TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 26/05/2025

D3.6 – Increased understanding of the potential contribution of CE to decarbonisation

WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs

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Grant Agreement Number	101137606		**Acronym**	TRANSIENCE
Full Title	TRANSItioning towards an Efficient, carbon-Neutral Circular European industry			
Topic	HORIZON-CL4-2023-TWIN-TRANSITION-01-36			
Funding scheme	HORIZON EUROPE, RIA – Research and Innovation Action			
Start Date	January 2024		**Duration**	48 Months
Project URL	https://www.transience.eu/			
EU Project Advisor	Fátima GONZÁLEZ GÓMEZ			
Project Coordinator	Institute of Communication and Computer Systems (ICCS)			
Deliverable	D3.6 – Increased understanding of the potential contribution of CE to decarbonisation			
Work Package	WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs			
Date of Delivery	**Contractual**	31/05/2025	**Actual**	26/05/2025
Nature	Report		**Dissemination Level**	Public
Lead Beneficiary	Utrecht University (UU)			
Responsible Author	Gergő Sütő		**Email**	g.m.suto@uu.nl
	UU		**Phone**	
Contributors	Li Shen, Ernst Worrell (UU); Teresa Domenech Aparisi, Zijie Ma, Haoning Liu (UCL)			
Reviewer(s)	Konstantinos Koasidis, Alexandros Nikas [ICCS]; Georg Holtz [WI]; Christian Bauer [PSI]			
Keywords	circular economy; decarbonisation; concrete; steel; plastics			

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

The report is targeted at the broader stakeholder community of the TRANSIENCE project, including scientific and policy audiences as well as the general public, providing a high-level overview of the potential contribution of circular economy approaches to mitigation efforts in industry.

3. Short summary of results (<250 words)

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is increasingly 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 (CE) and understanding its interactions with climate action. The TRANSIENCE project set out to investigate CE opportunities for the decarbonisation of three European basic industries: steel, cement, and plastics. The current deliverable report aims to answer a main question: what is known about each CE intervention's potential contribution to climate change mitigation for the three sectors in Europe? To answer this question, we examined primarily peer-reviewed literature that took aim at quantifying the potential impacts of any of the selected CE interventions. We critically reviewed the reported potentials for the reduction of greenhouse gas (GHG) emissions, while also considering connected influences on resource and energy use, behavioural changes, and economic impacts.

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
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PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
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Executive Summary

The TRANSIENCE project set out to investigate circular economy (CE) opportunities for the decarbonisation of three European basic industries: steel, cement, and plastics. Prior work has put forward a set of CE interventions in the respective value chains of these materials, spanning the manufacturing, use, and end-of-life treatment of products in major end use sectors. This report aims to answer a broader question: what is known about each CE intervention's potential contribution to climate change mitigation for the three sectors in Europe?

To answer this question, we have examined mainly peer-reviewed literature that took aim at quantifying the potential impacts of any of the selected CE interventions. We critically reviewed the reported potentials for the reduction of greenhouse gas (GHG) emissions, while also considering connected influences on resource and energy use, economic impacts, and behavioural changes, where relevant. We found that:

(1) CE interventions aimed at lifetime extension ('slow' strategies) or reducing material use ('narrow' strategies) often offer the highest GHG mitigation potential for all three sectors

(2) Some substitution interventions could also offer substantial GHG emission reductions, for example, using timber to replace cement

(3) major trade-offs between environmental and economic impacts of those CE interventions may exist, and it is therefore important to understand broader implications of circularity strategies from a systemic point of view.

Our findings are intended as an overview of which interventions have been found to have the largest potential impacts. Such overview will come useful as a point of reference for any results from the project's MIC3 modelling framework, when it becomes operational at later stages of TRANSIENCE.

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1 Introduction

As postulated by its ISO definition, a circular economy (CE) aims not simply at achieving resource efficiency but thereby also at mitigating climate change (ISO 59004:2024). With this notion in mind, the TRANSIENCE project set out to investigate CE opportunities for the decarbonisation of three European basic industries: steel, cement (and concrete), and plastics. This report aims to answer a main question: what is known about each CE intervention's potential contribution to climate change mitigation for the three sectors in Europe?

To answer this question, we examined current literature that took aim at quantifying the potential impacts of any of the selected CE interventions. We critically reviewed the reported potentials for the reduction of greenhouse gas (GHG) emissions, while also considering connected influences on resource and energy use, behavioural changes, and economic impacts. The findings are intended as an overview of the interventions that have been found to have the largest potential impacts. Such overview will come useful as a point of reference for any results from the MIC3 modelling framework, when it becomes operational at later stages of the project. Additionally, the review process revealed key considerations for both the integration of CE interventions in MIC3 and a transparent reporting of potential simulated impacts. Therefore, the learning points derived from this review will help the TRANSIENCE project advance its contributions to CE literature in terms of comparability, accuracy, and transparency.

After the methodology section (Section 2), the main body of this report is split into three sections corresponding to the material value chains of cement, steel, and plastics (Sections 3-5, respectively). Each section describes the literature findings and summarises the impact ranges from literature in the form of tables.

2 Method

This report builds on the earlier project Deliverable D3.5, which put forward a set of CE interventions in the value chains of plastics, steel, and cement. Using the structure of interventions provided by D3.5, the current report undertook a literature review of scientific articles and reports in the Scopus database. The queries targeted search terms found in the title, abstract, and keywords of papers published since 2015. Synonyms of key search terms, such as climate change, were included to maximise literature coverage. Querying was carried out separately for the three value chains of plastics, cement, and steel, from March to May 2025.

The entries returned by the database went through several rounds of assessment to exclude irrelevant studies. Papers perceived relevant based on title or abstract were downloaded. After further inspections, downloaded papers were either rejected or shortlisted for further review. Exclusion criteria were always argued and documented, typically because some articles were irrelevant to the aim of this review, crucially missing the quantification element of CE impacts. For example, many engineering-oriented studies (e.g., optimising the performance of industrial processes and products) mentioned CE and decarbonisation as their goal or motivation but ultimately did not quantify impacts on emissions or resource use. The span of literature was further expanded by snowballing from studies returned by the main query, particularly review papers. In line with the focus of the TRANSIENCE project, the primary attention was given to European studies as the impacts reported in other geographies are expected to be markedly different, decreasing their relevance. Ultimately, grey literature and studies with a geographical focus outside Europe were occasionally considered when more relevant studies were not found in our sample.

The presented results can be considered as a preliminary review, which we suggest expanding to eventually form a systematic review. In this report we provide a highlight of the findings obtained thus far. The ongoing work will be continued with the review of additional articles in the second phase of the project when the structure of MIC3 is more articulated.

3 Cement and Concrete

For the value chain of cement and concrete, a total of 213 peer-reviewed articles were initially returned by the Scopus database. Papers were prioritised for this preliminary review based on relevance of the assessed CE measures, quantified impact categories, and geographical coverage. To extend the body of literature reviewed, additional studies were added by snowballing through studies citing or cited by those in the original query. The present section highlights the findings from the 25 studies reviewed in-depth for this value chain.

The most frequently applied methodology in the literature identified was Life Cycle Assessment (LCA), accounting for about three quarters of the studies. A mix of both attributional and consequential LCAs appeared in the sample. Other methods included Material Flow Analysis (MFA), macroeconomic studies, such as Input Output Analysis (IOA) and Computable General Equilibrium (CGE) modelling. Notably though, Integrated Assessment Models (IAMs) were underrepresented in the reviewed literature.

Climate change mitigation was the primary focus of this review. A key difference is found in the scope of emissions. The majority of the identified studies assessed cradle-to-grave emissions excluding the use phase. For example, this can be problematic for building (or building stock) level assessments, because changes to the material composition of buildings can influence their use-phase (operational) energy use. A review by Hertwich et al. (2019) may illustrate the lack of building-related CE literature that includes operational energy use as the authors had sufficient evidence to indicate energy use impact only qualitatively, e.g., an increasing, decreasing, or neutral effect. Consequently, the findings of embodied-only studies need to be carefully put in context with those assessing both.

