TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT,
CARBON-NEUTRAL CIRCULAR EUROPEAN
INDUSTRY

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D3.3 – Conceptualisation of CE and policy mapping

WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This report will form the basis of the TRANSIENCE Policy Matrix; it will thus be disseminated through several routes: 1) it will be uploaded to the TRANSIENCE website; 2) a link to the report will be shared in the project's social media accounts; 3) highlights from the report will be condensed in a short LinkedIn article; 4) the report will be transformed into 1-2 peer review academic publications; while 5) findings from the paper(s) will be presented at the TRANSIENCE stakeholder engagement events. Therefore, the report's target audience includes policymakers, academics, and industrial organisations looking for a systematic review of circular economy opportunities.

3. Short summary of results (<250 words)

This report sets to analyse the current policy landscape for circular economy (CE) and decarbonisation in the EU. It departs from an analysis of key policy documents that set the basis for the EU climate and CE agendas, before then focusing on three key sectors as representative of energy- and material-intensive sectors: cement, steel, and plastics. These sectors form the basis for other key sectors in the EU economy, such as automotive, buildings and construction, electronics, packaging, and textiles. For each of these sectors, the report identifies key CE strategies using the framework of slowing, narrowing, closing, and regenerating resource flows as a classificatory axis. Our review considers, for each of the CE strategies proposed, potential synergies and trade-offs between CE and decarbonisation and challenges for current implementation of the CE strategies. Based on the analysis of CE interventions, the report summarises critical gaps in the current CE landscape to then propose, in Section 5, a consistent policy mix from a lifecycle perspective, which emphasises the need of working across value chains and sectors and embedding CE principles and the broad range of CE strategies along the different stages of the lifecycle of materials and products.

4. Evidence of accomplishment

This report.

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is growingly gaining attention in the policy world, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – Fundacion Tecnalia Research & Innovation	ES
UU – Universiteit Utrecht	NL
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE
PSI – Paul Scherrer Institut	CH
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Executive Summary

This report sets to analyse the current policy landscape for circular economy (CE) and decarbonisation in the EU. It departs from an analysis of key policy documents that set the basis for the EU climate and CE agendas, before then focusing on three key sectors as representative of energy- and material-intensive sectors: cement, steel, and plastics. These sectors form the basis for other key sectors in the EU economy, such as automotive, buildings and construction, electronics, packaging, and textiles. For each of these sectors, the report identifies key CE strategies using the framework of slowing, narrowing, closing, and regenerating resource flows as a classificatory axis.

For steel, key untapped opportunities relate to the tighter loops of CE. While steel is a robust and long-lasting material with a well-developed secondary market for scrap, opportunities for slowing and narrowing the loops are largely unexplored and underrepresented in policy actions. Reuse of structural elements is only starting to emerge and is phased with economic and regulatory barriers that reduce widespread adoptions. Strategies for lightweighting materials, building for adaptability, standardisation of structural elements, and actions targeted at demand reduction remain niche.

The cement sector shares some of the barriers to circularity practices listed above. Most of the regulatory and industrial interventions have concentrated in closing the loop of cement and concrete, generally through downcycling, or using waste and by-products as alternative fuels and alternative raw materials. While co-processing initiatives are certainly a way to increase circularity in the sector, more attention should be drawn to the reuse of concrete panels and life extension of concrete cements. Advances in self-healing concretes, use of Alternative Cementitious Materials and clinker replacements in concrete, and design of buildings and infrastructures for adaptability and reparability need to be better reflected in building regulations, to accelerate the uptake of circular strategies.

For plastics, finally, most policy and public attention has been drawn to plastic packaging which represents around 40% of all plastics. However, use of plastics in other sectors, especially as part of complex products, is largely unexplored and underregulated. While opportunities of closing the loop through better segregation and high-quality recycling are becoming more widespread, effectiveness to address reuse and reduction through regulatory actions is still largely unresearched. There is a need to draw further attention to widespread use of plastics across different sectors, to use composite materials, and to adopt a lifecycle approach when evaluating the advantages and disadvantages of using plastics as substitutes of other materials.

Our review has also identified potential synergies and trade-offs between CE and decarbonisation and challenges for current implementation of the CE strategies. Based on the analysis of CE interventions, the report summarises some key gaps in the current CE landscape to then propose a consistent policy mix from a lifecycle perspective, which emphasises the need of working across value chains and sectors and embedding CE principles and the broad range of CE strategies along the different stages of the life cycle of materials and products.

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1 Introduction

The concept of the Circular Economy (CE) is not entirely new. Its theoretical foundations date back to the work of Boulding (1966) and the concept *spaceship Earth,* and the later work of Pearce and Turner (1990) and emerging field of industrial ecology during the 1990s. However, the concept of the Circular Economy, especially from a policy perspective, has only gained policy momentum in recent times. The launch of the Circular Economy package in 2015 propelled CE at the core of policy making. While CE is generally seen as a complementary approach to decarbonisation, where the focus is on material resources rather than just GHG emissions, there is still important gaps in the understanding of the synergistic or opposing effects of both transitions. In fact, both CE and decarbonisation have evolved distinctively as they are nested in distinct scientific fields. In the policy realms, CE and decarbonisation agendas have evolved as separate policy fields, although more attempts have been done recently to bring them as part of the green deal and green transformation agenda.

In the CE policy context, the CE is defined in the following way (EC, 2024):

'In a circular economy, the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized. (…) By using and consuming in a more circular way, we can substantially reduce the impacts of human economic activities on the environment, including on biodiversity."

In the literature, the number of definitions of the concept have substantially increased with the widespread use of the concept. Ghisellini et al. (2015) identified over 100 different definitions. This led some scholars to highlight risks associated with the overuse of the concept and limitations of narrow approaches that in the practice have equated circularity with some form of improved waste management (Ghisellini et al. (2015) and Potting et al. (2017). Some of the critiques of the concept emphasise the lack of consensus about what circularity means for different stakeholders in different contexts and how some examples of application of the concept may undermine the component of systemic disruption that Circular Economy entails. As Ghisellini et al. (2015) puts it, the CE must detach itself of the label of 'more of the same' to introduce a truly innovative and disruptive element of changing the way socio-economic systems interact with natural systems, moving from an extractive and exploitative view to one that is synergistic and regenerative. The idea is that the CE requires a system transformation that radically alters the way human societies interact with natural supporting systems aiming at applying a regenerative lens to production and consumption systems which consider the life cycle interactions between natural and industrial systems.

The EU was among the early adopters of Circular Economy in the policy agenda after China, which launched its Circular Economy Law in 2008. Mirroring this discussion in the policy area, the interpretation of CE and the ambitiousness of CE policy goals and objectives varies considerably across global regions, and within the EU, MSs and within them different levels of policy making (local, regional and national). More conventional approaches still place significant emphasis on recycling, while targets and ambitions related to reduce and reuse loops are only now starting to get more policy recognition. The approaches which offer a more holistic understanding of the need for completely transform current practices of production and consumption are still largely missing from the policy development, although some of the latest policy actions have tried to advance in this direction such as the changes to product policies and inclusion of circularity principles in the design of products and solutions. The new family of ISO standards, with three new standards for the Circular Economy launched in 2024 have also helped to build consensus about the key concepts of Circular Economy (ISO 59004), guidance on the transition of business models and value networks (ISO 59010) and measuring and assessing circularity performance (ISO 59020). In ISO 59004 the circular economy is defined as

'an economic system Economic system that adopts a systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value, while contributing to Sustainable Development'

The aim of this analysis is to provide an overview of the policy landscape for decarbonisation and Circular Economy. We do this through the lenses of the three core focus sectors selected in TRANSIENCE: cement, steel and plastics. All three sectors are representative of high energy and material intense sector where the potential for Circular Economy and decarbonisation is highest, but they also face important challenges to achieve net zero and apply a broad range of CE measures beyond conventional recycling practices.

The analysis aims to shed light on the full spectrum of CE interventions and the linkage to decarbonisation efforts, highlighting both synergistic effects but also potential trade-offs. The analysis includes an overview of existing policy mechanisms but adopts predominantly a prospective perspective identifying different types of strategies towards CE. The specific policy instruments and policy instruments to promote CE practices across sectors is complex and beyond the scope of this deliverable, but some more general policy guidelines are provided as areas of future policy development.

2 Policy landscape of decarbonisation and CE in Europe

2.1 The EU's circular economy policy landscape

In 2015, the European Commission launched the Circular Economy (CE) package, placing CE at the core of EU policy. It was then followed by a second CE package and Action plan in March 2020 (see more details below). The latter initiative is integral to the European Green Deal adopted in 2020, reflecting the EU's commitment to sustainability and resource efficiency. The circular economy concept underpins this transition by promoting the decoupling of resource consumption from economic growth. More recently the CE has been a key element of the EU's effort to reduce raw material dependence as shown by the 2024 Critical Raw Materials Act, the first EU law on raw materials.

The shift from a linear to a circular economy is essential to address the unsustainable use of resources and its environmental consequences. The prevailing linear economy, characterized by the "take-make-use-dispose" model, perpetuates a cycle of resource depletion and environmental degradation. This model exerts immense pressure on scarce natural resources, leading to significant environmental harm and biodiversity loss. By 2050, global consumption is projected to exceed the Earth's capacity. In contrast, the circular economy model offers a more sustainable alternative. The CE aims to maintain the value of products, materials, and resources within the economy for as long as possible, minimizing waste and reducing the demand on natural resources. By prioritizing resource efficiency and waste reduction, it aims to close the loop on material flows, minimizing resource extraction and waste generation. According to the EU Commission, the transition to the CE could not only alleviate pressures on natural resources but also foster sustainable growth, job creation, and support the EU's long-term climate neutrality and biodiversity goals (EC, 2024).

Current levels of circularity in Europe are very low. The current circular material use rate, calculated as the share of used material resources which came from recycled waste materials, stands at a modest 11.5% in 2022, that is around 11.5% of material resources used in the EU came from recycled sources (Eurostat, 2024). While between 2010 and 2022 there has been an upward trend from 10.7% to 11.5%, the circularity rate is low and growing slowly despite policy attention. However, there were important disparities between MSs and some achieved a much higher rate such as the Netherlands (27.5%), Belgium (22.2%) and France (19.3%), all three with ambitious CE agendas. At the global level, circularity levels are also low and declining, from 9.1% in 2018 to 7.2% in 2023. According to the Circularity Gap report (2023).

The CE not only plays a critical role in enhancing resource efficiency and waste reduction but also plays a crucial role in decarbonisation by minimizing greenhouse gas emissions associated with resource extraction and waste management. Around 50% of GHG emissions are linked to the way we produce and consume resources. The environmental impact of the linear economy is evident in various fields. Studies indicate that 90% of biodiversity loss may be attributed to primary resource extraction and processing activities (IRP, 2019). Furthermore, a large part of the product's environmental footprint and potential for circularity and recovery at the end of life may be determined at early stages of the design phase, underscoring the importance of adopting circular principles early in the product lifecycle but also systemically across sectors of the economy.

To address some of these issues and to accelerate the CE transition, the European Union launched in 2015 the first Circular Economy Action Plan (CEAP) followed by a new CEAP in March 2020, as part of the broader European Green Deal initiative. The new CEAP outlines 35 actions aimed at promoting sustainable products and services, reducing waste generation, and empowering relevant stakeholders. Key objectives include doubling the EU's circular material use rate[1] and minimizing the consumption footprint, thereby advancing the EU's commitment to sustainable development and environmental stewardship. The EU's approach emphasizes regulatory measures combined with strategic and voluntary actions to foster a comprehensive transition to a circular economy.

As part of the overview of the EU's general CE policies, this section will continue with the analyses of three main overarching EU policy initiatives, namely the European Green Deal, Fit for 55, and the EU Circular Economy Action Plan.

2.1.1 CE green deal

The European Green Deal, introduced in 2020, sets an agenda to transform the EU's economy towards net zero and sustainability. The Green Deal sets targets and pathways for Europe to become climate-neutral while ensuring a just transition. This strategy considers the interlinked nature of social, environmental, and economic dimensions. The green deal revolves around three core aims: 1) no net emissions of greenhouse gases by 2050; 2) decoupling growth from resource use and 3) ensuring an inclusive transition. This led to the EU Climate Law being approved by the EU parliament on 24 June 2021, which establish a legally binding target of 55% reduction of GHG by 2030 and achievement of climate neutrality by 2050.

The Green Deal has a broad scope that spans areas such as energy transition, environmental protection, sustainable agriculture, efficient transport, green industry, research, innovation, finance, and regional development. Aligning with the Green deal, there are several strategies across core key areas of policy making including Fit for 55, the climate Law, EU strategy on adaptation to climate change, EU biodiversity strategy, Farm to Fork strategy, European Circular Economy Action Plan (CEAP), a Just transition mechanism, the EU chemical strategy for sustainability, Forest strategy and deforestation and other sectoral initiatives. For its relevance for the links between decarbonisation and CE, we will refer briefly to the Fit for 55 and CEAP in the next sections.

2.1.2 Fit for 55

The 'Fit for 55' strategy sets the basis for achieving the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030. The policy package aims to bring EU legislation in line with the 2030 goal through comprehensive interventions across a set of key sectors. The strategy includes the following key elements:

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[1] The EU's circular material use, referred to as the circularity rate, is the share of used material resources that come from recycled waste materials, reflecting the extent to which materials are reused within the economy (Eurostat, 2023).

Reform of the EU trading system

Emission reduction targets for transport, buildings, agriculture and waste

Reaching climate goals in land use and forestry

Promoting more sustainable transport

Adopting a **carbon border adjustment mechanism (CBAM)** as a way of creating incentives for non-EU producers to reduce emissions and address the emissions of the EU abroad. The CBAM will in principle cover 6 main sectors: iron and steel, cement, fertilisers, aluminium, hydrogen production and electricity

Increasing the uptake of greener fuels in maritime and aviation transport

Establishing emissions reduction in methane

Establishing stringent GHG emission standards for cars and vans

Revise energy taxation

Promote renewable energy and become more energy efficient

Shifting from fossil fuels to renewables in energy generation

Making buildings more energy efficient, with more stringent energy performance standards

Figure 2-1: Key elements of the 'Fit for 55' strategy

2.1.3 The first CEAP

Published in 2015, the first Circular Economy Action Plan (CEAP), was a pivotal strategic framework designed to promote the transition from a linear to a circular economic model. It comprised 54 specific actions and four legislative proposals targeting waste management, including landfill, reuse, and recycling targets for 2030 and 2035. The core strategies were organised to address the entire lifecycle of products, focusing on sustainable design, circular processes, and waste prevention, ensuring resources remain within the EU economy for as long as possible.

