tAl secondary aluminium production emits only 0.3 tCO_2/t_{Al} (both depending on location and CO_2 intensities in the power sector). Below, the energy and emission reduction potentials through secondary material production for China are exemplified. Currently,

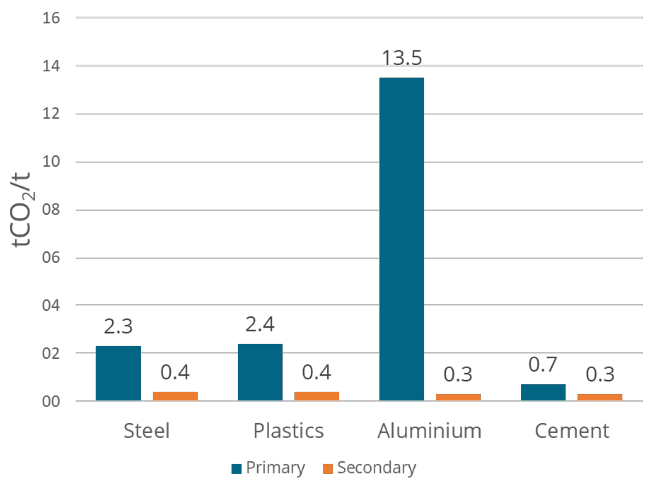
Figure 23: Aluminium – Emission reduction potentials for different share of primary production and different CO_2 intensities for electricity. Source: Emission Factor



aluminium production in China results in approximately 670 Mt of CO_2 per year, with a recycling rate of just under 20%. Production totals around 50 Mt when primary and secondary production are combined. The graph illustrates how emissions are expected to change depending on the recycling rate for various emission factors of the electricity mix. A potential of 40–50%, similar to Europe, can also be considered realistic for China.

Depending on the evolution of the CO_2-intensity of the electricity mix, a reduction of emissions by 50% would be possible. The emission factor for the production of Al_2O_3 from bauxite remains unchanged; hence, the potential is even higher if this energy is also provided with lower greenhouse gas emissions.

Figure 24: CO_2 Intensity Factors of Primary vs. Secondary Production Routes. Source: Agora Industry 2022 based on Material Economics analysis (2021), based on Wood Mackenzie and S&P Global Platts Analytics



7.2 Potential Energy Savings through circular solutions for plastics

Energy and carbon emission saving potentials for plastics through recycling can be significant, as energy is only required to transform plastic waste back into plastic products. Within the recycling processes, mechanical recycling is the most efficient recycling technology in terms of energy, material, and cost, but it requires relatively pure waste streams.

The advantage of current recycling is the significant emission reduction because incineration is prevented through recycling (see Figure). In the future, recycling will lead to significant energy savings, as the alternative GHG-neutral production route using hydrogen and CO_2 requires significantly higher energy demand.

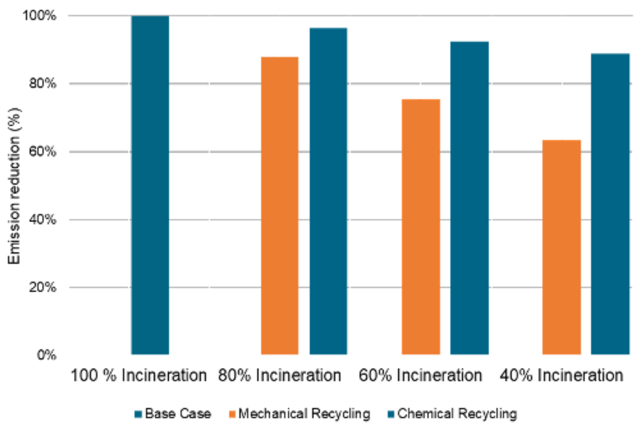
Increasing the current recycling rates of 15% sustained by mechanical recycling to 35% could reduce CO_2 emissions by up to 27 $MtCO_2$ in 2050 in Europe, compared to a business-as-usual scenario (Agora Industry 2022). As shown in Figure 25 mechanical recycling leads to 2.1–3.5 t $CO_2/t_{Plastic}$ in comparison to 5.4 t $CO_2/t_{Plastic}$ for incineration.

When considering chemical recycling, it is important to note that there is a relatively high energy demand, which is often met by incinerating a portion of the waste. Additionally, the energy required for the production of new plastics in the steam cracker must be taken into account. As can be seen from Figure , this is why the emissions are approximately 4.4 t $CO_2/t_{Plastic}$, making them lower than those from incineration. Furthermore, it should be emphasized that this allows for the use of new plastic, resulting in a higher-value product compared to the heat generated primarily during the thermal treatment of waste.

Studies have found that incineration may perform better in some impact categories compared to pyrolysis, and gasification routes may result in higher emissions and acidification potential. Overall, chemical recycling methods require more research and development to address these issues (Zero Waste Europe 2020).

When considering the impact of different recycling rates on emissions reduction, the advantage of mechanical recycling becomes evident. It should be noted that emission values can also decrease when renewable energy is used, both for chemical recycling and incineration, provided that CO_2 is captured after the process.

Figure 25: Emissions for treament of 75 Mt plastics. Source: dena



One important insight of the short analysis is that the current CO_2-intensity of the electricity mix has a significant impact on the results. This holds particular significance in the Chinese context, given the prevalent utilization of coal-based electricity generation. This circumstance offers a substantial opportunity for the reduction of emissions.