Not all studies assessed climate change impacts. Several studies focused on resource use and/or energy use, with notable differences in their scope, e.g., inflow, outflow or stock addition, as well as primary or final energy. Many LCA studies also reported impact on eutrophication, acidification, etc., although usually receiving minimal attention in these papers. Assessments of the economic implications of CE strategies were notably scarce in the identified literature, even though the search query is not expected to explicitly exclude studies from economic fields.

Besides differences of methods and scopes, another aspect complicating the inter-comparison of studies is the unit of product for which impacts are estimated. In LCA studies, this usually corresponds to the functional unit and differences thereof. For example, a unit of concrete can be expressed in terms of kilograms (kg), square (m^2), or cubic meters (m^3). Therefore, a full comparison should consider the related physical properties, such as the density, thickness, or compressive strength, of the different concretes. Table 1 shows the value chain stages and corresponding measurement units that were typically observed in the reviewed literature.

Table 1. Different units observed in literature to report specific GHG emissions in given value chain stages.

Value chain stage	Measures of unit
Clinker	kg
Cement	kg
Concrete	kg, m^2, or m^3

Construction element	m^2 or m^3
Structure (building or infrastructure)	m^2, or single structure
Stock (of buildings or infrastructure)	m^2, single structure, or total stock

Table 2 then provides the overview of the mitigation potential of key CE interventions for the use of cement and concrete as reported in the literature identified and reviewed for this report. The following subsections then describe the measures and enabling conditions in further detail, including the interplays between resource and energy use, economic consideration and behavioural aspects where relevant.

Table 2. Overview of the climate change mitigation potential of CE interventions in the cement value chain, as reported in reviewed literature.

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
Narrowing CE strategies				
Reducing floor space demand (C1.1)	Pauliuk & Heeren, (2021), Germany	Avg. 32 m^2 floor area per capita	Avg. 41.6 m^2 floor area per capita	-6.3 $MtCO_2e$ (-8%) in 2050
	Pauliuk et al. (2024), global	–1 m^2 floor area per capita	LEMD, SSP1, and SSP2 reference scenarios	-3 to -10 $GtCO_2e$ (1-3%) cumulative 2020-2050
Design buildings for longer life and repurposing (C2.1)	Eberhardt et al. (2019), Denmark	Office building with DfD elements, with 2-3 use cycles	Conventional design (227 $kgCO_2/m^2$)	-15% to -21% per m^2 floor area
	Brambilla et al. (2019), United Kingdom	DfD floor slab, with 2 use cycles	Floor slabs, with 2 use cycles (296-336 $kgCO_2e/m^2$)	-27% to -35% per m^2 floor slab
Design of buildings with less cement and concrete (C2.3)	Scott et al. (2019), United Kingdom	Resource efficient design optimisations, with up to 9% material savings	Conventional construction practices (under current policies)	-7.1 $MtCO_2e$ (or -24%) in construction sector in 2032
Substituting CE strategies				
Timber as substitute for concrete (C4.1)	Fischer et al. (2023), Austria	Timber structure	Reinforced concrete structure	-118% per building
	Petersen & Solberg (2005), Norway & Sweden	Various timber substitutes	Various conventional concrete elements	-100 to -400 $kgCO_2e$ per m^3 timber
	Kumar et al. (2024), USA	Mass timber construction of multi-story houses	Reinforced concrete construction of multi-story houses (460-508 $kgCO_2e/m^2$)	-39% to -51% per m^2 floor area; -81% to -94% incl. carbon sequestration
Cement with clinker substitutes (C4.2, C4.4)	Bushi & Meil (2014), Canada	Portland-Limestone Cement (13% limestone)	OPC (0.95 $kgCO_2e/kg$)	-10% per kg cement
	Pillai et al. (2019), India	Limestone Calcined Clay Cement (31% calcined clay, 15% limestone)	OPC (0.82 $kgCO_2e/kg$)	-32.5% per kg cement

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
		Slowing CE strategies		
Renovation of buildings (C6.1)	Silva et al. (2022), Portugal	Residential building refurbishments (7 cases)	Full reconstruction (50-65 kgCO_2e/m^2)	-73 to -87% per m^2 floor area
Reuse of building elements in new construction (C5.1, C8.1)	Küpfer et al. (2024), Switzerland	Secondary reinforced concrete floor slabs	Primary RC floor slabs (68-85 kgCO_2e/m^2)	-80% per m^2 floor slab
	Andersen et al. (2020), Denmark	Reuse of concrete elements, on-site	Conventional concrete (103 kgCO_2e/m^2)	-95 to -96% per m^2 concrete
		Closing CE strategies		
Recycling concrete waste as aggregate (C10.1)	Mostert et al. (2021), Germany	Concrete with recycled aggregate	Conventional concrete (312-320 kgCO_2e/m^3)	-4% to +1% per m^3 concrete
	Andersen et al. (2020), Denmark	Concrete with recycled aggregate	Conventional concrete (103 kgCO_2e/m^2)	-10% to +9% per m^2 concrete
	Kursula et al. (2024), Finland	Concrete with recycled manufactured aggregate	Conventional concretes (320-330 kgCO_2/m^3)	-38% to -39% per m^3 concrete
Recycling cement and concrete waste as ACM (C10.3)	Sousa & Bogas (2021), Portugal	Recycled cement as clinker substitute	OPC clinker (0.80 kgCO_2/kg)	-32% to -38% per kg cement

Note. The system boundaries of studies are not harmonised, thus GHG emissions are not directly comparable. Intervention identifiers (IDs) refer to Deliverable D3.5.

New cements and Alternative Cementitious Materials

Alternative (or Supplementary) Cementitious Materials (ACMs) can be used to replace a part of clinker in cement production. ACMs have recently gained attention mainly for having lower embedded GHG emissions than clinker. Their complete substitution, however, is not feasible due to ACMs possessing other engineering properties. Depending on the type of ACM used, blended cement compounds can demonstrate either lower, equivalent, or, in specific applications, higher binding qualities than Ordinary Portland Cement (OPC).

The use of ACMs is common practice in cement production. In Europe, the average clinker to cement ratio, also known as clinker factor, is around 77% (CEMBUREAU, 2024). Limestone, blast furnace slags (BFS, from primary steel production) and fly ash (FA, from coal-fired power plants) are the most common ACMs by weight (Favier et al., 2018). Cement made with some combination of these three ACMs is categorised as CEM-II by the harmonised European standard EN 197-1. Due to the planned decrease of coal power supply, the availability of FA is expected to become progressively more limited. Similarly, the increase of steelmaking without blast furnaces (e.g., direct iron reduction, secondary steel) can curb BFS outputs, even though the slow expansion of these alternative production routes suggests the continued availability of BFS for the foreseeable future. Bushi & Meil (2014) estimate that a 13% replacement of clinker by limestone alone can decrease GHG emissions by about 10% per kg of cement, when compared to OPC. Nehdi et al. (2024) indicate limestone to be a weak ACM by itself, while its combination with other ACMs holds greater mitigation potential. This is supported by Pillai et al. (2019) who found cement consisting of 31% calcined clays and 15% limestone to be associated with 32% lower GHG emissions than the same unit of OPC.

The comparison of new cement types to OPC as a standard is found commonly in literature and is useful in

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the intercomparison of studies. At the same time, OPC actually makes up a minority of cement use in Europe, about 20% (Favier et al., 2018), implying that the embodied GHG emissions of the 'industry average cement' are lower, which, in turn, can lead to an overestimation of savings when alternative cements are compared to OPC.