Key main areas adopted are summarised below:

1. **Production and Product Design**:
    - **Eco-Design Directive**: Encourage the design of durable, repairable, and recyclable products.
    - **Extended Producer Responsibility**: Hold producers accountable for the environmental impacts of their products through their lifecycle.
2. **Consumer Empowerment**:
    - **Right to Repair**: Support consumers' ability to repair products, extending product life and reducing waste.
    - **Consumer Information**: Increase transparency on product durability and repair options to help consumers make informed choices.
3. **Waste Management**:
    - **Improved Waste Regulations**: Set ambitious recycling targets (e.g., 70% recycling for packaging waste by 2030) and reduce landfilling.
    - **Single-Use Plastics Directive**: Tackle plastic pollution by restricting or banning certain single-use plastic items.
4. **Innovation and Investment**:
    - **Support for Circular Economy Projects**: Fund research and innovation projects focused

    on circular practices, especially for industries like plastics, electronics, and textiles.
    - **Circular Economy Finance Support**: Promote sustainable investments and financial instruments that back circular economy initiatives.
5. **Market Development for Secondary Raw Materials**:
    - **Standards and Quality for Recycled Materials**: Improve the quality standards of secondary raw materials to boost market demand.
    - **Public Procurement Policies**: Encourage governments to prioritize circular and sustainable products in public purchasing.
6. **Global Circular Economy Leadership**:
    - **International Partnerships**: Promote circular economy principles globally and collaborate with countries and organizations to tackle environmental challenges.

To assess the progress and effectiveness of the circular economy initiatives, the EU also revised the circular economy monitoring framework initially adopted in 2018. The 2023 revision introduces new indicators for Material Footprint and Resource Productivity to gauge material efficiency and Consumption Footprint to ensure EU consumption aligns with planetary boundaries (EC, 2024).

By 2019, all 54 actions had been adopted or implemented and legislative proposals in final stages of adoption. By 2024, all key elements of the CEAP have been implemented.

2.1.4 The second CEAP

In March 2020, the EC launched the second CEAP. One of the core areas of policy focus in this second CEAP has been the changes in the Eco-design requirements to embed CE principles and the Product Environmental Footprint (PEF) initiative. The Eco-design and sustainable product regulations, (ESPR), entered into force on 18 July 2024, with the aim of reducing the overall impact on the environment of products. This new regulation establishes eco-design requirements which cover the following dimensions:

- product durability, reliability, reusability, upgradability, reparability, ease of maintenance and refurbishment;
- restrictions on the presence of substances that inhibit the circularity of products and materials;
- energy use or energy efficiency of products;
- resource use or resource efficiency of products;
- minimum recycled content in products;
- ease of disassembly, remanufacturing and recycling of products and materials;
- life-cycle environmental impact of products, including their carbon and environmental footprints;
- preventing and reducing waste, including packaging waste.

By prioritizing eco-design principles, the EU aims to create a market where sustainable products are the norm and where consumers can make informed decisions. The ESPR also includes new mandates covering: a) product passports; b) rules to address unsold consumer products and c) green public procurement. The ESPR text requires the Commission to adopt and publish the first ESPR working plan in the first half of 2025. Priority sectors have been identified as follows: *iron & steel, aluminium, textiles (garments and footwear), furniture (including mattresses), tyres, detergents, paints, lubricants, chemicals, energy-related products (including new measures and revisions of existing ones) and ICT products, as well as other electronics*. An important aspect of the ESPR is that it will apply to all products placed on the EU market irrespective of whether they have been produced in the EU or abroad. The product regulations are accompanied by mechanisms of Consumer empowerment, such as the introduction of the *Right to Repair* and product information on durability, repairability, and life expectancy and the Restrictions in the use of single-use and harmful materials.

The 2020 CEAP places importances on addressing the value chains of priority products including:

- **Electronics and ICT**: Develop a *Circular Electronics Initiative* to improve recycling and reusability in electronics and ICT, including a new take-back scheme.
- **Batteries and vehicles**: Promote sustainable battery use and recycling with the *Batteries Regulation* to support the production and recycling of sustainable batteries, especially for electric vehicles.
- **Packaging**: Update the *Packaging Directive* to ensure that all packaging is reusable or recyclable by 2030.
- **Plastics**: Introduce measures to reduce plastic waste, particularly microplastics and single-use plastics.
- **Textiles**: Establish a comprehensive *EU Strategy for Textiles* to promote circularity and sustainability across the textile industry.
- **Construction and buildings**: Improve material recovery in construction through circularity requirements and better waste management.
- **Food, water, and nutrients**: Advance sustainable food systems and water reuse practices and tackle food waste.

The CEAP also continues to place attention on improving waste Management and waste prevention, with the introduction of reduction targets for specific waste streams (e.g. packaging), waste segregation requirements across the EU and more stringent regulations on waste exports and shipments.

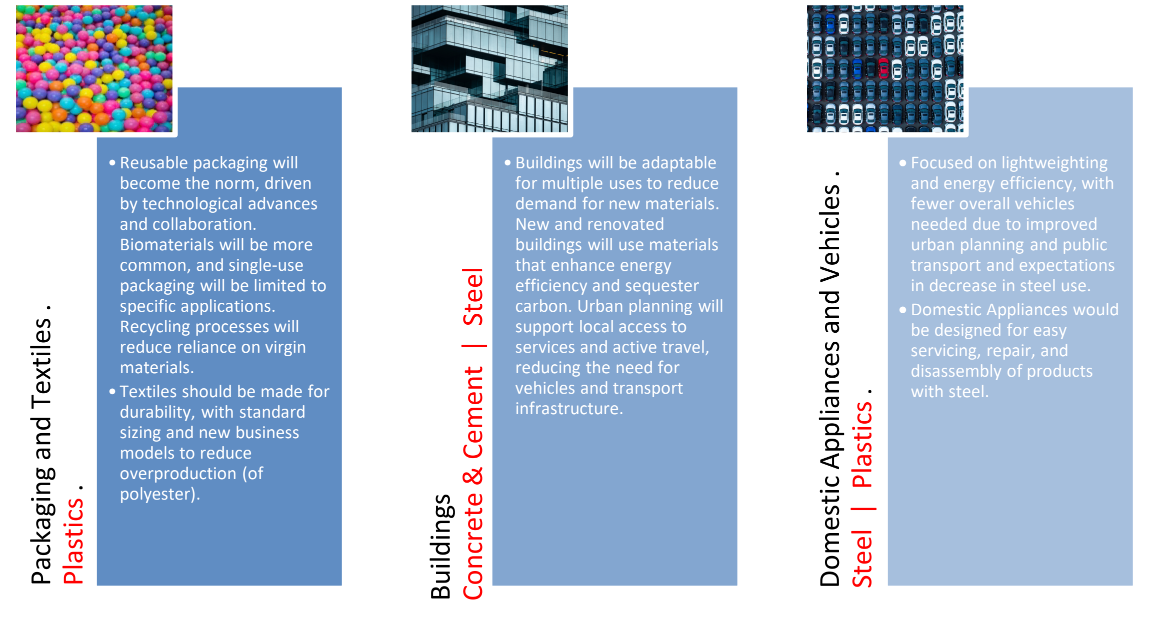
The CEAP has also implied a harmonized selection of CE indicators based on the newly updated *Circular Economy Monitoring Framework*.

3 CE and decarbonisation in the three focus sectors: Steel, Cement and Plastics

CE policy development has been significant in the last decade. The first CE package and CEAP in 2015, followed by the second CEAP in 2020, have contributed to advance policy development in this area substantially. As noted in previous sections, the emphasis is on making sustainable products the norm and ensuring progressive ambition to address the CE loops related to reduction reuse. Also there has been increasing emphasis on trying to treat Circular Economy and Decarbonisation as interlinked domains. The CEAPs are in fact part of the EU green deal, however, when it comes to policy design and implementation there is still lack of adequate integration resulting in separate agendas.

The three core sectors analysed as part of TRANSIENCE have been steel, cement and plastics. All three sectors are energy and material intensive and therefore provide an adequate ground to test the interlinkages between circularity and decarbonisation pathways. While there is a general consensus that CE strategies could contribute to the net zero pathways in these sectors, there is little understanding of the specific pathways through which decarbonisation potential of CE strategies can be realised and of potential trade-offs. Most roadmaps and vision documents for these sectors tend to view these two transitions independently rather than jointly.

An exception is possibly the white paper '2040 vision for a sustainable future' (Eunomia, 2023). The paper points to the need to adopt new integrated approaches towards waste and resources by realigning incentives of different stakeholders. The white paper points to the CE potential in buildings, packaging and textiles and vehicles and domestic appliances, which cut across the core three sectors of plastics, cement and steel, which are the core focus of this project.



- Reusable packaging will become the norm, driven by technological advances and collaboration. Biomaterials will be more common, and single-use packaging will be limited to specific applications. Recycling processes will reduce reliance on virgin materials.
- Textiles should be made for durability, with standard sizing and new business models to reduce overproduction (of polyester).

- Buildings will be adaptable for multiple uses to reduce demand for new materials. New and renovated buildings will use materials that enhance energy efficiency and sequester carbon. Urban planning will support local access to services and active travel, reducing the need for vehicles and transport infrastructure.

- Focused on lightweighting and energy efficiency, with fewer overall vehicles needed due to improved urban planning and public transport and expectations in decrease in steel use.
- Domestic Appliances would be designed for easy servicing, repair, and disassembly of products with steel.

Figure 3-1: Highlights from the White Paper on WFD regarding 3 focus materials of this paper (The relevant focal materials are shown in red in the vertical texts on the left of each box)

In the sections below, we discuss some of the key policy developments in the area and emphasise policy developments as well as gaps in advancing decarbonisation and circularity.

3.1 Steel

3.1.1 Introduction

Steel is a core component of modern societies, playing a crucial role in the development of other industries such as construction, infrastructure, transport, energy, and machinery. Globally, steel manufacturing represents around 7% of total GHG emissions, and around 5% of GHG emissions in Europe (IEA, 2020). The transition to net zero is also highly reliant on steel and other metals, including critical raw materials. Current wind turbine models require between 107 and 132 tonnes of steel per megawatt (MW) of installed capacity, while photovoltaic (PV) panels need around 60.7 tonnes of steel per MW. This significant demand highlights steel's essential role as a foundational material for the energy transition and emphasises the need for its own decarbonisation to achieve global carbon targets (Carrara et al., 2020).

Around 95% of world's steel is produced via three main routes: the blast furnace-basic oxygen furnace (BF-BOF) route, the direct reduced iron- electric arc furnace (DRI-EAF) route, and the scrap-based electric arc furnace (scrap-based EAF) route. The first two routes are known as 'primary' steel production because they use iron ore as their main source of metallic input. However, scrap also contributes around 15-25% of the metallic input in primary production. In contrast, the last route is referred to as 'secondary' production because it relies on scrap metal. In the BF-BOF route, blast furnaces extract iron from iron ore using coke, which is then turned into steel in a basic oxygen converter. BF-BOF accounts for around 70% of global steel production and around 90% of primary steel production (IEA, 2020). In the DRI-EAF route, natural gas, gasified coal or hydrogen is used to produce direct reduced iron form iron ore pellets, which is then turned into steel in an electric arc furnace. In the scrap-based route, steel scrap (recycled steel) and electricity are used to manufacture steel. The remaining 5% of the world's steel is produced by technologies with limited penetration (i.e. smelting reduction, open-hearth furnace, and induction furnace) (IEA, 2020).

On average, every tonne of steel produced results in 1.9 tonnes of direct and indirect carbon dioxide (t CO_2) emissions. BF-BOF produces ~2.2 t CO_2, natural gas-based DRI-EAF ~1.4 t CO_2, and scrap-based EAF ~0.3 t CO_2 (IEA, 2020). Moreover, recycling one tonne of steel can save on average 1.5 tonnes of CO_2, 1.4 tonnes of iron ore, 740 kg of coal, and 120 kg of limestone compared to producing the same amount of steel in a traditional blast furnace (WSA, 2023). A transition towards scrap-based EAF could potentially reduce carbon emissions while decreasing demand for primary materials. Furthermore, the integration of hydrogen in DRI production, coupled with EAF smelting, might presents a pathway towards carbon-neutral steel production. Projects such as HYBRIT in Sweden (see here) and Tata Steel's initiatives (see here) exemplify pioneering efforts in this direction. Furthermore, there is a growing number of newly announced H_2 and low-CO_2 DRI projects, with installed capacities reaching 46.6 million tons and 101.3 million tons per year, respectively (see Figure 3-2).

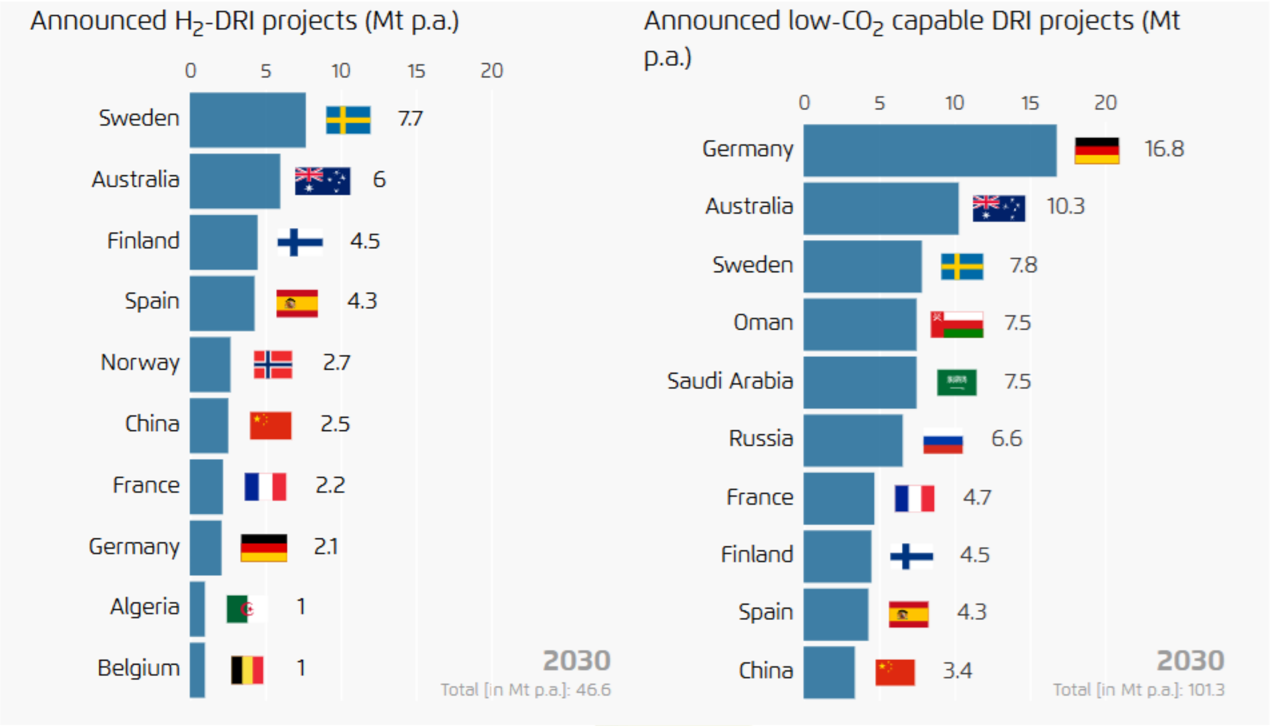


Figure 3-2: Announced new DRI capacity by 2030 (Source: Agora Industry, 2024)

Note: low-Co2 capable DRI projects includes new natural gas-DRI plants, which are assumed to be H2-ready if using the latest DRI technology.