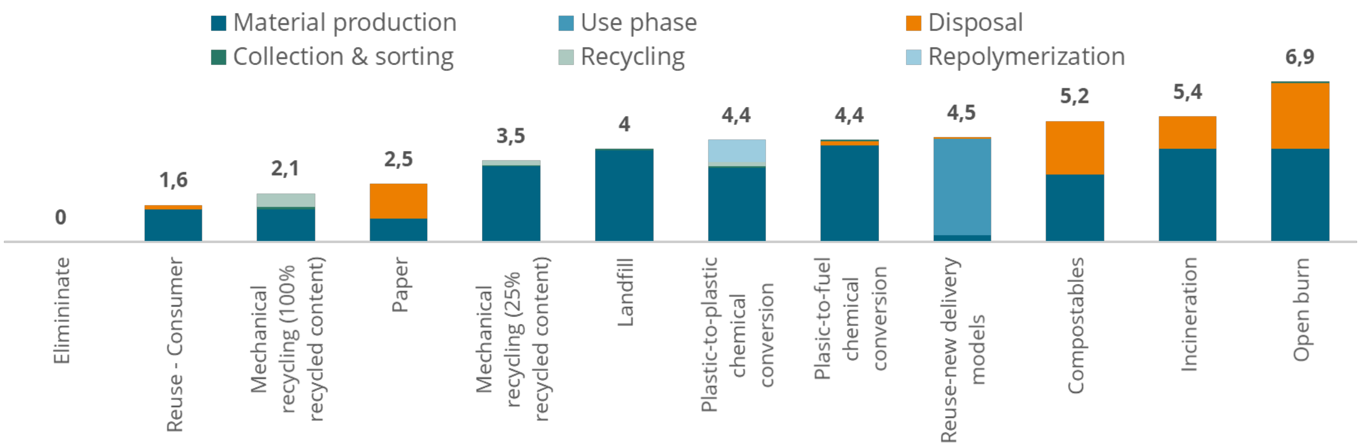
Given the relatively low recycling rates in China, transitioning to recycling offers substantial energy savings and emissions reduction potential, even while maintaining a high CO_2 intensity. The energy savings can lead to further positive effects in the future, highlighting that recycling not only enhances energy efficiency but also increases the likelihood of achieving climate goals in China.

Plastic waste (1 tonne) can be converted into approximately 0.41 tonnes of new HVC (raw material for plastics). Consequently, this saves 0.41 to 0.58 tonnes of hydrogen and 10.1 to 14.3 MWh of electricity in future GHG-neutral production processes that use CO_2 as a starting material (Carbon Capture and Utilization).

In a future energy system primarily based on renewable electricity and utilizing electricity-based fuels, electricity becomes a crucial commodity. The production of energy-intensive products like steel and basic chemicals (e.g., plastics) is highly electricity-intensive, as both energy and raw materials (hydrogen) for emissions reduction are derived from electricity. Recycling becomes even more efficient in these processes. When these energy quantities are no longer necessary for industrial purposes due to a shift towards secondary production, the energy is available for the decarbonization of other sectors (transportation, buildings). A reduced demand also offers the advantage of a slower expansion pace, reducing the need for new construction materials and resources.

Furthermore, this approach can lead to a lower backup capacity requirement for power plants, as a reduced amount of renewable energy capacity is needed. Reduced overall load fluctuations can also relieve strain on the power grid.

Figure 26: Overview of GHG emissions of 1 t of Plastic Utility. Source: PEW and SystemIQ 2020



7.3 Potential Energy Savings through Material Efficiency of concrete

While circular measures can lead to substantial energy savings potential for materials like metals and plastics, the dynamics shift when considering materials such as concrete and cement. Recycling concrete, although pivotal for waste reduction, yields comparatively modest energy savings as most emissions come from the chemical process of cement and concrete production (process emissions) and not the burning process itself. Instead, the significance here lies not primarily in energy savings, but in resource conservation. By optimizing production volumes and employing innovative alternatives to concrete-intensive practices, heavy industries can achieve multifaceted benefits.

Research in this area of circular economy is still at very early stages and not many studies or publications exist that discuss the energy and GHG saving potential of material efficiency in concrete and cement. However, one study by Shanks et al. 2019) analysing material efficiency measures in the UK showed that in terms of material demand reduction, substituting cement with calcined clay and limestone bared significant mitigation potential, followed by reducing the cement content of concrete. In total, the six technical measures investigated were estimated to hold the potential of reducing the UK's cement emissions by 44%. Further, optimising designs can bring the reduction potential to 51%. Importantly for policy, none of these options would require changes in consumer habits, and only minimal changes in the way buildings are designed. Rather, they need production at scale of novel but available concretes as well as designers to have better incentives to optimise the design of buildings (Shanks 2019).

Another study by Watari showed that demand-side measures, such as performance-based concrete design, use of precast concrete, post-tensioning, and avoidance of over-design, more intensive use of buildings and infrastructure through means such as increased sharing practices and consolidation of urban functions, which further extend the life of buildings and infrastructure, could bring significant emissions reductions.

8 Policy Recommendations

8 Policy Recommendations

This report identified twenty policy recommendations, which were later evaluated by the Wuppertal Institute. The following are the policy recommendations considered to have the greatest impact in the Chinese context. The policy recommendations were assessed along three key dimensions: effectiveness, technological availability, and feasibility.