Innovative cement types with a wide range of ACMs are undergoing research and development. A recent review of the new alternatives in cement production is offered by Nehdi et al. (2024). The most common barriers for new cement types to gain widespread use have to do with the availability of their ACM components and/or their use being limited to specific applications in construction. The latest net-zero roadmap for the European cement industry by CEMBUREAU (2024) counts on ACMs and new cement types to reduce the average embodied CO_2 emissions of cement by 0.41 $kgCO_2/kg$ (or 6%) between 2021 and 2050. Additionally, this roadmap set the 2050 target for the clinker factor of cement at 60%, advancing from the earlier 65% target in the 2020 roadmap (CEMBUREAU, 2020), suggesting confidence in further progress on the increased use of ACMs.

Lifetime extensions by renovation and reuse

The extension of the lifetime of structures and their concrete-containing components holds potential for climate change mitigation by avoiding the construction and manufacturing of new ones. Lifetime extension at the scale of structures is commonly referred to as renovation and has a long-standing tradition in the construction industry. In CE literature, the categorisation of different kinds of renovations is not always consistent or straightforward (Lotz et al., 2024). Using the widely adopted 9R framework, the strategy Repair may best refer to maintaining a structure's original functionality, or restoring it thereto in case of damage or degradation. Repairing a structure extends its technical lifetime. When the renovation includes the upgrade of the structure's original functionality, such as the case with energy efficiency improvements, it is typically referred to as Refurbishment. Refurbishing a structure can extend both its technical and functional lifetime, by keeping up with the progression of building standards and changing user needs.

For both repair and refurbishment, the mitigation potential depends on a couple of factors. As any form of renovation is associated with added embodied emissions, the lifecycle climate impact is determined by subsequent operational emission savings, if any, and the duration of lifetime extension realised (Ramon & Allacker, 2023). Silva et al. (2022) discuss advanced structural inspection techniques that enables the refurbishment of old buildings, thereby avoiding demolition and complete reconstruction. In seven case studies, they found 73-87% reduction of embodied GHG emissions per gross floor area, while assumed operational emission energy use to be equivalent. It is suggested that the realised mitigation benefit of refurbishments can be significant but has to be evaluated on a case-by-case basis.

Another CE strategy for lifetime extension is the reuse of concrete elements if the structure around them is scheduled for demolition or deconstruction. The potential for reuse occurs when the technical lifetime of an element is longer than the functional lifetime of the structure containing it. Conceptually, this activity can be categorised in the 9R framework as either Reuse or Remanufacturing, though the terminology is not consistently applied in literature. In practice, reinforced concrete (RC) elements are liberated from the rest of the structure via saw-cutting into appropriate pieces. According to Küpfer et al. (2024), most reinforced concrete floor slabs destinated for demolition are likely to meet structural requirements for reuse in new buildings. In their assessment, reusing these floor slabs saves on average 80% GHG emission per m^2 compared to the manufacturing of new slabs. Similar findings were also reported by Andersen et al. (2020) who assessed the on-site reuse of concrete elements and found 95-96% GHG saving potential over primary

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manufacturing, suggesting that avoiding transportation of the heavy slabs has sizeable additional mitigation potential.

The largest barriers to reuse are twofold. On the one hand, deconstructing structures in a way that preserves usable elements is considerably more complex and therefore expensive than conventional demolition (Lotz et al., 2024). Additionally, the process of verifying the suitability of reusable components (e.g., quality assessment of technical performance) is not fully established and governed.

Towards addressing these barriers, various adaptations in the design of structures have been put forward to enable easier reuse at the end of their life cycle. Design for reuse includes the standardisation of elements, modular design, and the documentation of technical properties via material passports or Building Information Modelling (BIM) software. Since a longer lifetime is assumed for elements 'designed for reuse', these are often built with additional robustness (e.g., thicker, stronger) than their single-use counterparts. This trade-off means that 'design for reuse' may lead to additional resource use and embodied emissions on the short term, with benefits only realised with significant time delay and on the condition of successful reuse. To illustrate this, Lotz et al. (2024) estimate that a widespread adoption of design for reuse in the EU could *increase* the demand for cement and concrete by as much as 25% in 2050, compared to a reference scenario. Even so, studies that looked beyond 2050 in fact found considerable GHG emission savings overall. Brambilla et al. (2019) assessed DfD for reinforced concrete floor slabs and found 27% to 35% mitigation potential, compared to conventional designs over 2 use cycles. A similar range of impact is found by Eberhardt et al. (2019) who considered a number of DfD elements for an office building and estimated GHG emissions savings of 15-21% per m^2 floor area over 2-3 use cycles. The comparison of these studies suggests that 'design for reuse' has a notable mitigation potential which however might be realisable in a few decades time and on the condition of effective governance that enables reuse. Additionally, a successful decarbonisation of primary cement and concrete production could also lower the relative emissions savings from reuse in the future.

Recycling

Waste concrete from construction and demolition (C&D) can be utilised as secondary material in different applications. Concrete waste is commonly crushed into coarse particles and used as partial replacement for excavated aggregates. The most common application of crushed concrete is as filling material in road construction. While often referred to as recycling, using crushed concrete in road beds does not preserve the integrity of the material and is therefore accounted in the European Union's waste statistics as *backfilling*, a type of recovery distinguished from *recycling* (Eurostat, 2023).

Higher value applications can be achieved by the adequate sorting and processing of C&D waste, producing recycled (concrete) aggregates (RA), which can then be used in new concrete production as replacement of natural aggregates. A considerable amount of literature has focused on the impacts of concretes incorporating RA. Findings indicate that RA-based concretes have benefits for primary resource conservation, but their emission mitigation potential depends on certain enabling conditions as aggregates are not the most emission-intensive components of concrete. Due to the bulky nature of aggregates, the most important enabling factors for their mitigation benefit are 1) the transportation distance between the sites of demolition, recycling facility, and new construction, and 2) the emission-intensity of the energy used for their processing. Mostert et al. (2021) compared RA-based and conventional concretes in different exposure classes and found average impact on GHG emissions between -4% to +1% per unit of cement. A study by Andersen et al. (2020) reported similar findings with slightly wider impact ranges, between -10% to

+9%. These studies suggest that the use of RA-based concrete can be disadvantageous from a mitigation perspective when the above-mentioned enabling conditions are not met. Additional embodied emissions can also result from low RA quality, requiring higher cement content to meet the same performance requirements for concrete. Lastly, even when all these conditions are met, the additional costs associated with RA processing can render the recycling of waste concrete more expensive than predominant applications, such as in road construction (Lotz et al., 2024).

Beside coarse aggregates, the recycling of concrete and cement waste in fine aggregate and powder form has also gained attention (Gastaldi et al., 2015). Sousa & Bogas (2021) found that a novel method for recycling cement paste into ACM was associated with increased energy use but 32-38% lower GHG emissions than OPC clinker due to the bypassing of high temperature calcination. In another study, Kursula et al. (2024) performed a technical and environmental assessment of the granulation of fine concrete waste into aggregate and concrete made thereof. The authors found 38-39% percent emission reduction potential for this technology in laboratory conditions. Marsh et al. (2022), however, argue that research and development of these recycling applications is still in its early phase with dispute on their technical performance. As such, evidence on the trade-offs between their environmental benefits, mechanical properties and large-scale applicability cannot yet be established.

Timber

The use of timber as a substitute for concrete elements is increasingly considered in material efficiency literature as a lightweighting option. Hertwich et al. (2019) indicate that the climate benefits of timber in buildings are considerable and well established. The mitigation potential stems from the sequestration of carbon in wood, preventing its oxidisation, and the displacement of emission-intensive materials, such as concrete. Petersen & Solberg (2005) reported avoided GHG emissions typically in the range of 100-400 $kgCO_2e/m^3$ across several case studies in Norway and Sweden. At the scale of a building, negative embodied emissions can also be achieved as found in the case studies of Fischer et al. (2023). In fact, the study of Eberhardt et al. (2019), discussed above on design for reuse, compared Design for Disassembly with optimised timber structure and found 15-21% and 59% reduction potentials, respectively.