The imperative for decarbonization is gradually shifting the industry towards the EAF route due to its versatility in utilizing both scrap steel and directly reduced iron (DRI) based on gas or hydrogen. This transition is particularly evident in North America and Europe. Given the high electricity consumption of the EAF route, access to low-cost and low-carbon electricity are key determinants for its feasibility and profitability, and they play a crucial role in guiding investment decisions towards this technology. The transition to EAF also depends on the future availability of scrap and the quality of that scrap to produce high-grade steel.

Primary steel can use both clean hydrogen and carbon capture, use and storage (CCUS) for decarbonisation. Clean hydrogen-based DRI-EAF is the most advanced technology, currently at a technology readiness level of 6-8, indicating it is in the large prototype and demonstration stage. CCUS is rapidly developing, with a technology readiness level of 5-8, also in the large prototype and demonstration stage (WEF, 2023). According to MPP (2022), the commercial availability of 100% green hydrogen DRI-EAF is anticipated by 2026, while BF-BOF with CCUS is expected by 2028. However, estimates by Agora Industry and Wuppertal Institute (2024) indicate that BF-BOF with CCS will not play a significant role in the global steel industry transformation, as it only reduces direct CO_2 emissions by 73% compared to the BF-BOF route. The main barrier for adopting these technologies are production costs, which are 40-70% higher than traditional steelmaking processes (WEF, 2023).

Transitioning to near-zero-emission production requires a substantial investment of approximately USD 1.8 to 2.6 trillion. The majority, about 90%, should be invested in developing clean hydrogen and power generation capacities, while the remaining funds should support CO_2 transport and storage. (WEF, 2023).

3.1.2 Key policy developments

Policy measures to promote and support the decarbonisation of the steel industry are still in their early stages, especially in the East Asia Pacific region, which accounts for 70% of the global steel production (WEP, 2023). As highlighted above, policy measures should support the development of infrastructure to produce clean hydrogen and electricity, provide incentives, and support research & development to accelerate the development of low-emission technologies. These measures should be complemented by demand-side interventions, such as promoting the circular economy to create a more sustainable and efficient steel industry.

While most efforts have focused on steel decarbonization, the sector is inherently well-suited for circular economy initiatives due to the high durability of steel and its efficient recyclability. However, CE policies in the steel industry remain underdeveloped. For example, although there have been attempts to increase the reuse of structural beams in the construction sector, these efforts face numerous challenges, including issues related to storage, testing, insurance, and certification. Most building standards currently place little emphasis on CE opportunities. Tools like building passports, which can help identify steel in the building stock and promote reuse and recycling loops, are still in the early stages of development.

The steel industry also offers good examples of CE potential, particularly in by-product utilization and heat exchange. Steel slag is a valuable by-product with multiple applications, especially in the production of cement. The steel sector has also been active in developing industrial heat networks and heat exchanges, contributing to energy reduction. Recently, initiatives have emerged to use circular carbon, recovered from biowaste, as an alternative to conventional fossil fuels.

On a broader scale, the fit for 55 initiative aims to reduce GHG emissions by at least 55% by 2030, compared to 1990 levels. This involves changes in the carbon pricing and free allocation of permits, and introduces a new instrument, the Carbon Boarder Adjustment Mechanism (CBAM), which will become effective in January 2026. The CBAM applies fees on imports of emission intensive goods such as steel products that are at risk of carbon leakage. The fees are calculated on the basis of embedded CO_2 emission of the imported goods to emulate the carbon price a domestic producer would have faced within the EU. CBAM aims to prevent carbon leakage to countries that lack equivalent climate legislation or carbon pricing. However, as highlighted by Eurofer (2023), carbon leakage must be addressed throughout the entire value chain, including downstream sectors not currently covered by CBAM. Moreover, carbon leakage needs to be addressed across global markets with an effective solution to preserve the competitiveness of European exports.

3.1.3 Existing roadmaps and visions

According to the International Energy Agency (IEA), the steel industry is expected to be one of the last sectors still using coal as a reduction agent by 2050 (IEA, 2023). Therefore, the decarbonisation of the steel sector will require the gradual adoption of a diverse mix of technologies. In the IEA's Net Zero Emission (NZE) scenario, the reduction of emissions in the steel sector will be achieved through a combination of technology options. By 2030, the share of steel production using BF-BOF is projected to decrease by around 10 percentage points, while EAF using scrap is expected to increase by 5 percentage points (IEA, 2024). The high level of scrap recycling, currently at around 85%, poses significant limitations in scrap availability, especially considering future demand projections. The other two key technology routes in the IEA's NZE scenario are hydrogen-based DRI-EAF and CCUS. These technologies may represent around 8%

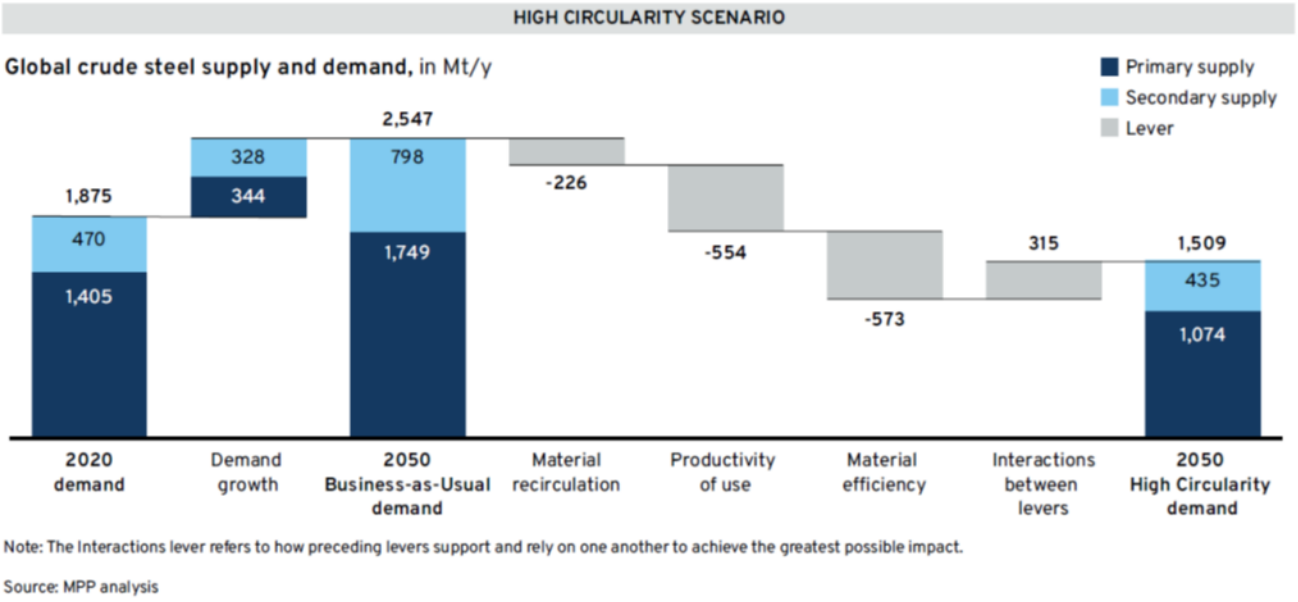
of primary steel production by 2030 (IEA, 2024).

By 2050, the IEA (2020) estimates that global steel production will comprise 40% scrap-based secondary production, 20% hydrogen-based production, 20% CCS-based steel production, 11% bioenergy and CCUS, and 7% unabated fossil fuels. In addition, material efficiency measures can significantly contribute, potentially reducing the global projected steel demand by around 20% by 2050. However, most of the steel decarbonisation pathways place little emphasis on demand management through circular economy strategies. Moreover, NDC Aspects (2024) emphasizes that any EU steel decarbonization policies should include a clear definition of green steel, which should promote circularity.

3.1.4 Key CE interventions for steel along its life cycle

The circular economy has emerged as a strategy for creating value at every stage of production and consumption. Its primary goal is to minimise waste and maximise resource value by promoting practices like reuse, repair, remanufacturing, and recycling. As discussed above, the global steel industry is already to some degree circular, with material efficiency and scrap recycling at the core of its activities.

In a High Circularity scenario, the Mission Possible Partnership estimates that the global steel demand could be reduced by up to 41% in 2050, compared to a Business-As-Usual scenario, avoiding 18Gt of steel production over the next three decades (MPP, 2022). This is achieved by a combination of material recirculation, productivity of use, and material efficiency. Many of the strategies to reduce demand require collaboration with downstream industries or significant behavioural change in society (e.g. design for end-of-life and reuse; a shared, service-oriented mobility; and substitution of steel with other materials) (see Figure 3-3).



Note: The Interactions lever refers to how preceding levers support and rely on one another to achieve the greatest possible impact.

Source: MPP analysis

Figure 3-3: Key levers behind the High Circularity Scenario (Source: MPP, 2022).
Note: The interactions lever refers to how preceding levers support and rely on one another to achieve the greatest possible impact.

Below, we highlight circular economy policies that align with the broader perspective of the World Steel Association, aiming to enhance sustainability and optimise resources across the entire value chain.

3.1.4.1 Slowing strategies

These strategies focus on extending the lifespan of products to slow down the flow of resources. It involves designing products for durability, repairability, and upgradability to ensure they remain in use for as long as possible. Policies and regulations need to offer appropriate incentives to encourage the optimal use of materials, introducing durability, reparability, dismantling and recyclability requirements into products' design.

3.1.4.1.1 Reuse in steel applications

Steel products are highly durable and can be easily reused or remanufactured at the end of their lifecycle. This practice eliminates the need to produce new products or reprocess the steel, thereby conserving resources and minimizing environmental impact. To facilitate an efficient reuse, it is crucial to consider the potential for reuse during the initial design phases. This will ensure that products can be quickly and effectively repurposed once their primary use is completed. Moreover, new business models can facilitate the entry of these products to secondary markets, thereby creating additional market opportunities and incentives.

3.1.4.1.2 Reuse in buildings

The building sector offers a substantial opportunity for steel reuse, but it is crucial to prioritise design for reuse right from the beginning. Modular building design provides the flexibility to repurpose buildings quickly and cost-effectively as needs change, without requiring remanufacturing. It needs demountable connections to enable relocation. The business model needs to change, in a well-established reuse economy, steel companies, in addition to sell new steel beams, could provide services for testing and recertifying used beams. Documenting the chain of custody would ensure traceability and quality assurance. This approach would offer builders the necessary safety guarantees, provide building owners with cost-effective and quick remodelling solutions, and create a new revenue stream for steelmakers.

3.1.4.1.3 Remanufacture of steel-containing products

Remanufacturing involves restoring a product that has reached the end of its life to a like-new condition. This process is distinct from repairing or refurbishing, which only make the product operational rather than fully restoring it (WSA, 2023). Remanufacturing is currently widely spread across different industries. The durability of steel components makes them ideal candidates for remanufacturing processes. Once these components are restored and certified as like-new, they can be reused effectively, ensuring high performance and extending their lifecycle.

3.1.4.2 Narrowing strategies

Narrowing resource flows means using fewer resources to produce the same product. This can be achieved through more efficient manufacturing processes, reducing material waste, and optimizing resource use. Emissions need to be reduced throughout the lifecycle of steel products. Policies and regulations need to offer appropriate incentives to encourage the optimal use of resources and ensure sustainable practices are adopted across the industry.

3.1.4.2.1 Reduce in steel applications

The development of new grades of advanced and ultra-high-strength steels has significantly reduced the weight of various steel applications. Lighter steel applications mean less material and energy usage. Additionally, lighter vehicles consume less energy and produce fewer emissions. In the construction sector, replacing regular steels with high-strength steels can reduce emissions by approximately 30% in steel columns and around 20% in steel beams (WSA, 2023).

3.1.4.2.2 Reduce during steel production

The steel industry has significantly reduced the use of iron ore and energy. Today, producing one tonne of steel requires only 40% of the energy it did in 1960 (WSA, 2023). This improvement was largely driven by the increased production of secondary steel. As highlighted above, the current commitment to reduce GHG emissions is gradually shifting the industry towards scrap steel and low-carbon energy inputs, envisioning a more sustainable and environmentally friendly steel production. However, this transition highly depends on securing the necessary resources to finance the required infrastructure investments.

3.1.4.2.3 Reduce through material efficiency

Material efficiency measures optimise the use of steel products, ensuring that resources are utilised more effectively, and waste is minimised. The steel production process results in 70% steel, 28% by-products, and 2% waste (WSA, 2023). Effective management of these by-products and waste is crucial to enhance sustainability and efficiency along the supply chain of the steel industry.

Over the past decades, the steel industry has achieved remarkable advancements in waste management. By-products like slag, dust, and process gases are effectively used in various industries, reducing the need of primary materials such as cement clinker and electricity.

3.1.4.2.4 Sharing economy

A share economy in the steel industry can enhance efficiency, reduce costs, and promote sustainability by leveraging shared resources, services, and infrastructure. Equipment leasing offers a flexible alternative to purchasing, enabling lower capital expenditures and more flexible operations, while providing access to the latest technology and machinery. Establishing material exchange platforms where companies can buy, sell, or trade excess raw materials, by-products, and waste would minimise waste and ensure efficient use of materials across the industry. Equipment sharing enables companies to use machinery without the need for ownership, reducing costs and enhancing operational flexibility. Similarly, car sharing offers individuals and businesses access to vehicles on an as-needed basis, promoting efficient resource utilization.

3.1.4.3 Closing the loop strategies

The Circular Economy Action Plan provides a comprehensive framework for initiatives that advance circular economy practices, encourage sustainable consumption, and ensure that resources remain within the EU economy for as long as possible. Regulations need to be clear and not excessively restrictive to allow for innovation and flexibility.

3.1.4.3.1 Steel recycling

Steel is the world's most recycled material. All steel production routes use scrap, up to 100% in the EAF route, and up to 30% in BF-BOF route. All scrap that is collected is recycled, and the overall recycling rate today is estimated to be about 85% (WSA 2024). This includes home scrap produced during steelmaking, prompt scrap generated during the manufacturing of steel products, and end-of-life scrap from discarded steel appliances.