Effectiveness: Recognising the critical role that primary industries play in shaping the overall carbon footprint, our assessment focuses on identifying measures leading to tangible and substantial reductions in greenhouse gas emissions. This parameter assesses the potential of each measure to contribute significantly to the decarbonisation of primary industry.

Technological readiness: Assessing current technological readiness is of paramount importance when considering any policy recommendation. To this end, the maturity and availability of technologies have been considered. The report aims to identify measures that make use of proven and available technological solutions, while recognising the importance of fostering innovation to address any technological gaps.

Feasibility: The feasibility of introducing each measure within the existing regulatory and economic landscape has been assessed. This includes examining the alignment of proposed measures with existing policies, the financial implications and the availability of essential infrastructures.

Relevance for China: Next to the effectiveness and feasibility of the measures proposed as policy recommendations, the relevance for the Chinese context was evaluated.

8.1 Reducing the economic asymmetry between primary and secondary raw materials

8.1.1 Taxes and pricing mechanisms (Primary material, CO_2, plastics)

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Reduce, Recycle, Rethink	●●●○○	●●○○○	●●○○○

For some plastic recycling processes as well as in the cement and concrete industry, the costs for primary production are lower than for the production of secondary materials. By implementing taxes on the production of primary materials, plastics, or on CO_2 emissions, the production using primary raw materials could become more expensive. This helps create a level playing field, where the production of secondary materials becomes cheaper or has comparable to primary materials, leading to a shift towards the production of secondary materials.

A tax on primary raw materials would set market-based incentives to increase resource efficiency, reduce the demand for primary raw materials, and simultaneously increase the demand for secondary raw materials. The tax base could include both quantity and value as well as ecological relevance – for example, a primary raw material tax could be extended to all raw materials using indicators such as the ecological backpack[2] to prevent unwanted substitution effects. Currently, such taxes are mainly discussed for raw materials that are not profitable to transport over long distances such as construction materials and, therefore, are subject to less international competition.

CO_2 pricing mechanisms such as taxes or emission trading systems are currently being discussed or have already been implemented in some countries, particularly in the context of promoting renewable energy or increasing energy efficiency. However, they can also promote the circular economy if recycled materials with lower carbon intensity are financially favoured over primary raw materials.

Effectiveness

Imposing taxes on both virgin materials and CO_2 emissions presents a promising avenue to enhance resource efficiency and foster the transition towards a circular economy. The effectiveness of such dual taxation strategies hinges on various factors. In the case of a virgin

[2] The Ecological Backpack measures the net weight of materials used in a product or service, excluding the product's actual weight. It assesses hidden material flows and reflects environmental impact and resource efficiency through a life cycle approach.

material tax, its impact is closely linked to the level of taxation.

Similarly, the potential effectiveness of a CO_2 tax depends upon the carbon price. This tax could render recycling processes for secondary raw materials financially viable, which might otherwise remain uneconomical. However, elevated energy costs within recycling processes might prompt shifts towards alternatives, such as plastics, if their production demonstrates lower carbon intensity when contrasted with materials like metals.

Technological readiness

The actual influence of a virgin material tax on resource efficiency depends on the successful substitution of taxed primary materials with secondary alternatives. In the absence of such a shift, the tax might solely generate revenue without achieving the intended steering effect towards sustainability.

In parallel, a CO_2 tax poses methodological difficulties in attributing CO_2 savings throughout the value chain. This complexity leads to varying tax burdens for products based on their design's compatibility with recycling and emissions reduction. Resolving this issue is important, as it can impact the equitable distribution of tax incentives for early market entrants.

Feasibility

The feasibility of implementing combined taxes on virgin materials and CO_2 emissions requires careful consideration of practical challenges. With regard to a virgin material tax, complications emerge, particularly concerning import considerations to prevent market distortions. Limited information on the raw material content of imports raises questions about effective tax administration and the formulation of exemptions.

A CO_2 tax also necessitates comprehensive and accurate data on the carbon footprints of products across various production stages. Furthermore, to uphold the competitiveness of domestic industries, the tax should encompass imported products as well. These challenges highlight the need for robust data infrastructure and meticulous tax design to ensure the viability of such combined taxation strategies.

Chinese context

China introduced an ETS (Emissions Trading System) in 2020. It would be appropriate to consider implementing taxation through the ETS system. For instance, industries such as steel, cement, aluminium, and others could be fully integrated into the system. The same applies to waste incineration. It should be ensured that a return to landfilling is excluded and additional incentives for recycling are in place.

8.1.2 Promotion of new technologies that allow reuse through higher purities

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Recycle, Reduce	●●●○○	●●○○○	●●○○○

Controlling the purity of steel is a prerequisite for high-quality recycling. The necessary technologies to remove further impurities from steel are still lacking. It is essential to consider promoting such technologies in conjunction with other measures, such as appropriate product design.

To avoid downcycling, optimized processes can be employed even for established recycling systems such as glass, aluminium, and steel, focusing particularly on the pre-sorting and preparation of input streams. For this purpose, techniques like laser-induced plasma spectroscopy or X-ray fluorescence methods could be utilized. Ecologically, it should be considered that such highly complex sorting processes may also involve energy inputs that need to be assessed.