While displaying promising potentials for mitigation, the increased use of timber for construction is also problematic (Strengers et al., 2024). For one reason, timber cannot fully replace concrete elements, as is shown by the significant presence of reinforced concrete remaining in the timber scenario of the case studies above. More generally, Oliver et al. (2014) estimates that timber could replace about 10% of building materials. The availability of (additional) timber for use in construction is limited. In Europe, there are differences of both local availability and suitability for construction between Northern and Southern Europe. Additionally, increased timber production would compete with other (land) uses which can drive up prices of timber and other organic materials. Conclusively, the use of timber as substitute for concrete construction elements is a material efficient option that should be considered in the decarbonisation of construction, though important barriers limit its overall potential in the broader set of interventions.

Lessons learnt for TRANSIENCE

While the review presented in this study was not systematic, we draw a couple of cautious conclusions that can be taken up by the TRANSIENCE project. It has been observed that review papers valuably mapped out the various conditions and implications of CE interventions in the cement value chain (e.g., Hertwich et al., 2019; Nußholz et al., 2023; Gallego-Schmid et al., 2020; Nehdi et al., 2024). With the exception of Nehdi et al. (2024), these reviews were mostly focused on CE strategies in buildings and infrastructure, with the

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implications for basic industry minimally assessed. Additionally, the comparison of the impacts of CE strategies (e.g., which has higher mitigation potential) could only be established to a limited extent by review papers due to differences of methodological choices. Some modelling studies compared different CE measures but either reported their mitigation potential at a broader level (e.g., Narrow/Slow/Close distinction) or their methodology missed technical details. A comparative modelling of detailed CE measures is offered by Lotz et al. (2024) using material flow and stock modelling but only assesses impact on basic material demand, not climate change mitigation. There appears to be a gap in the literature for the comparative assessment of individual CE interventions (i.e., beyond the broad Narrow, Slow and Close sets) and their mitigation potentials for European basic industry. This gap could be effectively filled by the MIC3 model developed in the TRANSIENCE project—and is expected to be informed by the quantification of impacts of CE strategies in this report—as its modules offer the capability to represent individual CE interventions and the technical and socioeconomic implications thereof.

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4 Steel

Steel is one of the most widely used materials with applications in construction, transportation, industrial equipment, appliances, packaging and others. The current chapter focuses on the use of steel in buildings and passenger vehicles as these will be represented in detail in the EU MFA module of the project's MIC3 modelling framework. These product sectors are among the largest consumers of steel, with about one third of end-use steel going to buildings and one eighth to vehicles.

The initial search query in Scopus returned 692 studies. Similar patterns were observed for steel as for concrete regarding the most frequent methodological choices and impact categories reported. Different to cement, our literature search has uncovered a relatively low number of relevant studies focusing on Europe, while North American studies were represented to a much larger extent. While some studies are rather context independent, we are aware that this decreases the overall relevance of our findings to the context of the project. The current chapter is based on an analysis of 30 studies.

Table 3 gives the overview of the mitigation potential of key CE interventions in the value chain of steel as reported in the literature identified and reviewed for this report. As for the previous chapter, the subsequent sections describe the measures and enabling conditions in further detail, including the interplays between resource and energy use, economic consideration and behavioural aspects where relevant.

Table 3. Overview of the climate change mitigation potential of key CE interventions in the steel value chain, as reported in reviewed literature.

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
		Narrowing CE strategies		
Reducing floor space demand (S1.1, S2.3)	Pauliuk & Heeren (2021), Germany	Avg. 32 m^2 floor area per capita	Avg. 41.6 m^2 floor area per capita	-6.3 $MtCO_2e$ (or -8%) in 2050
	Pauliuk et al. (2024), global	–1 m^2 floor area per capita	LEMD, SSP1, and SSP2 reference scenarios	-3 to -10 $GtCO_2e$ (1-3%) cumulative 2020-2050
Public and/or non-motorised transport (S2.1)	Carroll et al. (2019), Ireland (Dublin)	+2.9% public transport use (1.8% diverting private car trips)	Urban transport system (Dublin) with high share of single passenger trips	-157.5 $ktCO_2$ annually
Car sharing schemes (S2.2)	Chen & Kockelman (2016), USA	Car sharing (adoption levels: low, mid, high)	Individual car ownership (245 gCO_2e/pkm)	-33% to -67% per passenger kilometre
Lightweighting steel beams (S2.4)	Drewniok et al. (2020), UK	Buildings with optimised beam design (-27% to -35% weight)	Buildings with regular universal beams (60 year lifetime)	Up to 5% per building life cycle
Modular construction (S2.5)	Teng et al. (2018)	Modular construction with various prefab methods, 26 case studies	Conventional construction methods (emb. 105-864 $kgCO_2/m^2$; op. 11-76 $kgCO_2/m^2/yr$)	-50% to +13% embodied; -11% to +6% operational CO_2 emissions

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
Lightweighting of vehicle components (S2.6, S3.1, S3.2, S4.2)	Lewis et al. (2014), USA	Lightweighting with aluminium (-15% to -35% body weight)	Plug-in hybrid vehicle (152 gCO_2e/km)	0% to -6% per vehicle kilometre
	Lewis et al. (2014), USA	Lightweighting with high strength steel (-15% to -20% weight)	Plug-in hybrid vehicle (152 gCO_2e/km)	-4% to -6% per vehicle kilometre
	Czerwinski (2021), Canada	100 kg weight reduction	Conventional ICE vehicles	-8 to -11 gCO_2 per vehicle km
Substituting CE strategies				
Timber construction (S4.1)	Kumar et al. (2024), USA	Mass timber construction of multi-story houses	Structural steel construction of multi-story houses (381-398 $kgCO_2e/m^2$)	-28% to -34% per m^2 floor area; -76% to -91% incl. carbon sequestration
	Kumar et al. (2024), USA	Mass timber construction of multi-story houses	Reinforced concrete construction of multi-story houses (460-508 $kgCO_2e/m^2$)	-39% to -51% per m^2 floor area; -81% to -94% incl. carbon sequestration
Synthetic fibres as concrete reinforcement (S4.3)	Fernández Ruiz et al. (2024), Switzerland	Synthetic fibre reinforced concrete wall	Partition wall made of steel reinforced concrete (63-87 $kgCO_2/m^2$)	-8% to -59% per m^2 partition wall
Slowing CE strategies				
Reuse of structural steel (S5.1)	Berglund-Brown & Ochsendorf (2025), USA	Reused steel sections (9 case studies)	Steel sections from recycled scrap (1.22 $kgCO_2e/kg$)	-60% to -83% per kg steel
	Küpfer et al. (2024), Switzerland	Secondary reinforced concrete floor slabs	Primary RC floor slabs (68-85 $kgCO_2e/m^2$)	-80% per m^2 floor slab
Design structures for disassembly (S5.4)	Eckelman et al. (2018), USA	DfD flooring system, reused 0 to 3 times	Traditional design, no reuse (129-145 $kgCO_2e/m^2$)	+25% to –70% per m^2 floor space
	Brambilla et al. (2019), United Kingdom	DfD floor slab, with 2 use cycles	Floor slabs, with 2 use cycles (296-336 $kgCO_2e/m^2$)	-27% to -35% per m^2 floor slab
	Eberhardt et al. (2019), Denmark	DfD load-bearing steel columns, office building, 2-3 use cycles	Conventional design (227 $kgCO_2/m^2$)	-18% to -24% per m^2 floor area
Closing CE strategies				

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
Recover and remanufacture (S8.1)	Hertwich et al. (2019)	Remanufactured diesel engine	Newly manufactured diesel engine	-69% embodied GHG emissions
Scrap utilisation for steelmaking in EAFs (S10.1, S10.2)	IEA (2020), global	Scrap-based electric arc furnace (EAF) steel	BF-BOF and natural gas-based EAF steel (avg. 2.2 and 1.4 tCO_2/t)	-79% to -86% direct & indirect CO_2 emissions per ton of steel

Note. The system boundaries of studies are not harmonised, thus GHG emissions are not directly comparable. Intervention identifiers (IDs) refer to Deliverable D3.5.