Steel recycling is a key circular economy strategy because it reduces the need for iron ore extraction and significantly lowers emissions. Despite significant progress in scrap collection and sorting, including the use of new AI-guided process, the high recycling rate indicates limited additional potential for further scrap collection and recycling today. Moreover, recycling is constrained not only by the quantity of available scrap but also by its quality. Contaminants like copper and tin in steel scrap can make it less suitable for certain applications (IRENA 2023).

3.1.4.4 Substitution strategies

When considering the substitution of steel with alternative materials, it is crucial to evaluate the full life cycle impact of both options. This assessment should include the environmental, economic, and social impacts associated with each material from extraction and production to usage and end-of-life disposal or recycling.

3.1.4.4.1 Substituting steel

There are only a few cost-competitive sustainable substitutes for steel, making it an indispensable material throughout the entire economy. Its unique combination of strength, durability, and versatility ensures that steel remains a critical component in numerous industries. As a result, the demand for steel is expected to continue rising to support the economic development of nations.

As mentioned above, the adoption of high-strength steel allows for reduced steel usage while maintaining functionality. However, in some applications, steel can also be replaced by lighter materials such as aluminium, plastics and, to a lesser extent, advanced materials like carbon fibre-reinforced polymers. For instance, plastics are increasingly being used instead of steel in certain building components (e.g. pipes and fittings) and automotive parts (e.g. bumpers and exterior body panels) (IEA, 2020).

3.2 Cement

Similar to steel, cement is also a central sector in the policies for decarbonisation. Currently cement contributes to around 8% of total global GHG emissions and around 4% of the GHG in the EU. Cement is also among the material foundations for buildings and infrastructures but also plays a key role in the deployment of renewable energy Technologies and required infrastructures to enable the net zero transition (Carrara et al., 2020). Direct emissions will need to come down by at least 24% compared to current levels from the cement industry to achieve reductions that would lead to >50% likelihood of staying below 2°C global, according to the IEA (2018).The sector thus has been heavily targeted by policies to tackle climate change and has been one of the key sectors of the 'fit for 55' strategy and climate policy.

This has turned the attention to technology and material changes. The technology changes have explored: 1) alternative fuels and 2) changes in the composition of cement, with the rise of ACM (alternative cementitious materials) and 3) new production technologies, such as new CO_2-free electrochemical processes to produce low-carbon cement. It has been estimated that by 2050, 40% of kiln energy will come from traditional sources, i.e. coal (30%) and petcoke (10%), while 60% of kiln energy could potentially be provided by alternative fuels of which 40% could be biomass. This fuel mix would lead to an overall decrease of 27% in fuel CO2 emissions. The focus on decreasing embodied carbon of cements, especially in construction, has already had an effect in changing the preference for cement types with lower clinker content. For example, the Portland cement, has lost market share in favour of Portland Composite (CEM II) and Blast Furnace Slag Cement (CEM III), both of which highly rely on alternative raw materials and use of by-products of other industries (e.g. Blast Furnace Slag cement) as well as limestone replacements (Xavier & Oliveira, 2021). Most of these shifts have been mainly motivated by embodied carbon reduction ambitions rather than policies. Strategies such as reducing cement content in concrete mix, using secondary aggregates for concrete, or avoiding over-specification of concrete have all been mostly guided by GHG reductions but have also led to important material savings. However, it is important to note that different cements will have different properties that need to align with the cement specifications and application areas.

Alongside this, more attention has been drawn to reducing waste along the value chain. CE strategies so far have been mainly motivated by changes in waste and ambition targets of landfill diversion for construction and demolition (C&D) waste. The Waste Framework Directive (WFD), for example, specifies a 70% recycling rate of C&D waste. Concrete makes a large fraction of demolition waste and, thus, many of existing initiatives have identified ways to reduce concrete waste, by using it as filling material or for foundations or by crushing and use it as a replacement for primary aggregates. New practices of planned demolition are starting to be enforced or voluntarily adopted, motivated in many cases by changes in local urban regulations and instruments such as the landfill tax, one of the most widely adopted economic instrument to encourage landfill diversion. Instruments such as demolition audits and demolition waste plans, have promoted the recovery of concrete for different applications. However, while current practice recovers part of the concrete for lower quality applications such as secondary aggregates, reprocessed concentre for roadworks, and other applications, there have been limited success in encourage reuse of the material for high value application. Also recently there has been some progress on re-carbonation of concrete and co-production of steel and concrete (Dunant et al., 2024).

3.2.1 Key policy developments

Table 3-1 below summarises some of the key policies specifically tackling decarbonisation of the cement industry. Apart from long standing instruments such as carbon pricing and ETS, the sector has recently been part of the CBAM instrument. Policies are thus directed to promote the adoption of new technologies, through a mix of regulatory and economic instruments, setting incentives to accelerate adoption of new technologies to reduce direct emissions.

Table 3-1: Key instruments of policies developed in the cement industry

Policy Area	Policy/Initiative	Description
Carbon Pricing	**EU Emissions Trading System (ETS)**	Cement producers must buy emissions permits under the ETS. Decreasing free allowances over time incentivizes emission reductions to avoid higher costs.
Innovation Funding	**Innovation Fund & Carbon Capture, Utilization, and Storage (CCUS)**	Funds breakthrough projects, including CCUS for cement, to capture CO_2 directly from production and support alternative low-carbon technologies.
Alternative Fuels & Raw Materials	**Clinker Substitutes & Waste-Derived Fuels**	Policies promote replacing clinker with low-carbon materials (e.g., fly ash, slag) and using waste-derived fuels like biomass to reduce fossil fuel use.
Circular Economy & Material Efficiency	**Recycling & Material Reuse Initiatives**	Supports recycling construction materials and using recycled concrete in new projects, reducing demand for new cement production.
Green Public Procurement (GPP)	**Low-Carbon Material Requirements**	GPP criteria encourage using low-carbon cement in public projects, creating market incentives for sustainable products.
Standards & Product Labelling	**Low-Carbon Standards & Environmental Product Declarations (EPDs)**	New standards for low-carbon cement types and EPDs promote transparency and encourage low-carbon cement use in construction.

These policies aim to collectively reduce the carbon footprint of the EU cement sector and foster innovation toward net-zero emissions.

The CE concept has more recently been considered in the sector. As noted by Marsh et al. (2022), while there have been important developments in terms of reduction of embodied carbon of cement, mostly focussed on technical aspects related to new technologies and cement types from a material and manufacturing perspective, more CE holistic approaches that consider the full range of CE strategies from a system-level perspective have been largely neglected.

3.2.2 Existing roadmaps and visions

Alongside regulations and specific policy targets and regulations, the cement policy landscape is made up of roadmaps and vision documents that try to identify possible pathways to decarbonisation.

There are several notable decarbonization roadmaps for the cement industry, established by various organizations aiming to guide the sector toward net-zero emissions. The table below (Table 3-2) provides a summary of key roadmaps and proposed strategies:

Table 3-2: Key strategies of existing roadmaps in the cement industry

Roadmap	Organization	Target Year	Key Strategies
Cement Technology Roadmap	International Energy Agency (IEA) & Cement Sustainability Initiative (CSI)	2050	Focuses on carbon capture and storage (CCS), alternative fuels, clinker substitution, and process efficiency.
Low Carbon Roadmap for the Cement Industry	European Cement Association (CEMBUREAU)	2050	Emphasizes clinker substitution, CCS, energy efficiency, alternative fuels, and circular economy practices.
Global Cement and Concrete Association (GCCA) Net Zero Roadmap	GCCA	2050	Aims for net-zero concrete by 2050 using low-carbon binders, alternative fuels, CCS, and supply chain collaboration.
Industrial Decarbonisation Roadmap	UK Government, in collaboration with industry stakeholders	2035/2050	Targets 2035 for major reductions and 2050 for net-zero, with a focus on CCS, hydrogen, and circular economy.
Mission Possible Report	Energy Transitions Commission (ETC)	2050	Supports pathways like process electrification, CCS, use of bioenergy, and material efficiency improvements.
Cement Industry Decarbonisation Pathway	World Business Council for Sustainable Development (WBCSD)	2050	Recommends reducing carbon intensity through CCS, alternative fuels, clinker efficiency, and value chain collaboration.

There are some common areas highlighted by all roadmaps which also help to stress the role of CE in the sector decarbonisation. These key areas include:

1. **Carbon Capture and Storage (CCS/CCUS)**: Widely considered essential to achieving deep emissions reductions, as it captures CO_2 directly from the cement production process.
2. **Alternative Fuels and Clinker Substitution**: Use of biomass, waste fuels, and substitutes like fly ash and slag reduce emissions associated with clinker production.

3. **Energy and Process Efficiency**: Improving energy efficiency and process innovations like electrification and low-carbon binders are pivotal for short- and mid-term reductions.
4. **Circular Economy Initiatives**: Emphasizing recycling, material reuse, and design for lower cement use, reducing the overall demand for new cement.
5. **Collaborative Action and Innovation Funding**: Industry collaboration with governments and financial support for R&D are integral for technological advancement and scaling low-carbon solutions.

While these roadmaps provide a strategic framework for aligning the cement industry with international climate goals and industry-wide collaboration, there is still a lot of uncertainty around how these pathways will be achieved and the necessary framework conditions to make them feasible.

Also, recently new standards have been developed including the PAS 2080:2016 “Carbon management in infrastructure”. This standard proposes the adoption of a **Whole Lifecycle Carbon Management, also the need to work across the Value Chain Approach by emphasising collaboration across key stakeholders to** reduce carbon at all stages; Establishes requirements for setting carbon reduction targets and tracking progress against established baselines and provides a framework for measuring and monitoring.

Also, recently more attention has been drawn to embodied carbon in the built environment which has been accompany by the development of new standards focus on embodied carbon or the inclusion of embodied carbon in existing building standards. Some of these initiatives are included in the summary table below.

Table 3-3: Key initiatives of existing standards in the cement industry

Standard	Organization/Region	Scope	Embodied Carbon Focus	Application
EN 15978:2011	European Committee for Standardization (CEN)	Sustainability of construction works	Provides a framework for assessing embodied carbon across the life cycle of buildings	Used for environmental performance declarations (EPDs) and sustainable building assessments
EN 15804:2012+A2:2019	European Committee for Standardization (CEN)	Environmental Product Declarations (EPDs) for construction products	Specifies how to calculate and report embodied carbon for construction products	Basis for product-specific carbon footprinting in the construction industry
ISO 21930:2017	International Organization for Standardization (ISO)	Environmental product declarations for buildings and civil engineering works	Covers the rules for declaring embodied carbon and other environmental impacts across a product's life cycle	Global standard for consistent carbon reporting and assessment of building materials
BS 8500-1/2:2015	British Standards Institution (BSI)	Specifications for concrete	Guidance on minimizing embodied carbon in concrete mixes	Used for designing low-carbon concrete mixtures in the UK
BS 8895-1:2013	British Standards Institution (BSI)	Material efficiency in building projects	Framework for reducing embodied carbon by optimizing material use and minimizing waste	Useful for architects and engineers to design buildings with lower embodied carbon
RICS Whole Life Carbon Assessment (2017)	Royal Institution of Chartered Surveyors (RICS)	Whole life carbon assessment for the built environment	Comprehensive guidelines for assessing both embodied and operational carbon in construction	Widely applied in UK construction and real estate for carbon assessments

PAS 2080:2016	British Standards Institution (BSI)	Carbon management in infrastructure	Encourages managing embodied carbon across infrastructure projects and value chains	Focused on reducing carbon emissions in large-scale civil engineering and infrastructure projects
CEN/TC 350 Standards	European Committee for Standardization (CEN)	Sustainability of construction works	Addresses embodied carbon as part of the sustainability performance of construction projects	Used in Europe for life cycle assessment (LCA) and sustainability analysis in the construction industry
LEED & BREEAM	US Green Building Council (LEED) / Building Research Establishment (BREEAM)	Green building certifications	Rewards reductions in embodied carbon through material selection, LCA, and sustainable construction practices	LEED in North America and BREEAM in Europe for sustainable building certification

Some MSs have also started to develop stringent building regulations which set to reduce the overall carbon footprint of buildings. Denmark has become the first country to introduce mandatory limits on embodied carbon in building regulations. For new buildings larger than 1,000 square meters, there is a threshold limit of 12 kg CO_2 equivalent per square meter per year (Buro, 2024). Sweden is also moving towards similar regulations. By 2025, they plan to implement mandatory life cycle greenhouse gas disclosures for buildings, aligning with broader EU directives and Norway has been proactive in addressing embodied carbon, with ongoing discussions about introducing limits. In France, the RE2020 for new buildings sets building emission goals, which include embodied emissions.

3.2.3 CE interventions

From a system perspective, though, the introduction of a full range and wide scope CE strategies is limited. Most of the work has concentrated on less preferable circularity options such as increasing recycling and valorisation and minimising waste, but less emphasis has been put on more advanced and potentially more ambitious interventions that align with the slow, narrow and regenerate loops.

Slow options include extension of the life of buildings and infrastructures, but also less explored options such as limiting the embodied carbon per m2 and optimising space in buildings. These solutions require changes across different sectors and levels of government and modify design principles and requirements to transform how buildings and infrastructures are designed and, more widely, how societal needs are fulfilled in the trinomial of buildings, cities and people.

3.2.3.1 Slowing strategies for cement

3.2.3.1.1 Rethink construction of buildings and infrastructures

More ambitious CE options require considerations about ways to reduce material intensity of societies. While cement and concrete are key materials in delivering some basic societal needs such as shelter and infrastructures, most developed economies already depart from large building stock concentrated in urban areas and connected with material and cement intensive infrastructures. CE interventions can try to optimise use of existing stock, by reducing structural waste, increasing adaptability and multi-functionality and extending its use life through policies that incentivise refurbishment instead of demolition.

Moving to an optimised use of the existing building and infrastructural stock is complex and requires changes in how cities are designed, changes in building regulations and incentives towards maintaining existing stock. Several MSs have introduced incentives for refurbishment of buildings to meet energy efficient standards but less attention has been given to embed circularity principles in refurbishment of buildings.

This requires changes in existing business models and value creation opportunities through efficient use of stock and disincentives towards inefficient uses.

3.2.3.1.2 Design for durability and adaptability

Extending the lifetime in use of buildings help to slow resource flows associated with the extraction of new materials and generation of waste. From the concrete perspective, keeping buildings and other infrastructures in the in-use stock for longer results in savings in concrete production and concrete waste.