Effectiveness

By removing impurities and pollutants, secondary raw materials suitable for higher-value applications can be produced. However, it should be considered that for steel alone, there are over 2,500 quality classifications, making it challenging to fully assess the effects.

Technological readiness

For "alloy-specific recycling," various technologies exist, but often they do not yet allow for the necessary mass throughput or are associated with high costs, which make them economically viable only for very specific material streams.

Feasibility

The evaluation of such processes, for example, within the framework of the "OptiMet" project, has shown that currently applied sensor-based sorting processes are only economically viable for particle sizes >10 mm. However, in the recycling sector, the focus often lies on complex particles that are not yet liberated or separated into different materials at this size range (e.g., metal/plastic composites).

Chinese context

For China, this approach is recommended, but it should be initially assigned a lower priority. Given the current production volumes, the focus should be on establishing the necessary infrastructure and designing products to be circular as soon as possible. In certain areas, it may be beneficial to establish targeted recycling facilities to prevent contamination from other sectors when mixing scrap. An example of this is automotive bodies.

8.1.3 Extended Producer Responsibility

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Recycle, Redesign	●●●●○	●●●●○	●●●○○

Extended Producer Responsibility (EPR) is an instrument in which the responsibility for the entire lifecycle of a product is transferred to the producers, i.e., manufacturers, importers, or brand owners. This means that manufacturers must take financial and/or physical responsibility for the collection, recycling, and disposal of their products. This is intended to create incentives for adjusting product design and investing in appropriate infrastructures. In some cases, Producer Responsibility Organizations (PROs) take on the responsibility on behalf of multiple manufacturers.

At the product level, extended producer responsibility also influences upstream value chains. For instance, manufacturers benefit from recycling-friendly product design as it reduces recycling costs at the end-of-life of a product. Additionally, consumers become more aware and informed. Moreover, the establishment of take-back systems and, if applicable, a PRO would create new job opportunities.

Effectiveness

Existing EPR systems demonstrate the generally high effectiveness of this measure and show a successful transfer of disposal costs from taxpayers to manufacturers. For instance, the introduction of the dual system, which governs the extended producer responsibility for German packaging manufacturers, has increased recycling rates of packaging waste in Germany.

Technological readiness

Since many materials already have established recycling infrastructures and technologies, the introduction of an EPR system for these products does not present a technical challenge. However, some collection and sorting technologies may need to be made more efficient to handle the increasing volume of recycled products.

Feasibility

Challenges include establishing a take-back and recycling infrastructure, as well as dealing with free-riders who do not invest in the system but still benefit from it. Additionally, it must be ensured that small and medium-sized enterprises (SMEs) are not disadvantaged by the introduction.

Chinese context

Especially for state-owned enterprises, such a system could be established in China, as it could be quickly implemented from a regulatory perspective. An authority could take on the collection, sorting, and other aspects on behalf of the companies.

Best Practice: EPR Systems in France

In all French EPR systems, the distributors must organise and/or finance the recovery and disposal of their products at the end of their life cycle. Producers can basically decide whether they want to set up their own take-back systems or use a collective system in which they take over the producer obligations. Distributors pay fees to the PROs, which are then used to organise the take-back infrastructure. Two systems exist in France: In the case of organisational systems, the PRO is directly responsible for waste treatment, while in the case of financial systems, it uses the collected fees to support the cities/municipalities, which take care of the final waste treatment. The PROs have to be re-approved by the authorities every six years, but once approved they can carry out their operational activities independently. Through an inclusive governance model, all stakeholders (including NGOs and consumer organisations) have the opportunity to decide on the design and objectives of the EPR system.

In 2021, the mandatory EPR systems raised about 1.8 billion € in eco-contributions, of which about 1.5 billion € was used for waste treatment (of which 830 million € via the municipalities and 738 million € via the PROs) and 403 million € for other expenditures (e.g. awareness-raising measures or research and development). As a result, a recycling rate of more than 50% was achieved across all waste types

8.2 Creating demand

8.2.1 Recyclate quotas – minimum quotas for the use of recyclates in specific products

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Recycle, Reduce	●●●●○	●●●○○	●●○○○

The sufficient provision of high-quality recyclates is a hurdle to establishing a recycling infrastructure and ensuring that recycling does not result in downcycling. German and the EU's experiences suggest that the introduction of recycling quotas should be accompanied by recyclate quotas to prevent the use of recyclates for products of inferior quality.

Minimum recycling quotas oblige manufacturers to use a certain proportion of recyclates in their products. Recyclate quotas, on the other hand, directly replace primary raw materials in the original product and no downcycling takes place. It is important to note, however, that differentiation is necessary for the products, as the requirements and the corresponding availability of the recyclates are different.

By mandating a specific percentage of recyclate content, the demand for high-quality recycled materials and properly sorted plastic waste is increased, thus providing incentives for more recycling-friendly product design in the medium term. Recyclate quotas could be product-specific, or also material-specific, e.g. for certain polymers. Polymer-specific minimum recyclate quota would not target manufacturers but rather the plastic producers earlier in the value chain. They would be obligated to guarantee a certain recyclate content in the volume of a specific polymer (e.g., PET, PP, or ABS) sold in the market. This instrument could either replace or complement product-specific minimum recycled content requirements. Polymer-specific substitution quotas would lead to a significant scaling-up of recycling – requiring substantial initial investments, but likely resulting in cost savings in the long run through economies of scale.