More intense use of buildings

The more intensive use of buildings is increasingly discussed in the circular economy literature as a strategy to reduce GHG emissions. This approach includes a range of practices such as repurposing unoccupied buildings, designing multi-functional spaces, and partitioning houses for rental – especially when family sizes shrink, for example after children move out. A common metric to assess the impact of such interventions is the average per capita floor area (measured in m^2/cap), which can be readily calculated and is available in European national statistics. From the perspective of construction materials, minimising the need for new construction lowers the demand for a range of construction materials, including steel, cement, and plastics, making this intervention inherently cross-sectoral.

The mitigation potential of this strategy is well documented, although the reviewed studies did not distinguish emission savings related to specifically to avoided steel production. Pauliuk & Heeren (2021) modelled various material efficiency interventions for buildings and passenger vehicles in Germany and found that reducing per capita floor area to be the most impactful on emissions. They estimated that a 20% reduction – from 41.6 m^2 in 2015 to 32 m^2 by 2050 – could lower GHG emissions by 6.3 $MtCO_2e$, representing 8% of total emissions in that year. Their dynamic stock-flow modelling also accounted for building lifespans and renovation cycles. A subsequent global study using the same model framework (Pauliuk et al., 2024) estimated that a uniform reduction of 1 m^2 per capita could avoid 3000-1000 Mt of cumulative steel production and 3-10 $GtCO_2e$ (1-3% of cumulative total) emissions between 2020 and 2050, depending on decarbonisation pathways. While the latter finding is arguably harder to contextualise for Europe, it illustrates the potential of pursuing floor space optimisation as a strategy.

Notwithstanding, behavioural and societal preferences remain a major barrier for these interventions: per capita floor area has historically increased in Europe, and while younger generations may now be opting for smaller homes, this shift is likely driven by rising housing costs rather than by preference (Lotz et al., 2024). Reversing the trend toward smaller personal space will therefore require both policy innovation and cultural change.

More intense use of passenger vehicles

Since most privately owned cars remain unused for the majority of their lifetime and single-occupant trips are common, there is considerable potential to reduce per capita emissions through increasing the intensity of vehicles. Two primary approaches are typically discussed: shifting travel from private vehicles to public transport (modal shift) and expanding the adoption of car-sharing schemes. While conceptually appealing, these strategies involve complex dynamics. Carroll et al. (2019) conducted a detailed modelling study of the passenger transportation system in the Greater Dublin Area, in collaboration with Ireland's transport authority. The authors found a 2.9% increase in the share of public transport trips feasible, 1.8% of which diverted passenger car use, suggesting a less than equal displacement between public and private transport. Even so, this shift was estimated to yield annual CO_2 savings of 157.5 kt, demonstrating the tangible potential of relatively small behavioural changes.

Car-sharing has been studied as a more direct method to increase vehicle utilisation. Chen & Kockelman (2016) assessed its adoption across dense urban areas in the United States under varying uptake scenarios. They reported emission reductions ranging from 33% to 67% per passenger-kilometre travelled (pkm) compared to individual car ownership, with a reference emission factor of 245 gCO_2e/pkm.

These studies did not explicitly evaluate implications for steel demand or other material impacts. Furthermore, increasing the intensity of vehicle use brings trade-offs, including more frequent maintenance and shortened vehicle lifespans, which applies not only for passenger cars but any road (and rail) vehicle. Vélez (2023) adds further nuance, suggesting that rebound effects (e.g., displaced consumer spending after cost savings) may offset 70–85% of the anticipated emission savings, as estimated for car sharing in the Netherlands. These considerations highlight the importance of system-level modelling to capture both the benefits and unintended consequences of mobility optimisation strategies.

Using less steel in buildings

Reducing the amount of steel used in buildings is another key material efficiency strategy. One major opportunity lies in addressing the over-specification design practices common at the early stages of structural design (Favier et al., 2018). Engineers often incorporate generous safety margins, resulting in steel use beyond what is structurally necessary. Research by (Moynihan & Allwood, 2014) showed that nearly 50% of the steel in steel-framed buildings could be eliminated without violating safety standards. Complementary findings by (Dunant et al., 2018), based on real-world case studies, suggest that 30–40% material savings are achievable through improved design alone. Further analysis by (Drewniok et al., 2020) on beam and cross-section optimisation found that design refinement could reduce steel use by 27–35% by weight, translating into a 36% reduction in embodied emissions and a 5% decrease in total life-cycle emissions.

Despite these clear benefits, economic and logistical trade-offs remain. There is a tension between standardised steel components, which tend to be heavier but cheaper to manufacture at scale, and specialised, optimised designs that use less material but incur higher production and labour costs – particularly in high-wage regions like Europe. Interestingly, while heavier standardised elements may increase material use, they can facilitate reuse during building deconstruction, as their predictability simplifies disassembly and repurposing. As such, decisions between standardisation and specialisation should ultimately consider not only immediate material savings but also long-term circularity potential and overall environmental impact.

Lightweighting of passenger vehicles

Lightweighting of steel components in passenger vehicles presents mitigation potential mainly through improved fuel efficiency. This strategy primarily includes using either advanced high-strength steels or alternative materials such as aluminium, magnesium, and carbon fibre reinforced plastics (CFRP). Research into lightweighting strategies has been ongoing since the late 1990s, with a number of studies assessing both the technical feasibility and the life cycle emissions of these materials (Kim & Wallington, 2013; Lewis et al., 2014; Kelly et al., 2015; Czerwinski, 2021; Zhang & Xu, 2022; Gonçalves et al., 2022; Kalhor et al., 2025).

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Across the studies in our sample, no single material emerged as universally superior, though high-strength steel frequently showed the lowest life cycle emissions due to its relatively low manufacturing energy demand. Aluminium, while more energy-intensive to produce, was shown to achieve greater weight reductions and thereby contribute to higher emissions savings in certain cases. In contrast, magnesium and CFRP offer even greater weight reductions but are associated with significantly higher embodied emissions. For example, magnesium production commonly involves the use of SF_6 – a potent greenhouse gas – as a so-called cover gas. Furthermore, the limited recycling infrastructure for magnesium and CFRP currently constrains their circularity potential.

Despite these insights, generalising findings from individual vehicle-level assessments to the broader vehicle stock remains challenging. Zhang & Xu (2022) emphasise the complex set of decision-making factors that influence material choices in automotive design, which vary widely across manufacturers and vehicle classes. In addition, the mitigation potentials reported in older studies may be overstated today. We expect that manufacturers have since implemented many feasible lightweighting options, as suggested by a recent mapping of material use in vehicles (Zhang & Xu, 2022). Moreover, the effectiveness of lightweighting differs by powertrain type: for electric vehicles, which have higher emissions during manufacturing, the relative benefits of lightweighting are smaller compared to internal combustion engine (ICE) vehicles (Lewis et al., 2014).

The studies identified through our review largely focus on specific vehicle types or components, limiting their direct applicability to TRANSIENCE. Consequently, further literature search is recommended – potentially including grey literature – to uncover material, energy, and emissions savings applicable to the full vehicle stock, aligning more closely with MIC3 modelling needs. For instance, the UK Automotive Council's 2020 roadmap outlines weight reduction potentials across different vehicle types through 2025 and 2035, and could serve as a useful data point[1]. Additionally, Allwood et al. (2012) note that historical gains from lightweighting have often been negated by rising consumer demand for comfort and safety features, which has increased the overall mass of passenger road (and rail) vehicles. This trend should be factored into scenario development within TRANSIENCE. Finally, we recommend exploring the integration of fuel savings from lightweighting into the energy system module of the MIC3 model to capture the co-benefits of this intervention more completely.