This though requires decision at the design stage to ensure that concrete load and mixes are specified with durability in mind, which may lead to initial increases in overall concrete requirements that will be compensated in the increased lifetime of the building or infrastructure. Therefore, new regulations around restricting embodied carbon may create potential trade-offs for durability. On the other hand, designing more durable structures does not guarantee that the socio-economic conditions change in the future leading to significant short lifetimes than technical lifetimes. Miller (2020) studied the impact of durability extensions of 50% in the USA building stocks estimating important reductions in cumulative CO2 emissions.

Therefore, at the design stage it is crucial to establish given the function of the structure whether it is preferable to reduce embodied carbon and assuming a shorter lifespan or increasing durability even when that leads to higher embodied carbon per m2.

When considering durability, aspects such as adaptability and modularity are critical. Design for Adaptability considers possible future adaptations of the structure to fulfil different needs, and, thus, contributed to extend the lifespan of the infrastructures. In building this may mean greater capacity to alter internal distribution, add additional floors or modify the internal or external appearance without altering structural elements. Mountable and dismountable structures and module construction strategies also enable changes of location, size and functions of buildings and infrastructures while preserving materials in the stock. An example is the dismountable car park in Schiphol airport in the Netherlands which provides flexibility to upsize or downsize in the future.

3.2.3.1.3 Reduction of concrete volumes in structures

Narrowing opportunities include the reduction of concrete intensity and overall concrete volume in structures. This includes new innovative ways of maintaining structural strength with less materials. Therefore, strategies such as reducing overspecification of materials, revising safety margins to ensure that they are adequate with loading requirements (Favier et al., 2018) or designing light-weight materials such as steel-concrete flooring slabs, smart design of structures through digital manufacturing and 3D printing (Tu et al., 2023). Lighter weight structures can be built using 3D concrete building leading to reduction in total concrete load. 3D printing also allows the incorporation of recycled materials and materials from waste.

3.2.3.1.4 Reduce cement content in concrete

Given that most of the embodied carbon from concrete is the cement a number of strategies have been introduced to reduce the cement content in concrete mixes. Using 'binder intensity' calculated as cement kg cement/m^3/MPa, is it possible to derive the strength class of concrete (Favier et al., 2018; Damineli et al., 2010) to explore the potential for cement reduction without affecting the performance of the material. This sometimes clashed with building regulations and material requirements for durability performance that tend to be material rather than performance based. This however needs to be evaluated depending on the overall function of the application, whether, for example we would want to increase strength in certain elements to reduce overall structural requirements or to increase durability and adaptability of, for example, a building or infrastructure.

3.2.3.1.5 Use of Supplementary Cementitious Materials (SCM)

The use of SCM has extended in recent years driven by the need for decarbonisation. Clinker production is energy and emissions intense due to the physical and chemical processes that occur in the conversion of limestone-based raw materials into Portland cement clinker. While improvement of energy efficiency can reduce emissions related to fuel combustion, emissions associated to the calcination process, which represent around 2/3 of direct manufacturing emissions, can only be tackled through the use of SCMs and limestone act as clinker replacements (Schneider, 2019). The clinker factor, or the % of clinker in cements, varies substantially. Globally the clinker factor is around 0.65 in 2014 while the European average was reported as 0.74 in 2016. However, there are countries with much lower clinker factors such as the Netherlands with 0.46 (Ibid).

Most commonly used SCM are industrial byproducts from pig iron processing, ground granulated blast furnace slag (GGBFS) and fly ash, from furnaces fired with pulverised coal. The availability of these two sources of SCM is depended on the decarbonisation pathways of both steel and energy systems. The future availability of GGBFS may be limited through the transition to EAF which rely on scrap, although limitations in scrap availability seems to suggest that pig iron will still be needed in the future. Fly ash production is dependent on coal-firing power plants which are expected to substantially decrease and be substituted by renewables. While this process will take longer in China and Asia, in Europe, availability of fly ash is expected to decrease significantly.

The alternative to conventional SCMs is the use of natural pozzolans, which need to be pre-treated, and are available only in certain regions, and calcined pozzolans. While regional clay availability tends to be good globally, they are not by-products and will require ad hoc production facilities. Studies have also demonstrated that cements with calcined clay show good durability. The cement European standard EN 197-1 establish minimum reactive silica content to ensure adequacy of calcined clays. Other common alternatives are gypsum and limestone that are also widely available.

From a CE perspective, there are two key areas of concern: 1) the first one relates to the local/regional availability of these materials and 2) the second refers to how SCMs can impact performance and durability of concrete and the need for further developments that ensure minimum requirements of SCMs. The local/regional availability is also strongly connected with a good traceability of indirect emissions associated with treatment and transportation of secondary materials and alternative natural pozzolans. A system perspective is thus required to consider inter-dependencies across sectors, especially related to use of conventional by-products, and transportation, investment and processing impacts related with the use of natural clays,

3.2.3.2 Narrow the material loops

3.2.3.2.1 Use of alternative fuels

The concrete industry has also made considerable progress in the use of alternative fuels. Alternative fuels are generally used to achieve decarbonisation but also play an important role as a CE strategy as it relays mainly on the use of different types of waste some with an important biogenic content. While globally the contribution of alternative fuels is limited and stands around 10% in 2016 (GNR, 2016), in some areas such as the EU contribution is much higher, with plants in The Netherlands achieving substitution rates of over 80%. Substitution rates are linked to the availability of suitable waste and pre-treatment facilities in cement plants. Suitability depends on calorific value and stringent limitations of chlorine content. Among common alternative fuels are tyres, pre-treated industrial and municipal wastes, Refuse Derived Fuels, used oils, paints and solvents, plastics, textiles waste, paper wastes and agricultural and other biomass waste, such as sewage sludges.

Therefore, the use of alternative fuels represents a valorisation strategy for waste which are hazardous or difficult to treat, and present advantages in terms of safety and value compared to incineration and waste to energy alternatives. This may be promoted by more stringent regulations to divert waste from landfill in Europe and find alternatives to dumping and burning of waste in other parts of the world, where suitable waste management sectors are underdeveloped. There have been some concerns about valorisation preventing other higher CE options such as reuse or recycling but the regulations in terms of activity licenses which list permitted alternative waste and raw materials ensures that waste valorisation does not detract from reuse and recycling to accept waste which would be difficult or not economically feasible to recycle. A study by ECOFYS and CEMBUREAU mapped the share of co-processing of waste in cement kilns in EU countries, which represents a very small percentage of around 1.17% of all waste (De Beer, 2017). An advantage of co-processing compared to incineration is that the ashes are incorporated into the clinker, resolving a major issue compared to incineration processes.

3.2.3.2.2 Alternative binding materials

Alternative binding materials have been developed to replace some cement fractions. These include belite clinker, with low amount of alite but 40%–90% belite, calcium sulphoaluminate (CSA) clinker and alkali-activated binders (Schneider, 2019). At pilot stage, there are carbonated calcium silicates and pre-hydrated calcium silicates. Overall carbon reduction potential is difficult to estimate given complex supply chains associated with the extraction and processing of alternative minerals.

3.2.3.2.3 Reuse of concrete slabs and concrete structures

Another CE strategy includes the reuse of concrete structures and components. Reuse of concrete slabs have started to emerge as a practice in the built environment for low-carbon reinforced concrete flooring. This requires saw-cutting reinforced concrete (RC) pieces, which are salvaged from existing buildings before they are demolish. A study by Kupfer et al. (2024) demonstrated that this is not only a technically viable solution, and that most CR slabs that are destined to demolition are likely to meet structural requirements for reuse in new office or housing buildings (in the study they tested 18-cm thick or thicker flat slabs common in EU building stock and spanning up to 4 m to be technically reusable). Moreover, this practice could represent a saving of over 80 % of GHG emissions compared to regular structural flooring solutions, with as little as 5 $kgCO_2e/m^2$.

Reuse of Extracted Concrete in new Structures (PRECS) is a practice recognise by the IEA to increase material efficiency and reduce carbon impacts of loading and structural materials. Kupfer et al. (2024) gather evidence from 77 case studies of concrete reuse. In their study they identify Germany and The Netherlands as two of the pioneering MSs in reuse of concrete structures. The types of projects vary significantly and cover from high-rise apartment buildings, low-rise buildings, pavilions, and other infrastructures. In terms of most common reused components the most prevalent is precast panels, band other precast components, pieces of concrete extracted from monolithic structures, or, more recently bridge girders to be reused new bridges in the Netherlands.

However, moving from demonstration case studies to mainstream practices is faced by several barriers. One fundamental barrier is the lack of industry standards or frameworks providing a standardised protocol and quality assessment for PRECS and related to this lack of common knowledge and shared practices on how to implement the connections, how to ensure reused elements integrate requirements in terms of for example fire regulations or sound proofing of new designs and barriers around technologies and practices for deconstruction that maintain the integrity of the materials (Kupfer et al., 2024).

3.2.3.2.4 Repair and maintenance of buildings and infrastructures

Improving the maintenance of buildings and infrastructures through planned maintenance and smart remote sensing can help to extend the lifetime of the structures and their components. Maintenance also includes preventive and mitigation measures to protect concrete such as coatings. Reparability implies the replacement of elements that have been damaged, and refurbishment have generally a wider scope and include replacing and adapting existing structures or components. It is important to note that repair mortars tend to be specified at a higher cement content to ensure durability. The European standard EN1504 defined and specifies the requirements in terms of performance and safety of structural and non-structural repair and protection of concrete.

3.2.3.3 Strategies for closing material loops

3.2.3.3.1 Concrete recycling

The most widely adopted CE strategy for concrete and the one mainly promoted by policy instruments such as Aggregate Levies introduced in some EU MSs is the recycling of concrete into aggregated from C&D waste. Demolished concrete structures can be crushed and then the crushed can be used as a replacement of excavated aggregates. While this is considered ‘downcycling’ as it requires energy and does not preserve the integrity of the material, there are higher value uses as ‘recycled concrete aggregates’ which have been adequately segregated and then used as a replacement of aggregates in concrete production and other forms of recycled aggregates used as road base or for other low value applications. The benefits of using recycled aggregates are highly dependent on transport and energy used in the crushing process. While recycled aggregates can contribute to material efficiency, the benefits in terms of decarbonisation potential may be marginal or difficult to establish, as more cement is needed to manufacture concrete using recycled aggregates of equal strength and thus, benefits and trade-offs need to be evaluated in a case-by-case basis.

Different regional and national standards and building regulations establish the permitted recycled aggregates content in concrete and structures and grain size. These parameters vary according to the concrete application area, exposure and the strength.

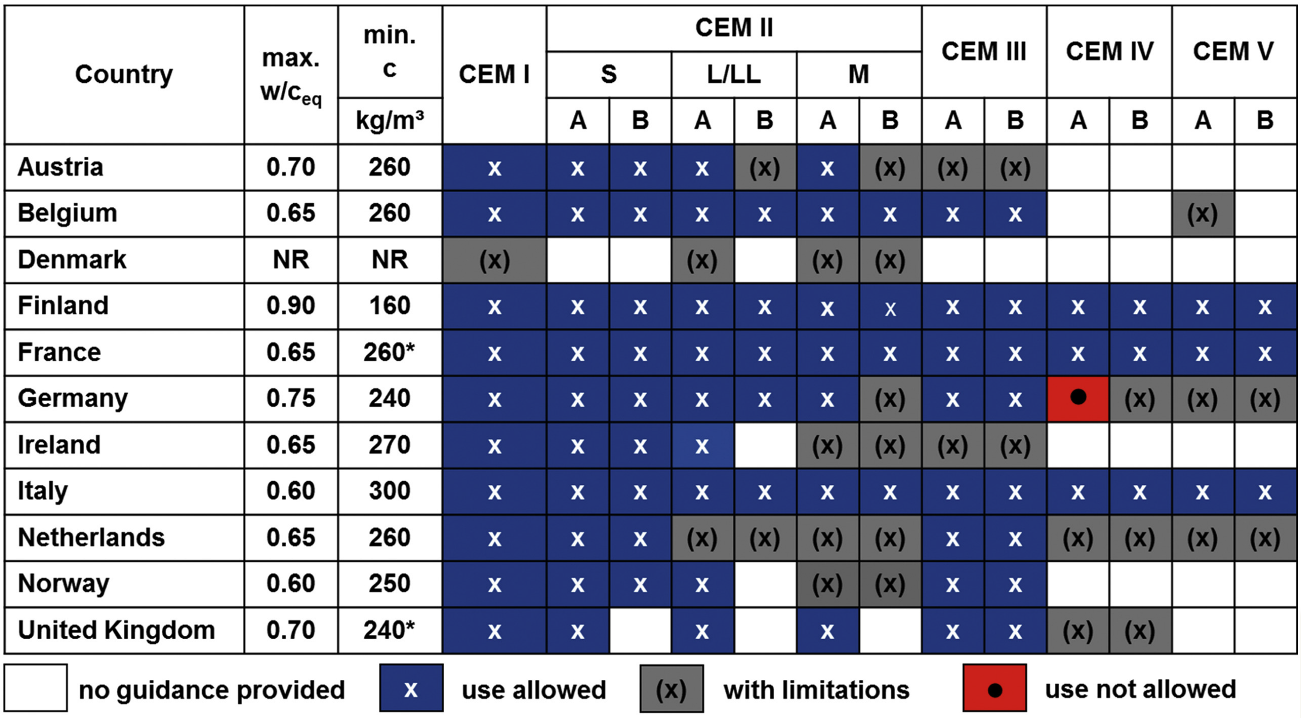
Research have also pointed to the potential of using the fines and powders from the crushing process into new concrete (Marsh et al., 2022), by transforming them into cement paste and used it as a supplementary cementitious material; however, the feasibility of this process relies on the development of efficient techniques for the separation of fines (Zajac et al., 2021)

3.2.3.3.2 New Cements with decarbonisation potential

Countries in the EU are subjected to different regulatory frameworks in terms of permitted cement types for different applications. Each type of cement has different product specifications and limitations in the use of SCMs or clinker replacement.

Traditionally there have been concerns around the performance and durability of these concretes. New research (Evangelista and De Britto, 2019) seems to suggest that durability can be optimised through well-defined requirements in the mixing and composition design of FRA concrete.

Figure 3-4 below provides an overview of the different cement types that are allowed in different MSs and across different applications and the lack of harmonisation which can pose barriers to the further uptake of CE approaches in construction.