Effectiveness

Such an instrument would have a high effectiveness, as it leverages a significant mechanism for closing the material loop of plastic waste. This would automatically lead to increasing volumes of plastic waste that need to be effectively recycled, creating strong incentives for plastic manufacturers to invest in circular business models to secure access to plastic waste.

Technological readiness

The technological availability is generally given, but sufficient treatment capacities may not be currently available. Additionally, it would be necessary to assess which recycled content levels are technically feasible for different application areas.

Feasibility

Similar to minimum recycled content quotas for individual products, achieving polymer-specific quotas is a challenge. Using mass balance approaches, companies must meet quotas over time, not per batch. This streamlines compliance monitoring, as 20 companies cover 80% of the global plastics market. International agreement, like in the Global Plastics Treaty under negotiation, is essential for example.

Chinese Context

In the Chinese context, the implementation of quotas appears more suitable than financial incentives due to the stronger state-oriented system.

Minimum Recyclate Quota in PET Bottles (EU)

The central example of success for the implementation of a minimum recycling quota is the 25% share of plastic recyclate in plastic beverage bottles set by the European Commission. The introduction of this quota has triggered massive investments along the entire value chain, which pay off on the recycling of plastics through various impact mechanisms:

With the introduction of such an obligation, numerous EU member states have started to prepare the introduction of deposit systems for plastic bottles. In order to be able to successfully meet the quotas, the collection of the material in as pure a form as possible is a central condition, which can be implemented very successfully, especially via deposit and separate return systems.

The scarce supply of high-quality rPET compared to the demand it creates has led to a massive price increase for freely tradable quantities. For the companies, this was associated with a high incentive to integrate the value chain, e.g. by setting up their own take-back systems and recycling capacities or by buying up corresponding companies (example Black Group and PreZero). This would open up completely new business models, for example, to save costs by improving the recyclability of their own products.

The obligatory introduction of a minimum recycled content was connected with the clear signal to consumers that the use of recycled plastic does not represent an inferior quality for cost reduction (which was then also often connected with a lower willingness to pay). Instead, this triggered a competition between the major brands to see who could offer the highest recycled content and thus present themselves as the "most environmentally friendly" bottle.

8.2.2 Promoting circular technologies through Public Procurement

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Reduce, Recycle, Remanufacture, Reuse	●●●●○	●●●○○	●●○○○

A significant challenge for recycled products, particularly for plastics, is the lack of demand, hindering the establishment of recycling infrastructure, among other things. Accordingly, one approach is to generate demand for recycled products through public procurement.

In most economies, the public sector accounts for a significant portion of the market demand for goods: For Germany, the total share of public procurement within the GDP is estimated to be around 15%. The instrument of circular procurement aims to integrate criteria such as the recycled content, recyclability, or reparability into public tenders. This is intended to create a reliable demand for circular products, which will then trigger private investments either in R&D for such products or in new production capacities.

A central approach for environmentally friendly public procurement is reliable systems for determining the total costs over the lifecycle ("life cycle costing"), which are becoming increasingly important. In cases where public procurement also succeeds in focusing more on used or repairable products, positive employment effects are associated with it.

Effectiveness

The effectiveness is high – numerous examples demonstrate that companies quickly adapt to such requirements and include products/services in their portfolio that meet the corresponding criteria (for example, more durable electronic products).

Technological readiness

The technological availability needs to be considered differently: The structures of public procurement are established, and the integration of additional criteria does not present a particular challenge. However, in practice, there is often a lack of specific technical descriptions of such criteria which prevents a legally secure implementation: a concrete example of this is the repairability of products, for which a standardized assessment basis for public procurers does not usually exist.

Feasibility

The greatest challenges are seen with regard to implementation. The German Circular Economy Act regulates that in principle the public sector should only purchase linear products when additional costs are economically unreasonable. However, there is a lack of monitoring to assess whether and how this requirement is being implemented, and especially a mechanism for recourse.

Chinese Context

In the Chinese context, this measure can particularly help create demand in the economy, especially with the appropriate availability of secondary materials. Introducing this approach can be suitable, especially for products like recycled concrete or clinker reduced concrete, which face scepticism in the industry but could be used in large quantities in public procurement.

8.3 Circular Design

8.3.1 Eco-Design Directive

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Recycle, Reduce, Rethink, Repair, Reuse	●●●●●	●●○○○	●●○○○

Eco-design regulations enable products to be designed with circularity in mind, thus allowing for reuse, repair, and effective recycling. The potential for recycling is often limited by the design of the product and accompanying additives.

Effectiveness

The effectiveness is high since eco-design regulations target the beginning of the value chain and can exhibit a significant impact on the circularity of a product. Product designs facilitating disassembly and separation of individual materials lead to efficient and cost-effective recycling processes. Additionally, legally mandated requirements for reparability extend the lifespan of a product, delaying the need for relatively complex recycling processes. Furthermore, these requirements enable other R-strategies: easy disassembly promotes not only recycling but also refurbishment, and durable products or components are better suited for reuse.

Technological readiness

The technological availability depends on the specific requirements set out in the directive. Nevertheless, some product examples demonstrate that adapting the design for better circularity (e.g., producing a functional jacket from a single polymer) and enabling repairability (e.g., Fairphone) are already feasible.