Reuse and Design for Disassembly

The main uses of steel in construction can be broadly categorised in three forms: structural sections (e.g., beams and columns), reinforcing bars (rebars) within concrete, and sheet steel for cladding and purlins. Among these, structural steel offers the greatest opportunity for reuse, largely due to the high degree of standardisation in steel profiles. Allwood et al. (2012) note that even 40-year-old steel sections remain within current specifications, enabling easier recertification and reuse. They estimate that up to 80% of structural steel from buildings could be suitable for reuse. Their reuse from infrastructure (e.g., bridges) is less common, as these structures often serve their full technical lifespans. A study by Berglund-Brown & Ochsendorf (2025) demonstrated the mitigation benefit of reuse, finding that repurposing steel sections in multi-storey residential buildings could reduce GHG emissions by 60% to 83% per kg of steel, compared to

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[1] https://www.apcuk.co.uk/wp-content/uploads/2021/09/https___www.apcuk_.co_.uk_app_uploads_2021_02_Exec-summary-Technology-Roadmap-Lightweight-Vehicle-final.pdf

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using recycled scrap steel. However, the reuse of rebars is only viable when reinforced concrete components are reused as a whole, due to the difficulty and cost of separating steel from concrete. This underlines the importance of modular construction and design for disassembly (DfD).

The practical implementation of steel reuse involves a sequence of steps: deconstruction, design integration, reconditioning and certification, fabrication, and finally reconstruction. While deconstruction is essential in enabling reuse, it is more time- and labour-intensive than demolition, typically requiring specialised equipment and incurring higher costs. Certification and quality assurance further add to these costs, especially when material properties are unknown and must be re-tested. Storage is another logistical consideration, as reusable steel elements do not always find immediate buyers and must be stored for extended periods of time before reuse. Additionally, the current availability of reusable steel is limited due to the still-growing stock of buildings and infrastructure in Europe and the long average lifetime of structures, meaning that the amount of steel components from End-of-Life structures are far below their demand in new construction.

Utilising steel scrap

Steel is among the most widely recycled materials globally, with collection and recycling rates exceeding 90% for both production scrap and end-of-life products across all application sectors. The recycling process is technologically mature, with Electric Arc Furnaces (EAFs) used to produce secondary steel by re-melting scrap. However, the share of secondary versus primary steel production varies significantly between countries, including within Europe (Watari et al., 2025). According to the International Energy Agency, scrap-based steel production can result in 79–86% lower CO_2 emissions compared to primary production methods (IEA, 2020). Despite these high recycling efficiencies and the availability of low-emission production routes, primary steelmaking continues to account for approximately two-thirds of global output—a figure that has remained largely unchanged for over two decades (Watari et al., 2025).

This stagnation is primarily attributed to the structural imbalance between the growing global demand for steel and the limited availability of end-of-life scrap. While recycling helps reduce emissions significantly, it cannot alone satisfy material demand in a growing economy. Moreover, the increasing use of advanced steel alloys further complicates recycling efforts. Alloys with diverse chemical compositions must be carefully sorted to prevent cross-contamination, requiring more complex and resource-intensive processing. As a result, while steel recycling remains a cornerstone of circular material flows, its future potential to drive deep emissions reductions is considered limited without a concurrent reduction in overall steel demand and greater uptake of reuse and material efficiency strategies.

Lessons learnt for TRANSIENCE

CE interventions targeting products (e.g., buildings, vehicles) or services (e.g., housing, transportation) can reduce the demand for steel production and thereby hold mitigation potential. The literature identified for the purposes of this report, however, estimated GHG emission reductions from these interventions only at the level of product or service. The specific contribution of avoided or displaced steel production was thus not distinguished in the studies we found and reviewed. We recognise this as a potential knowledge gap, which could be addressed with the project's MIC3 modelling framework.

Additionally, the review highlighted a range of contextual and systemic factors that shape the feasibility and effectiveness of CE interventions across the steel value chain. These include technological, economic, behavioural, and regulatory dynamics, which must be considered for accurate and representative modelling of CE strategies. For example, in the context of vehicle lightweighting, changes in material use are

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intertwined with fuel efficiency improvements, which we suggest capturing in MIC3. Many such co-benefits and trade-offs can also inform scenario development, particularly in determining the plausible extent to which interventions can be implemented. Going forward, further research is needed to more robustly quantify the implementation potential and real-world uptake of these CE strategies, which will be crucial for assessing their role in decarbonising the steel sector.

5 Plastics

As with cement and steel, plastic is also a foundational material in modern societies. 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).

Packaging represents around 40% of all plastics. The revised EU Directive in Packaging and Packaging Waste established targets for recycling of plastic packaging of 50% in 2025 and 55% by 2030. For the first time, the Directive also includes reduction targets (5% by 2030, 10% by 2035 and 15% by 2040) specifically on plastic packaging waste as well as targets on the reuse of packaging (binding for 2030 and indicative for 2040). Importance is placed on reducing unnecessary packaging and empty space in packaging to minimise the weight and volume. Packaging is also part of Extended Producer Responsibility (EPR) schemes to financially contribute to its management, including the plastic tax/levy and charging non-recycled plastic packaging waste produced by Member States. Moreover, recent regulation has imposed bans on single-use plastics in certain applications and requires separate collection systems for single-use plastic bottles to achieve at least 90% collection rate or set up deposit return systems (DRSs) otherwise.

While packaging is the largest part of plastics, 60% of all plastics are used in areas of application across buildings and construction, vehicles, electronics, agriculture, and other applications. In construction, around 25% of plastics are currently recycled, followed by incineration (around 47%) and landfilling (27%), though large variations exist among polymer types (Plastics Europe, 2024). There are no specific regulations establishing requirements for plastics used in construction, beyond product regulations. For vehicles, the European Commission has set a target for plastics in new vehicles to consist of 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.

CE interventions

Slowing strategies imply slowing the flow of resources to keep plastics in the stock for longer to avoid waste generation. In the case of durable plastic products, relevant strategies include modular product design, affordable reuse and repair services, and refurbishing and remanufacturing plastic parts in specific sectors such as electronics and automotive. Some studies further examine the repurposing of synthetic textile fibres for use in building materials, such as insulation or composite construction components. Slowing plastic flows, however, also requires considerations around potential health and safety implications of extending the life of some of the plastics.

Narrowing strategies imply reducing the amount of primary plastics produced. Narrow strategies include lightweighting of plastics, new technologies for enhanced material-efficient design, and eliminating unnecessary or hard-to-recycle plastics. While these approaches can reduce material use and waste generation, they may also involve trade-offs—for example, between reduced weight and potential for life extension or long-term reusability.

Substitute and regenerate strategies propose the progressive shift away from fossil-based plastics to the use of bio-based, compostable, or paper-based alternatives, which have been mostly applied to the area of plastic packaging. While these alternatives have generally broader consumer acceptance, there have been ongoing concerns regarding their performance, scalability, costs, and end-of-life treatment in real-world conditions. Some LCA studies have also highlighted no or minimal benefits compared to conventional

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plastics.

Finally, closing the loop strategies focus on the end-of-life stage, and refer to ways to recover the primary material contained in plastic products. Recycling plastic technologies are generally divided into mechanical and chemical recycling methods, along with energy recovery strategies, which include forms of thermal recovery technologies such as pyrolysis and gasification. The use of recycled plastic content in packaging, construction, automotives, and other areas of application has been promoted by regulatory requirements. Valorisation of plastics as an alternative fuel in cement production has also been promoted in the cement sector as a way to comply with stringent GHG emissions limits in Europe and to reduce costs. Some challenges associated with the use of secondary plastics have been raised associated with the difficulty in guaranteeing the level of performance and specification, cross-contamination and chemical load, and costs of secondary plastics.

Overall, these interventions reflect the complex and multi-dimensional nature of transitioning to a circular economy in the plastics sector and the differences across areas of applications and types of polymers.