Country	max. w/c_{eq}	min. c	CEM I	CEM II						CEM III		CEM IV		CEM V	
				S		L/LL		M							
		kg/m³		A	B	A	B	A	B	A	B	A	B	A	B
Austria	0.70	260	x	x	x	x	(x)	x	(x)	(x)	(x)				
Belgium	0.65	260	x	x	x	x	x	x	x	x	x			(x)	
Denmark	NR	NR	(x)			(x)		(x)	(x)						
Finland	0.90	160	x	x	x	x	x	x	x	x	x	x	x	x	x
France	0.65	260*	x	x	x	x	x	x	x	x	x	x	x	x	x
Germany	0.75	240	x	x	x	x	x	x	(x)	x	x	●	(x)	(x)	(x)
Ireland	0.65	270	x	x	x	x		(x)	(x)	(x)	(x)				
Italy	0.60	300	x	x	x	x	x	x	x	x	x	x	x	x	x
Netherlands	0.65	260	x	x	x	(x)	(x)	(x)	(x)	x	x	(x)	(x)	(x)	(x)
Norway	0.60	250	x	x	x	x		(x)	(x)	x	x				
United Kingdom	0.70	240*	x	x		x		x		x	x	(x)	(x)		

☐ no guidance provided   x use allowed   (x) with limitations   ● use not allowed

NR: No requirement
* / (x) Indicates that there are qualifications, e. g. types of main constituents

Figure 3-4: Cement application in the EU: Example for XC1 (Source: Schneider,2019)

CEM I to CEM V cement types refer to the classification of cement based on the composition and proportions of the main constituents used in their production. These classifications are specified by the *European Standard EN 197-1*, which defines five main types of cement, each suited to different construction needs and environmental conditions. The numbers (I to V) denote different types of cement, which vary in clinker content, addition of supplementary cementitious materials, and specific applications.

Table 3-4: Types of cements and applications (Source: Adapted from EN 197-1)

Type	Main Constituents	Clinker %	Applications
CEM I	Pure Portland Cement (mainly clinker)	95-100%	General construction, high early strength
CEM II	Portland-Composite Cement with limestone, fly ash, slag	65-94%	Moderate strength, general construction
CEM III	Blastfurnace Cement with GGBS	5-64%	Marine, mass concrete, sulfate resistance
CEM IV	Pozzolanic Cement with fly ash, natural pozzolana	45-89%	Dams, hydraulic structures, durability
CEM V	Composite Cement with slag and pozzolanic materials	20-64%	Mass concrete, sulfate-resistant structures

3.2.3.3.3 Concrete recarbonation

Carbonation of concrete is a well-established technique which can be considered in the design of structures. The fines in crushed concrete are made up of calcium silicate hydrates which can act as a carbon capture material through recarbonation and sometimes also be used in the production of clinker, as their silica content makes them suitable as a raw material replacement. The contribution to energy reduction and process emissions will depend on the CO2 captureb by the fines before entering the kiln.

Some previous studies have tried to quantify carbon uptake potential of concrete through recarbonation. Xi et al. (2016) estimated CO_2 uptake from concrete at the regional and global levels from 1930 to 2013. The findings indicated that around 43% of the process emissions from cement could then be taken up by concrete along its full life cycle, which considering also fuel related emissions corresponds to around 27% of the total emissions from cement.

3.2.3.4 Regenerative CE solutions for concrete

There are different regenerative strategies for concrete. The most important one would be self healing concrete. There is also potential for replacing concrete in construction through reliance on, for example, biobased building materials. However, performance of these materials is distinctively different and suitable applications may also differ.

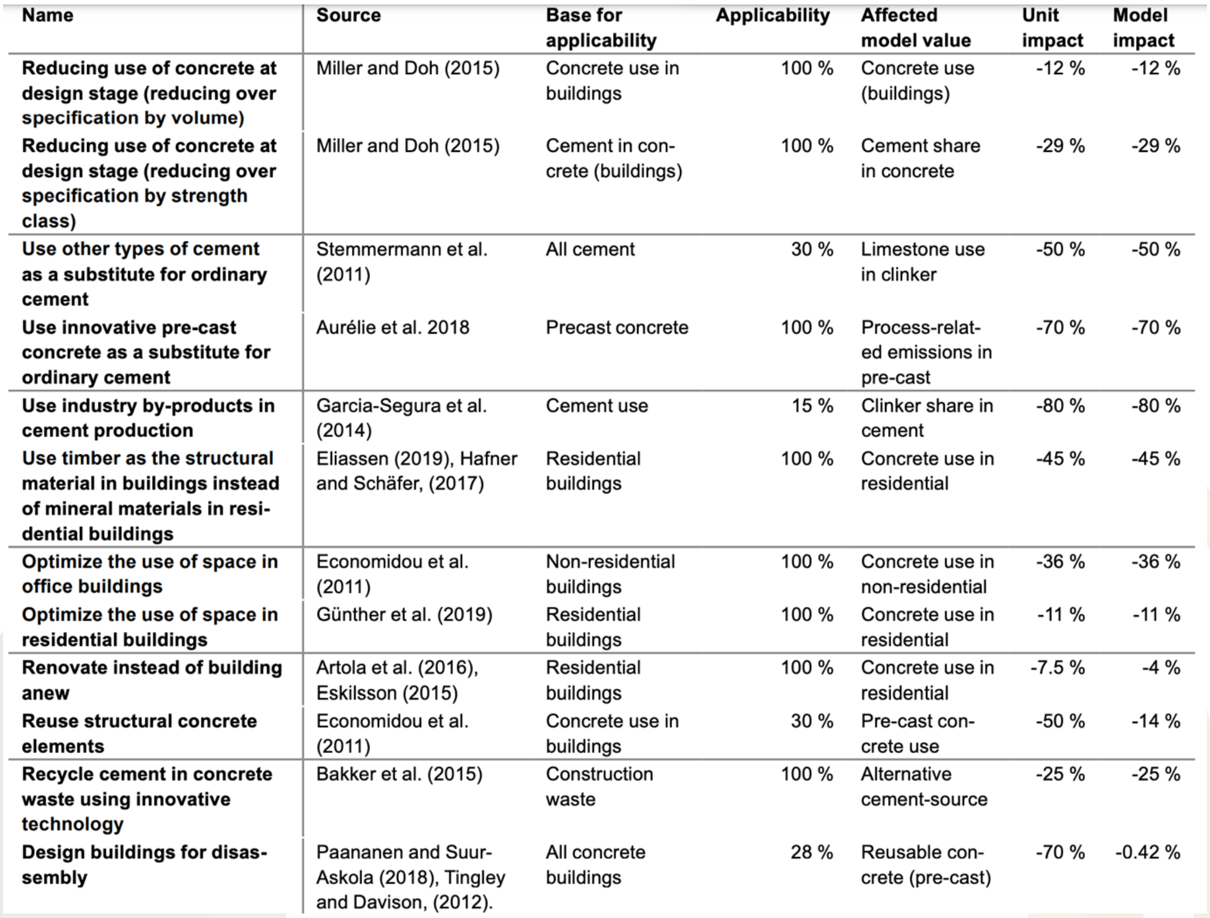
3.2.3.4.1 Self-healing concrete

Bio-concrete or self-healing concrete has been seen as a long-lasting alternative to current concrete. While the practice can be traced back to the Romans, the concept has attracted recent attention for its potential for increasing material efficiency and reducing embodied carbon over the lifetime of concrete structures. The self-healing properties are achieved through the addition of materials with bacteria spores which will release limestone when activated when water penetrates concrete cracks, sealing the cracks and restoring the concrete. Basilisk a spin off from TUDelft in the Netherlands has been pioneering the use of self-healing concrete for infrastructure projects. Findings from early applications show very significant impact on life extension (e.g. bus lane in Schiphol Airport in the Netherlands could be extended by 15 years), leading to GHG reductions by 90% over the whole project life cycle and 1/3 reduction of costs.

3.2.3.5 Potential impact of CE interventions in cement and concrete

There have been some attempts to model the impact CE interventions along the supply chain. Table 3-5 summarises some of the key literature contributions and potential reported impact on decarbonisation. While the modelling approaches used are significantly different and so are system boundaries, model characterisation and assumptions, the table below offers some measure of impact potential across different types of interventions in the cement and concrete sector.

Table 3-5: Model implementation and specific potential of CE-actions (Source: Rehfeldt et al., 2020)



Name	Source	Base for applicability	Applicability	Affected model value	Unit impact	Model impact
Reducing use of concrete at design stage (reducing over specification by volume)	Miller and Doh (2015)	Concrete use in buildings	100 %	Concrete use (buildings)	-12 %	-12 %
Reducing use of concrete at design stage (reducing over specification by strength class)	Miller and Doh (2015)	Cement in concrete (buildings)	100 %	Cement share in concrete	-29 %	-29 %
Use other types of cement as a substitute for ordinary cement	Stemmermann et al. (2011)	All cement	30 %	Limestone use in clinker	-50 %	-50 %
Use innovative pre-cast concrete as a substitute for ordinary cement	Aurélie et al. 2018	Precast concrete	100 %	Process-related emissions in pre-cast	-70 %	-70 %
Use industry by-products in cement production	Garcia-Segura et al. (2014)	Cement use	15 %	Clinker share in cement	-80 %	-80 %
Use timber as the structural material in buildings instead of mineral materials in residential buildings	Eliassen (2019), Hafner and Schäfer, (2017)	Residential buildings	100 %	Concrete use in residential	-45 %	-45 %
Optimize the use of space in office buildings	Economidou et al. (2011)	Non-residential buildings	100 %	Concrete use in non-residential	-36 %	-36 %
Optimize the use of space in residential buildings	Günther et al. (2019)	Residential buildings	100 %	Concrete use in residential	-11 %	-11 %
Renovate instead of building anew	Artola et al. (2016), Eskilsson (2015)	Residential buildings	100 %	Concrete use in residential	-7.5 %	-4 %
Reuse structural concrete elements	Economidou et al. (2011)	Concrete use in buildings	30 %	Pre-cast concrete use	-50 %	-14 %
Recycle cement in concrete waste using innovative technology	Bakker et al. (2015)	Construction waste	100 %	Alternative cement-source	-25 %	-25 %
Design buildings for disassembly	Paananen and Suur-Askola (2018), Tingley and Davison, (2012).	All concrete buildings	28 %	Reusable concrete (pre-cast)	-70 %	-0.42 %

3.3 Plastics

As per cement and steel, plastic is also a foundational material of modern societies. Its versatility and low production costs has led to an exponential growth in the use of plastics since their introduction in the 1950s. The plastics industry in the EU is globally relevant, with the EU being the second largest producer of plastics after China and generating a turnover of EUR 304 billion in the EU (Plastics Europe, 2024). Geyer et al. (2017) estimated that all plastics ever made amounted to about 8300 mill tonnes and that about 6300 M tonnes have become waste. Moreover, only around 9% of all waste has been recycled globally, while around 80% has accumulated in landfills or directly in the environment (ibid).

Increasing citizen awareness around the problem of plastic waste and changes in the trade of plastic waste after the introduction of the Chinese green sword policy[2], triggered further policy focus on plastic waste. The packaging directive and its recent review into the Packaging and Packaging waste regulation, have established more stringent targets on plastic packaging waste prevention and high-quality recycling. This includes a reduction in packaging waste of 5% by 2030 and 15% by 2040, better information about material composition of the packaging and targets on reuse of packaging. Also, by 2030 all packaging put on the market has to be recyclable. Packaging is also part of Extended Producer Responsibility schemes to financially contribute to its management and an economic instrument, the plastic tax/levy, charging non-recycled plastic packaging waste produced by MS which have resulted in unharmonized application of plastic levies across MSs. New regulations around single use plastics have also ban single use plastics in some applications and introduced new obligations. However, less has been done for other types of plastics which are ubiquitous and used across all industrial sectors and represent around 60% of all plastics. The revised End of Life Vehicles Directive proposes a minimum of 25% recycled plastic content in new vehicles and a 30% recycling target of plastic parts in vehicles and some incentives to encourage the sale of spare parts.

Plastics in construction are poorly regulated. New composite materials in construction, aerospace and other industries have also created new materials which are strong and lightweight but may be difficult to recycle at the end of life.

Thus, CE strategies in the sector has mainly focused solely on packaging and overlook other more complex plastic products. Despite the introduction of new reuse and prevention targets, most of the emphasis is on promoting less preferable options from a CE perspective, mainly focusing on plastic recycling. Even for plastic packaging, the recycling rate is to achieve 50% by 2030 and 55% by 2040, which is comparatively less ambitious than for other packaging materials, recognising the inherent added difficulty of recycling a wide range of plastic polymer materials.

3.3.1 Key policy developments

Plastic waste and plastic pollution have been the focus of several new policies in the EU. These policies have mainly focused on trying to reduce plastic pollution and increase plastic recycling. Plastic as a versatile material is used across many sectors of applications. While packaging makes up around 40% of all plastics the larger part of plastics, 60% of all plastics, are distributed across buildings and construction, vehicles, electronics, agriculture and other applications (Plastics Europe, 2024).

3.3.1.1 Plastic packaging

Plastic packaging represents around 40% of all plastics. However, it has raised concerns as a growing

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[2] The *Green Sword Policy* is a regulatory initiative launched by China in 2017 to curb the import of foreign waste, especially plastic and other recyclable materials, in an effort to address environmental pollution and improve domestic waste management. This policy followed the earlier *Green Fence Initiative* of 2013 and preceded the more comprehensive *National Sword Policy*, which introduced strict restrictions on waste imports and placed stringent standards on waste quality. Together, these policies aim to reduce China's reliance on foreign waste, boost its recycling industry, and protect the environment from the adverse effects of improperly managed waste.

source of waste. The total packaging waste in the EU increased from 66 million tonnes in 2009 to 84 million tonnes in 2021. The per capita production of packaging waste was around 188.7 kg in 2021, but it is likely to rise to 209 kg by 2030. Plastics is after 'paper and cardboard' the second largest fraction of Packaging waste

The revised EU Directive in packaging and packaging waste establish targets of recycling of plastic packaging of 50% in 2025 and 55% by 2030. It also specifies that EU MSs need to have producer responsibility schemes for all types of packaging. For the first time, the Directive also includes reduction targets (5% by 2030, 10% by 2035 and 15% by 2040) with a special focus on plastic packaging waste and binding targets on reuse of packaging by 2030, which vary depending on the type of packaging, and indicative targets for 2040. It reduces unnecessary packaging and reduce empty space in packaging to minimise weight and volume of packaging. Also, by 2029, the separate collection systems for single-use plastic bottles need to achieve at least 90% collection rate and set up **deposit return systems** (DRSs) unless they already have a system in place with collection rates that will reach the 90% target by 2029.

The new regulation has also imposed plastic waste bans on single use plastics for certain applications, such as unprocessed vegetables and fruits, packaging for foods and beverages filled and consumed in cafés and restaurants, individual portions, miniature packaging for toiletry products and very lightweight plastic carrier bags. There is also a ban on PFAS (per and poly-fluoroalkyl substances) for food contact packaging.