Feasibility

The requirements necessitate a rethinking of products and infrastructures. Given that structural changes take time and require continuous implementation, this should be seen as a long-term measure. Challenges may also arise due to certain trade-offs (e.g., high-quality and durable materials vs. energy-efficient manufacturing).

Chinese context

Eco-design regulations can be of significant relevance for China due to its current primary production of steel, cement, and plastics. If a circular design is pursued in the next few years, it could considerably simplify the transition to a circular economy in 20 to 30 years, leading to various advantages such as energy savings, among others.

8.3.2 Legal requirements that prioritize reuse of existing buildings over demolition and new construction

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Reduce, Reuse, Rethink	●●●●○	●●●●○	●●○○○

Demolition and new construction of buildings can lead to an increase in energy efficiency in use; however, the "grey energy" required for the production of construction raw materials is often not taken into account.

Effectiveness

Extending the life of buildings through targeted renovation or reuse for different purposes can lead to significant savings in resources and greenhouse gas emissions. Due to the increasing use of renewable energy for heat generation in the use phase of a building, the relevance of "grey energy" increases when considering emissions over the entire life cycle.

Technological readiness

The technical feasibility strongly depends on the concrete building fabric. Lifetime extensions need to be carefully assessed taking into account the structural durability.

Feasibility

Incentives for a stronger focus on renovation can be set via different instruments, e.g. via urban land use planning, requirements for the preparation of dismantling concepts or the adaptation of funding instruments to increase energy efficiency.

Chinese Context

The extension of building life spans could be an effective lever particularly for China since average lifespans of buildings are as short as 25–30 years and demolition rates are very high, resulting in vast amounts of construction waste and resource use.

8.4 Developing a suitable infrastructure

8.4.1 Recycling quotas

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Recycle	●●●○○	●●●○○	●●●○○

A significant challenge in increasing recycling is ensuring a consistent demand and providing confidence to companies that appropriate recycling infrastructure is established. Clear quotas can serve as guidelines and provide assurance for the recycling infrastructure, thus ensuring a steady market with a secured demand for recycled materials.

Mandatory recycling quotas specify how much of a material is to be recycled annually by the respective systems. The quotas aim, among other things, to increase the recycling rates of the materials concerned (e.g. ferrous metals, aluminium or glass), to ensure more efficient use of resources and to minimise dependence on the production of new materials. The quotas can also set benchmarks for resource-efficient material recycling. Some recycling quotas have already been set in the EU: For example, a recycling quota of 80% for ferrous metals and 60% for aluminium is targeted in the long term. As a rule, however, such quotas refer to products, not to individual materials (example: packaging waste or waste electrical equipment).

Mandatory recycling rates can have an impact on the upstream stages of the value chain (collection and sorting, product design), e.g. recycling-friendly product design and efficient separate collection have a positive impact on the recycling process. Mandatory recycling quotas can also promote circular business models where companies retain ownership of their products and thus have secure access to recyclable material. The expansion of recycling infrastructures could also create new jobs.

Effectiveness

The effectiveness of this measure depends on the level of recycling quotas: higher recycling quotas will lead to more effective recycling.

Technological readiness

For some materials, efficient recycling technologies already exist (e.g. steel), which guarantee a largely consistent quality, while for others there is often still a loss of quality (e.g. plastics). For this reason, it is important that recycling rates are set realistically for the respective materials. Further, the recyclability of many materials is already given, but the economic efficiency sometimes leads to restrictions in the implementation.

Feasibility

The introduction of mandatory recycling quotas should take place in close consultation with industry experts in order to assess their feasibility. In addition, investments in infrastructures and technologies are needed in advance to establish and develop suitable infrastructures. To minimise this challenge, continuously increasing quotas are an option.

Chinese context

In China, recycling rates in various sectors, such as glass and aluminium, are still significantly below the global average. Mandatory recycling rates could therefore advance the development of appropriate recycling infrastructures.

8.4.2 Obligation for reusable systems

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Reduce, Reuse	●●●○○	●●●○○	●●○○○

Currently, especially packaging and everyday consumable products are often used only once. This mainly applies to plastic, but also to aluminium, glass, and paper products. To increase circularity, it is of great interest to keep these products in circulation for a longer time by using reusable products. An obligation for reusable systems lead to a significant reduction in waste generated by single-use products. For instance, since 2023, Germany has implemented the mandatory use of reusable containers for take-away service for restaurants of a certain size. Deposit amounts on these containers create incentives to return them to the recycling system.

The development of new infrastructures for the collection, cleaning, sorting and distribution of reusable systems will create a demand for more skilled workers, leading to the creation of new job opportunities. Additionally, the demand for input materials will shift: for instance, ceramic or glass may be used for the respective reusable solutions instead of plastic. However, it is essential to consider that shifts to other, less sustainable materials could also occur, such as increased use of aluminium foil.

Effectiveness

Reusable systems can prevent waste generation and continuous resource extraction. However, for each product to be integrated into reusable systems, lifecycle assessments should be carried out since reusable systems may cause certain environmental impacts in other areas. For example, the production of reusable products is often associated with higher energy and raw material requirements, and the cleaning of these products results in higher water consumption compared to single-use solutions.

Technological readiness

While several deposit and return schemes with reusable solutions already exist, necessary infrastructures are often not available at all companies. Especially small and medium enterprises might face challenges implementing reusable systems by facing additional costs for the products and cleaning devices or services.