Contribution of circular strategies in plastics to decarbonisation

An analysis of the literature was undertaken. The 40 documents reviewed in detail for this report mainly included peer reviewed papers published in international journals since 2015 with a focus on assessing the impact of circular economy strategies in Europe. Assessment methods varied widely in terms of scope and methodological approaches employed to explore the environmental, resource, economic impacts, and decarbonisation potential of circular economy strategies in the plastics sector across all stages of their life cycle. The overall results are listed in Table 4. Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are prominent methodologies, frequently used individually or in combination. MFA is an effective tool which has been widely applied to assess the resource use impacts of circularity strategies. For example, Lase et al. (2023) used an EU-level MFA model to show that combining improved mechanical and chemical recycling could raise recycling rates to 73–80%, significantly increasing the availability of secondary plastics. Similarly, Eriksen et al. (2020) applied dynamic MFA to PET, PE, and PP flows and found that combining interventions—such as better collection, design-for-recycling, and stable demand—could enable recycled plastics to meet up to 65% of future demand. These studies highlight the role of MFA in quantifying both sector-specific and systemic circularity potential.

Evaluations of resource use impacts—particularly those using MFA—indicate that strategies targeting the early R's (refuse, rethink, reduce) and those focused on narrowing and slowing material loops (reuse, recycling) often deliver the greatest environmental benefits (Hsu et al., 2021; Gonçalves et al., 2024). Hsu et al. (2021) highlight the limitations of recycling alone, emphasising the need for upstream reduction and reuse to address material losses. Similarly, Gonçalves et al. (2024) further showed that enhancing recyclability and recycled content can significantly improve circularity indicators like the material use rate and material circularity indicator, even in systems with short product life cycles such as plastic packaging. Recent studies that combine MFA with LCA provide a more holistic understanding of resource use and emissions, showing that coupling MFA with LCA can provide a more comprehensive picture of both material flows and their associated environmental impacts. The systematic mapping of the EU plastic value chain by Amadei et al. (2023) through MFA has underlined key inefficiencies and resource losses, while highlighting that current end-of-life recycling rates, calculated in this paper as recyclate produced over waste generated, is approx. 19% and plastic losses ~4% of production, leaving considerable room for improvement. Besides, they also demonstrated that reducing plastic production volumes could decrease climate change impacts

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by up to 28%, far surpassing the effect of downstream recycling alone. These findings reinforce the importance of system-level modelling frameworks for fully capturing the potential of CE strategies in reducing both emissions and resource consumption.

The systematic analysis is summarised in Table 4. The overarching conclusion is that CE interventions in the plastic sector lead to a reduction of GHG. One of the most reported benefits of CE interventions is, indeed, its contribution to climate change mitigation. The studies analysed suggest that CE interventions demonstrate substantial potential for GHG emission reduction. Studies tend to focus on the positive impact of recycling interventions compared to landfill and incineration as destinations of waste. Recycling, particularly mechanical recycling, has been linked to both emission reductions and decreased reliance on virgin materials. Other CE interventions, related to slowing and narrowing approaches are less well studied. The range of the impact is, though, subjected to uncertainty, and varies significantly across types of interventions and sectors of application. Evaluation of impacts suggest that CE interventions addressing the initial R's or the narrow and slow loops are likely to provide the largest positive impact on GHG reduction. Impacts of packaging-free products or higher recycled content in packaging have been estimated at around -33 Mt and -34 $MtCO_2e$ emissions, respectively, in the period between 2020-2030 in the EU (Andreasi Bassi et al., 2022), reusable packaging presenting an opportunity to reduce impact by -0.79 $MtCO_2e$ yearly (Abejón et al., 2020) for Spain. Reusable packaging has also been shown to lead to very significant reductions between 2.5-3.7 $GtCO_2e$ emissions for the period of 2020-2030 (Andreasi Bassi et al., 2022). Besides, refurbishment of electronic products could also achieve savings between -25% to -97% for the lifetime of the products (Pamminger et al., 2021; Fangeat et al., 2022) with similar savings suggested for remanufacturing of vehicles (Carlson et al., 2025). Benefits of recycling compared to other end of life treatment options are also well supported in the literature.

Table 4. Overview of the climate change mitigation potential of CE interventions in the plastic value chain, as reported in the reviewed literature

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
		Narrowing CE strategies		
Ban single-use items (straws, cutlery) (P1.1)	European Commission et al. (2018), EU	0% use of single-use plastic items in one year	100% use of single-use plastic items	-1.28 $MtCO_2e$ yearly
	Herberz et al. (2020), EU	0% use of single-use plastic items in one year	100% use of single-use plastic items	-1.56 $MtCO_2e$ yearly
Packaging-free products (P1.2)	Andreasi Bassi et al. (2022), EU	Limiting annual PET packaging consumption growth (the same of 5.1 Mt annually as 2020)	Linear increase from 5.1 Mt (in 2020) to 6.9 Mt (in 2030)	-35 $MtCO_2e$ cumulative emissions between 2020-2030
Material efficient packaging design (P3.2)	Vassallo & Refalo (2024), Malta	70% less material	Single-use plastic product	-7% to -13% per item product
		Substituting CE strategies		

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
Bio-based polymers and compostable packaging (P4.1)	Shen (2022), EU	Bio-based product	Single-use plastic product	-11% to -13% per item product
	Abbate et al. (2022), EU	Bio-based product	Single-use plastic product	-1% to -25% per kg product
Paper packaging (P4.2)	Tacker et al. (2025), EU	Paper-based product	Single-use plastic product	-10% to +10% per product
	Schenker et al. (2021), EU	Cellulosic fibre-based product	Single-use plastic product	-50% to -70% per kg product
Increase recycled content in the product (P4.3)	Andreasi Bassi et al. (2022), EU	100% Recycling Content	Single-use plastic product	-33.83 MtCO_2e cumulative emissions between 2020-2030
	Vassallo & Refalo (2024), Malta	100% Recycling Content	Single-use plastic product	-42% to -60% per item product
		Slowing CE strategies		
Reusable packaging (P5.1)	Abejón et al. (2020), Spain	Reusable plastic crates	Single-use cardboard boxes	-0.79 MtCO_2e yearly
	Accorsi et al. (2022), Italy	Reusable plastic containers	Single-use plastic containers	-51.6% to -72.8% in 10-year time span
Deposit-return schemes for packaging (P5.2, P2.3)	Tallentire & Steubing (2020), EU	69% waste collection rate	29% waste collection rate	-13% yearly
	Andreasi Bassi et al. (2022), EU	100% waste collection rate	23% waste collection rate	-21 MtCO_2e cumulative emissions between 2020-2030
Modular design for durable plastic applications (P6.1)	Ferreira et al. (2021), EU	New modular LED	Traditional disposable lighting	-30% per one lighting system (369 luminaires)
	Proske & Jaeger-Erben (2019), EU	New modular smartphone	Traditional smartphone	-28% yearly
Affordable repairing services (e.g., by providing subsidies and tax rebates) (P6.2)	(Sánchez et al., 2023), EU	5-7 years lifespan	3 years lifespan	-28% to -43% yearly
	Singh & Ogunseitan (2022), Global	50%-100% lifespan extension	Usual lifespan	-2.5 to -3.7 GtCO_2e cumulative emissions between 2020-2030
Provide affordable refurbish service for	Boldoczki et al. (2020), Germany	Reuse of used electronic product	Direct disposal of used electronic product	-12% to -63% per product lifetime