In 2021 the EU introduced a plastic levy. The levy required MS to pay a levy of EUR 0.80 per kg of not recycled plastic waste. While some MSs pay the levy directly from national budgets some other MSs have introduced taxes, duties and fees to tax plastic products, or penalise those below certain thresholds of recycled content. This has created a complex and fragmented regulatory landscape for plastic which MSs having different instruments targeting different types of plastics. In fact, the plastic industry association, Plastics Europe, advocated for minimum recycled content targets to be included in the new Packaging and Packaging Waste directive. The new packaging has established mandatory minimum recycled content for plastic packaging by 2030 of 30% for contact sensitive PET packaging and single use plastic bottles and lower at 10% for other plastics. Bioplastics are excluded from this.

In 2019, the EU passed a directive on 'the reduction of the impact of certain plastic products on the environment' aiming to tackle marine litter, which emphasises the role of reuse models and established a 25% target for recycled content in plastic bottles by 2025 and 30% by 2030.

3.3.1.2 Plastics in construction, automative and composites.

Actions across other sectors beyond plastics packaging are mostly non-binding and of voluntary nature.

The construction sector has seen a rise in the use of plastic polymers across different applications, representing around 20% of all plastics (Plastics Europe, n.d.). Among main applications, plastics are present in sealants, gaskets, piping and conduits, different profiles (windows and doors), cables, floor coverings, and insulation. This also includes many polymeric composites and glass reinforced plastic materials used structurally for their strength, lightweight and formability and resistance to corrosion. However, recovery of plastics in the sector is problematic. According to Plastics Europe (2024) recycling of most types of polymers in construction is around 25%, with variations across polymers, being energy recovery (around 47%), followed by landfill (26.7%) the main destinations. There are no specific regulations establishing requirements for plastics used in construction, beyond product regulations.

The End of Life of vehicles Directive has introduced measures to tackle plastic recycling and closed loop recycling of plastics by setting targets of plastic recycling. As part of the proposed revisions to the End of Life of Vehicles (ELV) Directive, the European Commission has set a target for new vehicles to include at least 25% of recycled plastics derived from post-consumer waste by 2030. This initiative is crucial for promoting a circular economy and reducing the environmental impact of plastic waste in the automotive industry, which currently sees over 80% of its plastic waste being landfilled or incinerated.

There have been other areas discussed such as composite materials in aerospace, automotive or wind technologies, but initiatives in these spaces have been mainly voluntary and limited to some organisations within the sector.

3.3.2 Existing roadmaps and visions

In 2018, the EU launched the CE plastic strategy entitled ‘A European Strategy for Plastics in a Circular Economy’. The strategy pursued tackling the increase in plastic waste changes in the design and production of plastics to reduce waste, promote re-use, repair and recycling while exploring alternative sustainable materials. Among its key initiatives, it included new rules on packaging to increase recyclability and recycled content, separate collection of plastic waste, a new directive on single use plastics, actions to tackle marine litter and measures to promote bio-based, biodegradable and compostable plastics.

While most of these measures have been fully or partly implemented, the overall impact on plastic waste generation has been questioned, although data shows a slight increase in plastic packaging recycling.

Following the CE strategy, several public and private institutions have developed their own roadmaps. In 2023 Plastics Europe released the ‘**Plastics Transition Roadmap’** outlining a strategy for the European plastics industry to transition towards circularity by 2050. Key targets include:

- Aiming for circular plastics to account for 25% of European demand by 2030 and 65% by 2050.
- Reducing greenhouse gas emissions from the plastics system by 28% by 2030, ultimately achieving net-zero emissions by 2050.
- Emphasizing the need for minimum circular plastic content targets and enhanced chemical recycling infrastructure.

Complementary, the **Plastic Waste Management Roadmap**, also developed by Plastics Europe focuses on developing a comprehensive waste management strategy to facilitate better collection, sorting, and recycling of plastic waste. It includes fostering collaboration across sectors to optimize the recycling process and reduce the volume of plastic that ends up in landfills.

The UNESDA (Union of European Soft Drinks Associations) ‘Circular Packaging Vision 2030’ also provides their own roadmap to increase circularity of plastic packaging aiming to achieve full circularity for beverage packaging by 2030. Key pillars of the vision include: a) 100% Collection target for Packaging; b) 100% Recycled Content: and sets a target that by 2030, all PET (plastic) bottles used will be made from 100% recycled content, significantly reducing the use of virgin materials. And Circularity: ensuring the development of end-of-life management of packaging which aligns with closed loop recycling, meaning that every package used can be collected, recycled, and reused to make new packaging.

Also internationally, the UN plastic waste treaty have led to coordinated global action to stop plastic pollution. Proposed in March 2022, the treaty is officially known as the *UNEA Resolution on Plastic Pollution*, adopted during the United Nations Environment Assembly (UNEA) in Nairobi, Kenya. It aims to establish a legally binding international framework by 2024 to reduce plastic pollution through prevention, recycling, and sustainable waste management. Among its key objectives it includes: 1) a commitment to **reduce Plastic Production and Use, with** targets to reduce single-use plastics, packaging, and other plastic products that contribute significantly to pollution; 2) **Promotion of Sustainable Design and Recycling** including design for reusability and recyclability; 3) **International Cooperation and Responsibility** to encourage for plastics to be reused and recycled, rather than discarded and provisions around international cooperation, with wealthier countries aiding developing nations in waste management and recycling capabilities; 4) **Harmonization of Standards and Policies**, especially with regards to how plastics can be produced and how they should be disposed of or recycled; and 5) introduction of extended producer responsibility (EPR) shemes, which would make companies responsible for the lifecycle of the plastics they produce.

3.3.3 CE interventions

CE interventions in the plastic sector have attracted considerable attention in recent years. As mentioned before, they have mainly followed on packaging with only niche initiatives across other applications. Given that complexity of plastic polymers used across different sectors, we will mention examples of specific measures across key sectors.

3.3.3.1 Slowing strategies for plastic circularity

Slowing strategies imply slowing the flow of resources keeping plastics in the stock for longer to avoid waste generation. In the case of plastics, though, slowing plastic flows require also considerations around potential health and safety implications of extending the life of some of the plastics.

3.3.3.1.1 Reusable plastics

Part of the problems associated to plastic waste stem from the fact that plastics are durable materials used for short-term applications. Shifting the perceptions around plastics may encourage new designs that embeds reusability in the design of plastics. The new regulation sets specific targets for both alcoholic and non-alcoholic beverages set at a minimum of 10% by 2030, and aiming to reach at least 40% by 2040, although exceptions in the application have been criticised for reducing effective implementation of these targets. The new regulation also introduced Deposit return schemes systems for plastic bottles. While reusability is in principle aligned by CE principles, it is important to ensure that 'reusable' packaging material are effectively reused rather than disposed, through for examples, incentives to reuse of containers and packaging.

However, beyond packaging examples of plastic reuse are limited. Plastics used in structural applications, cars or aerospace are generally recycled rather than reused, given potential safety implications and wear off.

3.3.3.2 Narrowing strategies for plastic circularity

Narrowing strategies imply reducing the amount of primary plastics produced.

3.3.3.2.1 Eliminating unnecessary plastics

Eliminating unnecessary plastic packaging is a cost-effective strategy that slows the flows of plastics and contributes to decarbonisation and avoidance of waste and pollution. This includes reducing unnecessary packaging or additional packaging used for marketing purposes.

While there are some legislative measures for the elimination or reduction of plastic packaging such as unnecessary packaging for fresh produce, there is still room to designing more efficient solutions which moves away from conventional packaging.

3.3.3.2.2 Lightweight of plastics

Another key strategy is lightweighting of plastic packaging and other packaging applications. While plastic materials are commonly used to reduce weight, generally substituting metals and minerals in other applications (e.g. aerospace), and therefore improve efficiency, it is also possible to identify opportunities to lightweight plastics materials. This strategy focuses on reducing material use while maintaining performance. This can be done through optimised design or removing unnecessary parts. This strategy has been largely applied to beverage bottles to reduce plastic content, plastic bags and other packaging applications; however, use of stronger plastics and digital manufacturing also could contribute to changes in design of more complex products such as electronics, cars and construction materials (e.g. insulation).

3.3.3.2.3 Eliminating hard to recycle plastics

With the regulatory push to make all plastics used in packaging recyclable in the new PPW regulation by 2030, there have been increased attention to alternatives to substituting hard-to-recycle plastics with paper and coated paper composites and bioplastics. Applications such as vegetable/fruit punnets, food service clamshells, and dry food multilayer film packaging are all suitable for replacing hard to recycle plastics for alternative materials, which are easier to recycled.

3.3.3.2.4 New technologies: Digital manufacturing and 3D printing

New technologies such as digital manufacturing and 3D printing can help deliver narrowing strategies. 3D printing has emerged as a valuable tool in reducing plastic use and minimizing waste through more efficient and sustainable manufacturing processes. There are several avenues through which 3D printing can contributes to narrowing plastic strategies. These include:

1. On-Demand, Localized Production

- **Reduced Overproduction**: Traditional manufacturing often requires producing items in bulk, leading to excess inventory and waste. 3D printing enables on-demand production, meaning products are only printed when needed, reducing the risk of overproduction.
- **Localized Production**: By enabling production closer to the point of use, 3D printing reduces the need for packaging and transportation, which often involves single-use plastics.

2. Optimized Design and Material Efficiency

- **Lightweight and Material-Efficient Designs**: 3D printing allows for complex, optimized designs that use less material while maintaining structural integrity. This means that less plastic is needed to create each product, especially for industries like aerospace and automotive, where weight reduction is critical.

- **Waste Reduction**: Unlike subtractive manufacturing, which cuts away material from a larger block (leading to waste), 3D printing is an additive process, building objects layer by layer. This approach minimizes scrap material, often resulting in close to zero waste.

3. Recycled and Biodegradable Materials

- **Recycled Filaments**: Many 3D printing companies are now offering filaments made from recycled plastics (e.g., PET from water bottles or waste PLA). This process turns post-consumer or industrial plastic waste into new, usable products, reducing reliance on virgin plastics.
- **Biodegradable Filaments**: Materials like PLA (polylactic acid) are bio-based and biodegradable under certain conditions. PLA is commonly used in 3D printing and provides a more sustainable alternative to petroleum-based plastics.

4. Prototyping Without Plastic Waste

- **Efficient Prototyping Process**: 3D printing allows for rapid prototyping without the need for molds or extensive materials. Traditionally, prototypes required molds or casting, often resulting in large quantities of plastic waste. 3D printing eliminates the need for single-use molds and cuts down on the material wasted during iterative design phases.
- **Iterative and Precise Prototyping**: With precise control over material use, 3D printing enables designers and engineers to test multiple iterations without using excess plastic, especially when compared to traditional prototyping.

5. Extending Product Life and Supporting Circular Economy

- **Replacement Parts**: 3D printing can be used to create replacement parts for existing products, extending their lifespan and reducing the need to discard items prematurely. This helps prevent plastic waste and supports a circular economy model.
- **Closed-Loop Production Systems**: Some 3D printers are equipped with recycling systems that can process and reuse plastic waste, feeding it back into the 3D printer to create new products. This closed-loop system minimizes the need for new plastic.

There are examples of application of 3D printing which may have contributed to plastic use and plastic waste reduction, across different sectors of activity these includes: 1) **Furniture and Consumer Goods**: Many companies now produce customizable and sustainable furniture and household items using recycled or biodegradable filaments; 2) **Medical and Automotive Parts**: Industries such as healthcare and automotive are using 3D printing for custom prosthetics, surgical models, car parts, and tools, often using less material and reducing waste and 3) **Packaging and Prototyping**: 3D printing can create prototypes and packaging without losses.

3.3.3.3 Closing the loop strategies

3.3.3.3.1 Plastic recycling

After incineration and EfW, Plastic recycling is the most widely adopted strategy to deal with plastics at the end of life. Plastic recycling can be grouped into two main types: (i) mechanical recycling of plastics and (ii) chemical recycling of plastics.

Mechanical recycling to the processing of plastics using mechanical processes, such as melting and re-extrusion, which do not significantly alter the chemical structure of polymers. Most thermoplastics can be mechanically recycled. Installed capacity for mechanical recycling of plastics in Europe increased from 2Mt in 1996 to 11.3Mt in 2021 (Plastic Recyclers Europe, 2021). Among the caveats of chemical recycling is that it is not suitable for all plastic polymers and that it degrades over time, so it requires additions of primary polymers.

The need to enhance recycling capacity and provide solutions to other types of polymers has drawn attention to chemical recycling of plastics. There are different processing methods included under the umbrella of chemical recycling. Among two main approaches are: a) gasification and the conversion of plastic waste to produce syngas or fuels and naphtha and other basic chemicals and b) processes of catalytic pyrolysis which enable the production of monomers and oligomers from plastic waste through depolymerisation. Other processes include solvolytic, dissolution and precipitation processes which also revert plastics back into monomers and oligomers. Obtained monomers and oligomers can be re-polymerized to produce plastics.

The table below summarises key main technologies for plastic recycling.

Table 3-6: Summary of key recycling technologies (adapted from Naderi Kalali et al., 2023)

Recycling Technology	Description	Process	Types of Plastics	Pros	Cons
Mechanical Recycling	Physically processing plastic waste through sorting, shredding, washing, and remelting.	Sorting → Shredding → Washing → Melting → Re-extrusion	Mainly thermoplastics (e.g., PET, HDPE, PP)	Low cost, widely used, energy-efficient	Quality degradation with each cycle (downcycling)
Chemical Recycling	Breaking down polymers into monomers or other basic chemicals to create new plastics or fuels.	Depolymerization → Purification → Repolymerization	PET, PS, Nylon, (limited applicability to mixed plastics)	Can handle contaminated plastics; high-quality output	High energy and cost, complex infrastructure needed
Glycolysis	A type of chemical recycling where glycols are	PET + Glycol → BHET monomers	PET	Produces high-purity monomers for PET production	Only applicable to PET, sensitive to contaminati

	used to break down PET into its monomers.				on
Pyrolysis	Thermal decomposition of plastics in an oxygen-free environment to produce oils, gases, and char (fuel).	Heating in absence of oxygen	Mixed plastics, PE, PP	Can process mixed and contaminated plastics	High energy use, produces CO_2 and other emissions
Hydrolysis	Chemical recycling method using water and heat to break down polymers into monomers, particularly PET.	Water + Heat → Monomer	PET	Produces high-quality monomers	Energy-intensive, limited to specific plastics
Solvolysis	Dissolving plastics in a solvent to recover polymers or convert them into monomers.	Dissolution → Polymer Recovery or Monomer Production	Various (e.g., PET, PS, PU)	Can handle mixed waste, yields pure monomers/polymers	Complex solvent recovery, solvent cost
Microwave-assisted Pyrolysis	A variation of pyrolysis using microwaves to heat plastics more efficiently.	Microwave Heating → Fuel/Monomer Production	Mixed plastics	Faster and more energy-efficient than traditional pyrolysis	Still energy-intensive, requires microwave technology
Depolymerization	A specific type of chemical recycling	Depolymerization Reaction → Monomers	PET, Nylon, PLA	High-quality monomers, useful for closed-loop recycling	Requires high purity, high energy input

	that breaks down polymers into monomers through chemical reactions.				
Enzymatic Recycling	Using engineered enzymes to break down plastic polymers into monomers in mild conditions.	Enzyme Treatment → Monomer Recovery	PET, PLA, (research on others like PEF)	Low energy usage, works at low temperatures	Limited scalability, slow process, high enzyme cost

There are many comprehensive reviews of recycling options for plastics and analyses of the environmental life cycle impacts across different options of plastics and end of life destinations. Marson et al. (2023) conducted a systematic review to conclude that while LCAs have been widely applied to compare across different types of plastics and end of life options, results lack direct comparability due to lack of harmonisation in terms of system boundary definition and model characterisation. Garcia-Alvarez et al. (2023) used LCA to compare plastics recovered through pyrolysis and plastics from virgin polymers. The study concluded that from the recyclers' perspective, the use of plastic waste at different substitution rates led to a decrease in GHG emissions for High Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE) compared to virgin plastic. However, there have also been concerns as after the process of pyrolysis additional steps are required to produce a polymer product, with additional inputs of energy and water, and thus implications for greenhouse gases (GHG). Das et al. (2022) set to identify whether the option of converting non-recyclable plastics to virgin plastics offers environmental benefits, compared to their conversion to fuels. The study concluded that for the EU and from a cradle to grave perspective, Naphtha and LDPE produced from non-recyclable plastics are less GHG-intensive than conventional routes to these products. However, further studies are needed to also consider other impact categories and potential trade-offs of chemical plastic recycling.