Feasibility

Challenges in implementing reusable systems include determining an appropriate deposit amount and addressing consumer acceptance aspects, such as the availability of return options. Not every company may have the capacity to adopt a reusable system.

Chinese Context

The implementation of quotas in China is feasible and a requirement should ensure that the products are available in sufficient quantity. A gradual ramp-up for deposit and return schemes could be helpful in this regard.

8.4.3 Bonus malus regulations for the recyclability of plastic products

R-Strategy	Effectiveness	Technological Readiness	Feasibility
Recycle, Rethink	●●●○○	●●●○○	●●●○○

One option to reduce non-recyclable products is to incentivize companies to design products accordingly through penalties and rewards. However, this approach requires a suitable recycling infrastructure. Within the framework of extended producer responsibility systems, product manufacturers typically pay licence fees based on the number and/or weight of their products. For packaging, material-specific licence fees are usually calculated, such as different fees for plastic packaging or packaging made from metal. Ecologically differentiated licence fees could also take into account the recyclability of the packaging.

Effectiveness

The effectiveness of such systems depends on the economic incentives or penalties. One possible side effect of bonus-malus systems is a focus on the recyclability of disposable products, which could undermine aspects of waste reduction or the promotion of reusable systems.

Technological readiness

An adequate and robust collection and recycling infrastructure is crucial for the effectiveness of the bonus-malus mechanism. Without a well-developed and efficient recycling infrastructure, potentially recyclable products would not yield real benefits and would not be effectively recycled.

Feasibility

The central requirement for feasibility is a universally accepted evaluation criterion for the recyclability of products. Building upon this, it requires actors such as the Central Packaging Agency to actually implement such a system of bonuses and penalties in a mandatory manner. The example of the Packaging Act in Germany shows that such a system does not develop solely through market forces.

Chinese context

As the recycling infrastructure is necessary for such a system, a bonus-malus system would be more appropriate as a complementary measure at a later stage.

Conclusion

The primary objective of this report was to provide a comprehensive overview of the current state of circular economy practices in Germany and China. Additionally, the report aimed to evaluate the challenges associated with implementing circular economy measures and to present technical and regulatory approaches to address these challenges. Furthermore, the report assessed the potential for energy savings and greenhouse gas (GHG) mitigation within the context of circular economy practices.

Key findings from the report underscored the substantial contributions of circular economy practices to energy savings and GHG emissions reduction. Notably, recycling processes for materials such as steel, aluminium, glass, and paper demonstrated significant energy savings compared to primary production methods.

However, the findings show that not every material can be recycled and not all forms of recycling reduce the energy needed for the production processes. This particularly applies to the recycling of concrete: although pivotal for waste reduction, it yields comparatively modest energy savings. Instead, a distinctive avenue emerges in the form of material efficiency strategies: the significance here lies not only in energy savings, but also in resource conservation.

Chinese Context

In the context of China, although development is still at an early stage compared to European developments in circular economy policies, the nation is showing a growing commitment to transitioning to a more circular and resource-efficient society. A crucial factor impacting the emission savings potential within several material streams build the CO_2-intensity of the electricity mix used for recycling processes. This holds particular significance in the Chinese context, given the prevalent utilization of coal-based electricity generation. This circumstance offers a substantial opportunity for the reduction of emissions.

However, certain challenges unique to China, such as limited scrap steel accumulation and elevated processing costs for scrap steel, pose hurdles to circular practices, particularly in energy-intensive industries like steel production. In terms of cement and concrete, China expects demand reduction to be the main driver of the decarbonisation of the cement and concrete industry. Especially through the slowdown of urbanization and infrastructure build-out. As urbanization and the demand for housing are expected to drop in the long run, the scale of new housing development will decline. While China still needs to improve the quality of its infrastructure, the scale of infrastructure construction is gradually diminishing. With the slowdown in construction sectors including housing, roads, and railways, a decline in cement demand will be inevitable. Even though Chinas demand for concrete is declining, it still accounts for most of the world's cement production and consumption. The potentials to reduce cement use through material efficiency measures therefore are still significant.

Regarding circular solutions for plastics, the focus is shifting to resource utilisation pathways, and the entire waste resource industry - encompassing physical and chemical recycling of plastics – is projected to enter a rapid growth phase. Both physical and chemical recycling methods are anticipated to witness an increase in the tens of millions of tonnes, with chemical recycling potentially becoming a more prominent approach to green plastic development. It is worth noting that these projections are subject to various factors and uncertainties. Furthermore, there is an anticipation that China's plastic recovery rate could reach 45 - 50% by 2030. However, it is important to consider that achieving this target will require concerted efforts and effective implementation of recycling initiatives.

German Context

Germany has achieved high recycling rates for a range of materials. Regarding secondary steel production, recycling rates of over 90% have been achieved for tinplate packaging while around 88% of steel parts in construction are recycled, with an additional 11% being reused.

Regarding cement and concrete, material efficiency has a marginal role to play within regulations of the building sector in Germany or Europe. The current European regulation aligns with the policy targets of promoting and enhancing material efficiency and overall resource efficiency. However, unlike energy performance which is governed by European Directives, material efficiency is relatively unregulated.

In the context of circular solutions for plastics through recycling, it can be concluded that the treatment of post-consumer plastics waste in Germany has undergone significant evolution in recent years. Analysis of the data showed that recycling played a substantial role, accounting for 42% of the overall post-consumer plastics waste treatment in Germany in 2020. Furthermore, 57% of the post-consumer plastics waste in Germany underwent energy recovery processes in 2020. Landfilling constituted only 1% of the total post-consumer plastics waste treatment in Germany.

Recommendations

In the context of policy recommendations within the EnTrans Project, the report proposed measures to reduce economic disparities between primary and secondary materials, stimulate demand for secondary materials, promote circular design, and develop recycling infrastructures. These measures encompassed various stages of the value chain and employed diverse instruments, from informational approaches to market-based and regulatory interventions. However, despite the wealth of strategies and instruments, the report acknowledged the need for accelerated implementation to advanced low carbon transitions of energy intensive industries.

The instruments presented here show that the transformation to the Circular economy can be supported in very different ways – there is no lack of ideas or concrete proposals. The instruments identified in the context of EnTrans can be applied at very different stages of the value chain and also make use of very different types of instruments – from purely informational instruments (especially if the relevant actors should actually have sufficient financial incentives for implementation) to market-based or regulatory market interventions. These are discussed in particular where circular approaches would actually be preferable from an economic point of view (e.g. with regard to climate protection potentials or jobs) – but this is not reflected in the individual incentive structures for individual actors. The reasons for this vary and include, for example, insufficiently internalised environmental costs (especially for raw materials that are imported from abroad), market distortions due to environmentally harmful subsidies (e.g. in the case of tax exemptions for the use of petroleum for plastics production) or prohibitively high transaction costs, e.g. when proving material qualities for secondary raw materials.

While there is no lack of possible strategies and instruments, the reality is that the speed of implementation is clearly too slow. A recent report by the European Court of Auditors states: "On the positive side, Member State governments have stepped up their circular economy activities since the publication of the first Action Plan. However, progress remains slow. The EU's target of doubling the share of materials recycled and reintroduced into the economy by 2030 remains a major challenge." For Germany in particular, this target would require a fourfold increase in the speed of transformation – despite an actually very good starting position. This would require not only more consistent policy-making, but also more ambitious implementation, which would have to be backed by corresponding budgets. The transformation to a circular economy will not be achieved by government action alone; this will require a significant shift in private investment – for this to happen, however, R&D programmes and public sector investments in particular would have to be geared much more strongly towards the circular economy.

The report provides an overview of selected possible approaches and their strengths and weaknesses – but the challenge of prioritising measures remains. Many actors, especially in the business community, feel overwhelmed by the many options for action when it comes to selecting the right starting points. For such a prioritisation and, if necessary, quantified evaluation of instruments, the instruments would have to be made much more concrete (e.g. taxes – how high should the tax be, how is the tax implemented in law, for what is the collected tax revenue ultimately used?) Such modelling is to be carried out as part of the scientific research accompanying the development of the national circular economy strategy, but would have overstretched the limits of budget and schedule here. The assessments made are therefore to be understood as a rough orientation and should provide the basis for more detailed discussions.

The report acknowledges the complexities of prioritizing measures and emphasized the necessity of making instruments more concrete and quantifiable. While it provided a broad orientation for discussions, the report recognized the need for more detailed analysis and modelling, particularly in the context of the development of a national circular economy strategy.

In conclusion, the report identified the growing interest in circular economy practices in Germany, the EU, and China. It highlighted the challenges associated with achieving high-quality circularity, including impurities in material streams, insufficient sorting and recycling infrastructures, and imbalances between primary and secondary material availability. The report underscored the importance of continued research and policy development to address these challenges and further advance circular economy practices.

Abbreviations

CCU/S	*Carbon Capture Use and / or Storage*
CE	*Circular Economy*
CEAP	*Circular economy Action Plan*
CEPL	*Circular Economy Promotion Law*
CISA	*China Iron and Steel Association*
CMU	*Circular Material Use Rate*
CPR	*Construction Product Regulation*
DRI	*Direct Reduced Iron*
DRI-H_2	*Direct reduction of iron with hydrogen*
EAF	*Electric Arc Furnace*
EEA	*European Environment Agency*
EPR	*Extended Producer Responsibility*
ETS	*Emissions Trading System*
EU	*European Union*
EuRIC	*European Recycling Industries Confederation, Siehe*
fa	*fly ash*
ggbfs	*ground granulated blast furnace slag, Siehe*
GHG	*Greenhouse Gas*
Gt	*Billion tonnes*
IEA	*International Energy Agency*
kt	*kilotonnes*
LCA	*Life Cycle Assessment*
MSW	*Municipal Solid Waste*
Mt	*Million tonnes*
NABU	*Naturschutzbund*
NDRC	*National Development and Reform Commission*
OPC	*Ordinary Portland cement*
PCR	*Post-consumer recycled material*

PE	*Primary Energy*
PET	*Polyethylene terephthalate, Polyethylen*
PHA	*Polyhydroxyalkanoates*
PLA	*Polyactic acid*
PP	*Polypropylen*
PROs	*Producer Responsibility Organizations*
SCMs	*supplementary cementitious materials*
SDGs	*Sustainable Development Goals*
SMEs	*Small and medium-sized enterprises*
SRM	*Secondary raw material*
UNEP	*United Nation Environment Programme*

List of figures

Figure 1: The role of ressource efficiency on the path to carbon neutrality. Source: dena 7

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