Another key recycling route is the enzymatic recycling of plastics. Enzymatic or biological recycling uses enzymes to naturally degrade plastic polymers at low temperatures. While most enzymatic processes are still at lab scale or limited to a restricted type of polymer, such as PET, it is likely that it will expand significantly.

A special mention is needed to address the growing and wider adoption of plastic composite materials. Mostly thermoplastics or thermosetting polymer composites. Composites refer to materials that combine a matrix material and a reinforcement material which are combined to enhance the sought properties of the material. Common matrix materials include metals, ceramic and other polymeric material (Utekar et al., 2021). For thermoplastic composites, there is potential for better recycling of the matrix materials, but this is more difficult in the case of thermoset composites.

can be recycled without or with less degradation of recovered polymer matrix material and reinforcement fibres but, in case of thermosetting composites it is not so easy to recover polymer matrix and reinforcement fibres without degradation in properties. The difficulties of recycling composites and costs of segregated collection mean that a lot of the composite materials will end up in landfill or incineration (Utekar et al., 2021). However, some industries such as wind energy, construction, automotive and aerospace with increased use of composite materials, such as carbon fibre reinforced composites, are introducing closed loop systems for the recovery of the composite material. Depending of the type of polymer used, composite recycling may include mechanical and chemical recycling (including thermal recycling). Regulation is thus needed to ensure composite materials can be collected and recycled at the end of life.

3.3.3.3.2 Use of recycled plastics in packaging and other applications

Regulatory mandates on the use of recycled content in packaging applications and cars, have helped to create a demand for recycled pellets in Europe. This raised some concerns among manufacturers as whether mechanical recycling would be sufficient to meet with regulatory targets especially for applications where certain specifications need to be met and where chemical regulations impose also restrictions in chemicals, as for example, plastics contaminated by chemicals that can be found in older cars. There has been a call for chemical recycling with a mass balance chain of custody approach to be accepted to obtained chemically recycled content in plastics that could count towards those targets. Mass balance is a transparent and auditable method.

In other sectors use of plastics in both plastic products and plastic-containing products is more complex. Plastics have been widely used as a substitute material for other materials, such as, for example the use of plastics in concrete mixes to substitute natural aggregates or in automotive to substitute metals.

The use of recycled plastic materials in conventional cement mortar and concrete happens in two main forms: as a replacement of natural aggregates, and as plastic fibres, which can be used in fibre-reinforced concrete (FRC) (Gu & Ozbakkaloglu, 2016). The properties of the mix have been extensively investigated (Pacheco-Torgal et al., 2012). Following the meta-analysis by Pacheco-Torgal et al. (2012), the use of recycled plastics in concrete seems to exhibit lower slump than conventional concrete. In terms of the compressive strength, elastic modulus, splitting tensile strength, and flexural strength may also decrease, especially when used as an aggregate replacement. However, the use of recycled plastic fibres in concrete may improve some concrete properties around ductility. One aspect which is also less well studied is around the recycling of concrete containing plastics after demolition. A potential possible solution would be to use it as recycled aggregates in new concretes, although as pointed out above this may not be an improvement compared with conventional mineral aggregates.

3.3.3.4 Regenerate strategies

Circular Economy approaches also propose the progressive shift away from fossil-based plastics to bioplastics, which are produced from renewable biomass. This has given rise to a rapid adoption of bioplastics especially in food packaging and other packaging applications.

The term bioplastics has different meaning and include plastics whose monomers were derived from biomass and then polymerized through chemical mechanisms, which will behave in the same way as traditional plastics polymers; plastics where polymer was extracted from biomass and plastics derived from biomass which are biodegradable.

Several studies have explored the potential benefits of moving away from fossil-based plastics towards bio-based plastics, but most of these analyses have also highlighted potential trade-offs. Rosenboom et al. (2022) conduct a review to conclude that bio-based plastics may exhibit a lower carbon footprint under certain circumstances and can be made compatible with existing recycling streams, as long as better information and segregation is provided, including Anaerobic Digestion and composting in controlled environments in industrial settings. The authors though list potential negative impacts on land and agriculture (e.g. competition with food production), current unclear EOL management routes and potential higher costs of both manufacturing and treatment.

Therefore, policy interventions need to ensure that the promotion of bioplastics is done under certain manufacturing conditions and EOL routes exist to manage bioplastics at the end of life, as well as providing further information to consumers about the carbon footprint of different alternatives.

4 Policy gaps

The review of CE policy, targets and roadmaps have provided an overview of existing policy landscape and prospective CE strategies that can accelerate the transition towards a circular economy. The review of existing policies and targets concludes that they tend to concentrate on the areas of recycling, recovery, and resource/material efficiency while more ambitious CE strategies, such as material conservation, reusing, refurbishing or Service Systems – PSS solutions are only started to be addressed by policy targets or are restricted to roadmaps and visioning documents. These findings align with previous studies reported in the literature such as Morseletto (2020), which also points to a narrow conceptualisation of CE policies. This implies that new policies and targets are urgently required to better reflect a system perspective that addresses the full range of CE strategies and understand the multifaceted nature of CE interventions.

As the review has also shown, most current CE policies tend to adopt a sector-by-sector approach while the intersectoral dependencies and feedback loops are less well understood. In steel and cement, where there are well established by-product exchanges and potential for shared interventions to improve material efficiency and decarbonisations, most actions are still restricted to intra-sector optimisation opportunities rather than exploring synergies across sector. An example of these ross-fertilisation opportunities is the co-production of recycled steel and cement. Through a new process, a spin-off of Cambridge university claims to have obtained emissions-free route for production of Portland cement combining steel and cement recycling into a single process using renewable electricity.

Another area of cross-sectoral innovation and collaboration is industrial symbiosis networks in Europe, which are present around highly concentrated areas of industry (Domenech et al., 2017), are where networking and collaboration to share materials, energy and materials as well as knowledge and other intangible resources have promoted slowing, narrowing and closing the loop strategies. While there is some regional support to this networks, targeted policies to promote these networks are largely missing from the overall policy landscape.

Connected to the above, better understanding of industrial ecosystems and geographical flows of materials and energy is needed to be the basis of informed policy decision-making around optimising industrial ecosystems and promoting cooperation within and across sectors. While there are some good comprehensive production, waste and emissions datasets they are not integrated and generally not have a local, regional resolution to identify opportunities to reduce and optimise resource use or adequate reutilisation of waste heat and resources. Some of these synergies also face obstacles in terms of lack of harmonisation of policies across MSs borders or complex regulatory requirements around the transportation of waste.

Another key important policy gap derives from the disparity between policy targets and ambitions and the ‘underlying operational policy frameworks’ which tend to reinforce linear rather than circular approaches (Milios, 2018). The analysis has revealed that while steel and cement have been subjected to stringent emission reduction regulations and pricing mechanisms, there have been much less attention to address material efficiency, unless connected with decarbonisation, through the slowing and narrowing strategies. In fact, while regulation has proven a key driver in the decarbonisation efforts of these two sectors, strategies such as the reuse of structural steel in buildings, or reuse of concrete slabs and panels are faced with numerous barriers, such costs associated with recertification or storage. Regulatory strategies to reduce construction waste from landfill have helped to promote recycling of concrete but this have tended to be in the form of downcycling as filling material or secondary aggregates rather than reuse or life extension.

While the secondary market of scrap steel works given sustained high prices of secondary steel, most of it would be either remelted or even exported to third countries. The use of scrap in electric arc furnaces (EAF) can result in significative reductions in energy consumption and savings in resource use. In 2022, secondary steel production accounted for around 43% of total EU steel production while the availability of scrap if it was not exported could satisfy material requirements of over 65% of EU production (Hague and Rulik, 2023).

For plastics, most of the policy effort has focused on packaging applications, while the other 60% of plastics used across other sectors are largely overlooked. New legislation has established new targets for reduction and reuse of plastic packaging, but effectiveness in reducing plastic packaging use and reuse is still unproven.

Furthermore, evidence of life cycle thinking and considerations along the life cycle stages is not always adequately reflected in current CE policies. While the new product regulations place special emphasis on design processes informed by life cycle assessment, there is lack for aligned interventions across actors along the life cycle phases. An example may be inconsistencies in the promotion of bioplastics as an alternative material to conventional plastics but inadequate systems to treatment at the end of life or the promotion of composite materials to increase material and energy efficiency that may led to generation of problematic waste streams.

Based on the analysis, we have identified several gaps in current policy landscape and key challenges for adoption of ambitious CE actions. These have been summarised in the table below.

Table 4-1: Areas of Policy Gaps for Circular Economy

Areas of Policy Gaps	Description of the gap
Lack of focus on resource consumption	Limited attention to absolute consumption of resources, with only target on reduction of waste of plastic packaging. Politt et al. (2023) have proposed a consumption charge for energy intensive materials in Europe with could help to reduce demand for these materials.
Traceability of emissions and raw material needs	EU lacks traceability of demand-based emissions and associated raw material requirements for imports of complex products and material intensive materials.
Misalignment of regulations	Lack of alignment between product regulations, chemical regulations, and end-of-life regulation.
Recycled content targets	Promotion of secondary materials through recycled content targets is limited to certain products or materials, and there is poor traceability of secondary, recycled sources.
Chemical recycling debate	The EU still requires an open discussion on whether chemical recycling with a mass balance chain of custody should count toward recycling content targets as well as an identification of environmental impacts of chemical recycling technologies.
Industrial symbiosis promotion	Limited promotion of industrial symbiosis as a tool for regional industrial development to address cross-sectoral opportunities to optimise material and energy cycles.

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Limited reuse initiatives	Minimal focus on reuse; only packaging has reuse targets, leaving potential in other sectors largely unexplored. Reuse of construction material has proven technically feasible but faces numerous barriers at the moment, as discussed in the steel and cement sections.
Barriers to reuse	Reuse is hindered by fragmented interpretations of the "right to repair," high labour costs, and low prices of imported products in sectors like electronics.
CBAM limitations	CBAM (Carbon Border Adjustment Mechanism) does not address broader environmental impacts beyond carbon, omitting material efficiency and upstream environmental impacts.
Consumer information on environmental impact	Citizens have limited access to environmental impact information on products; energy labels lack data on manufacturing and disposal impacts.
Product and building passports	Currently limited to batteries and buildings; There is potential for material passports to include a wider range of products and services for better material tracking.

5 CE key policy interventions along the life cycle

This report has provided a review of CE strategies with potential for decarbonisation across three main carbon intensive sectors of the EU economy. The strategies have been organised along the slowing, narrowing, closing the loop and regeneration framework. The review identify progress in the adoption of more ambitious circular interventions and further attempts for higher integration across decarbonisation and circularity pathways. However, the analysis has also highlighted that there is still policy gaps related to: 1) better integration of cross-sectoral opportunities for decarbonisation and circularity informed by a deeper understanding of industrial ecosystems and optimised used of materials and energy across sectors and 2) gaps related to addressing the tighter loops in CE moving away from recycling to a fully circular use of resources and materials.

There has also been increasing efforts for adopting a a life cycle perspective in the design of policies which has had a reflection in the new sustainable products regulations. However, a more systematic adoption of life cycle thinking across different policy domains and sector is still underdeveloped. This is key to ensure that the transition towards circularity is consistent with sustainability and decarbonisation and across sectoral interventions. In this paper, we propose the adoption of an overarching life cycle approaches which unveils interactions along the value chain and life cycle stages (as represented in Figure 5-1below).

The study also identify a number of policies which are transversal across all stages of the life cycle and that need to be considered in an ambitious and consistent decarbonisation and CE policy mix: (1) design of knowledge and information systems that increase traceability of resources, materials and products across different material and product systems; (2) policies for creating the conditions for secondary material markets to emerge and develop and (3) policies which engage public and private actors, including citizens, to move towards green procurement and consumption practices.

Mining/Extraction :	**Manufacturing**	**Use**	**End of Life**
Policies:	Policies:	Policies:	Policies:
•Sustainable resource extraction •Reduced material use, with targets for decoupling •Promote the use of renewable resources •Maintenance of natural capital	•Eco-design for longevity •Use of recycled content •Energy-efficient production •Waste minimization strategies	•Design for durability and repairability •Shared usage models (leasing, sharing) •Product maintenance support	•Recycling and resource recovery •Design for disassembly •Circular supply chains (closed-loop recycling) •Landfill reduction policies

Figure 5-1: Interactions of policies along the whole life cycle stages

While many of the policies listed have been discussed or are in the description of sectoral roadmaps, there is no overarching CE strategies across the different sectors, materials and life cycle stages. This creates additional burdens in the implementation of CE interventions and potential lack of alignment across policy areas. While the CE monitoring framework has been extended and improved in recent years, there are no KPIs around absolute decoupling and sustainable resource extraction. Recent policies such as the Raw Material Act, are a good example of integration of CE principles in the area of Critical Minerals but have a limited scope. More policy focus is needed in setting the structure of incentives for economic actors aligned with CE principles, to avoid a split of incentives in pursuing CE practices that incur additional cost.

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