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
durable plastic products (P7.1)	Pamminger et al. (2021), EU	Refurbish, repair, and part-remanufacture of used electronic product	Direct disposal of used electronic product	-25% to -71% per product lifetime
Rebates on refurbished products (P7.2)	Fangeat et al. (2022), EU/France	Refurbish of used electronic product	New electronic product production	-43% to -97% yearly
Recover components for reuse for electronics and other durable plastic products (P8.1)	Pamminger et al. (2021), EU	Remanufacture of used electronic product	New electronic product production	-35.2 $kgCO_2e$ per product lifetime
Remanufacture of large plastic parts in vehicles (P8.2)	Carlson et al. (2025), EU	Remanufacture of used vehicle	New vehicle production	-50% to -80% per item
		Closing CE strategies		
Repurposing of textile fibres, including synthetic fibres, for use in construction as insulation or for cast-in-place concrete mixes and other construction composites (P9.1)	Karmakar et al. (2025), lab study	Blended r-denim/PET (40/60) fibres	Virgin PET fibres	-34.1% per ton
	Violano & Cannaviello (2023), EU	Recycled-fibre insulation	Conventional insulation	-85.6% to +57.5% per kg
Mechanical recycling (P10.1)	Faraca et al. (2019), Denmark	Advanced mechanical recycling (aMR) with PP, PE, PET, and PS outputs	Simple mechanical recycling (sMR) with PP and PE outputs only	The aMR achieve net GHG savings (−717 $kgCO_2e/t$) compared sMR (+940 $kgCO_2e/t$)
	Stegmann et al. (2023), Netherlands	Closed-loop recycling	Open-loop recycling	-50% to -74% per item (250 ml bottle)
	Möck et al. (2022), EU	30% shift from chemical to mechanical recycling	100% mechanical recycling	-31% to -45% per kg recyclate output
Chemical recycling (P10.2)	Jeswani et al. (2021), Germany	Chemical recycling via pyrolysis	Incineration with energy recovery	-57% to -61% per ton
	Van Der Hulst et al. (2022), Netherlands	Direct chemical recycling	Incineration with energy recovery	-0.82 to -1.37 $kgCO_2e/kg$
	Hermanns et al. (2023), Germany	Direct chemical recycling	Incineration with energy recovery	-68% to -71% per kg

Intervention (ID)	Study	Circular alternative	Reference case	GHG emissions
	Vo Dong et al. (2015), France	Pyrolysis and fluidized bed recycling	Landfilling, Incineration, Co-incineration,	Pyrolysis achieves the lowest GHG emissions (−13 $kgCO_2e$ per kg EOL fibre reinforced polymers (FRP)).
Direct recycling of captured carbon from incineration, via e.g., CCU (P11.1)	Christensen & Bisinella (2021), Denmark	Retrofitting CO_2 capture (CCU) to incineration	Conventional incineration	-740 to -3000 $kgCO_2e$ per ton
Gasification or pyrolysis to recover calorific value of plastic waste (P11.2)	Arafat et al. (2015), Global	Gasification	Incineration, anaerobic digestion, bio-landfilling, and composting	Gasification yields the lowest CO_2 emissions
Plastic waste and hazardous plastic waste for alternative fuels in cement production (P11.3)	Khan et al. (2021), Finland	Different shares (0%, 30%, 50%, 80%) of solid recovered fuels (SRF)	100% conventional fossil fuels	-725 to -1036 $kgCO_2e/t$

Note. The system boundaries of studies are not harmonised, thus GHG emissions are not directly comparable. Intervention identifiers (IDs) refer to Deliverable D3.5.

Lessons learnt for TRANSIENCE

The literature review reveals several important knowledge gaps in terms of assessing the decarbonisation and impact reduction potential of CE interventions. From the analysis, the following main gaps have been identified:

1. Limited consideration of impacts beyond carbon: most of the assessments quantify the carbon impacts of CE interventions, but other impact categories are rarely considered, raising concerns around potential burden shift associated with some of the interventions (e.g., impacts of bio-based materials on water or land).
2. Limited focus on economic impacts: while most studies assess environmental impacts—particularly GHG emissions—few provide a robust quantification of the economic impacts of CE interventions. This limits the ability to evaluate trade-offs or conduct cost-benefit analyses that are essential for policy and technology investment decisions.
3. Limited focus on product-level optimisation in single-use plastics: many studies on single-use plastics primarily address policy instruments (such as bans) or material substitution, but they rarely explore improvements to product design specific to plastic, such as lightweighting, or enhancing material efficiency.
4. Lack of real-world application impacts: several interventions remain at the laboratory conceptual stage, with no clear evidence of application and implementation. Therefore, the practical effectiveness of the interventions remains uncertain, as challenges of implementation are rarely discussed.
5. Limited focus on plastics in key sectors: the current studies lack a specific focus on plastics in sectors

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such as transportation, construction, and durable household goods. Existing studies often conduct assessments at the product level (e.g., vehicles, smartphones), where plastics are grouped/combined with metals and other materials, making it difficult to evaluate the impacts of CE interventions on specific plastic components across different industry sectors.

6. Lack of integrated assessments: most of the studies considered focus on one specific dimension such as environmental impacts or, to a lesser extent, technology progress, but rarely do they provide an integrated assessment which considers environmental, economic, social, and behavioural aspects.

In addition to quantitative analysis to evaluate potential impacts on resources, environmental impacts, and economic implications of applying CE strategies across the whole lifecycle of the plastic value chain, qualitative approaches can also offer valuable insights into improving circularity. These approaches often address social, behavioural, and institutional dimensions that are not easily captured in quantitative methods such as LCA. For instance, behavioural change plays a critical role in reducing plastic waste and enhancing waste plastic management. The behavioural science literature has found that knowledge about reusing/recycling packaging and associated social values and norms can enhance the reuse/recycling of packaging (Babader et al., 2016). On the other hand, careless and less well-informed behaviours by end consumers and other societal actors (for example, failing to adequately segregate household waste and adequately dispose of plastic packaging), have been linked to environmental burdens and human safety issues (Kasza et al., 2022). Infrastructural conditions, while recognised as key enablers for adequate plastic circularity, are not always adequately considered in studies. For example, gaps in high-quality recycling of EOL plastics may limit opportunities to increase recycled content in products.

Some studies have assessed the impact of specific types of regulation. Recent achievements of Extended Producer Responsibility (EPR) schemes established for plastic packaging waste in Europe have been reviewed. These studies show that EPR schemes lead to higher collection and recycling rates of plastic waste management and do not necessarily entail higher costs (Colelli et al., 2022). However, the studies also note that gaps in efficient local recycling infrastructure are a major barrier to meet the EU recycling target, and, thus, point to the need to better support local authorities for the collection and sorting of packaging waste (Lorang et al., 2022). Most policy assessment studies also point to the need to enhance collaboration across actors and highlight how the misalignment across value chain actors may lead to negative outcomes or inadequate implementation of CE strategies (Hsu et al., 2021).

Therefore, integrating non-quantified dimensions and exploring consumer behavioural and socio-technical aspects with more quantitative approaches such as MFA and LCA and economic approaches can provide a better and broader understanding of the impacts of CE interventions on decarbonisation and, more generally, sustainability pathways (Corona et al., 2024).

6 Conclusions

This report presented a preliminary review of the climate change mitigation potentials associated with selected circular economy (CE) interventions of relevance to the TRANSIENCE project. The examined interventions span the value chains of cement, steel, and plastics and were explored through three parallel threads of literature review, each focused on a specific material group. Priority was given to peer-reviewed studies that focused on the European context and provided quantitative assessments of emission savings. Beyond collecting impact estimates, the review aimed to build a broader understanding of how energy and material flows intersect with economic and behavioural dynamics in achieving decarbonisation.

A key challenge encountered throughout the review was the diversity of methodological approaches and regional contexts across the literature. Importantly, this means that the direct comparison of quantitative findings is challenging. While some contextualisation was possible, the lack of inter-comparability highlights a persistent knowledge gap in assessing individual CE interventions (i.e., beyond the "Narrow", "Slow", and "Close" classifications) and their respective contributions to emissions reduction for European basic industries. The MIC3 modelling framework developed under TRANSIENCE offers a promising pathway to address this gap, as its modular structure allows for representing the technical and socioeconomic implications of individual interventions in a systemic perspective.

A recurring theme across all material streams was that interventions focused on reducing material use and extending product lifetimes tended to deliver the greatest emissions reductions. Although this review could not definitively confirm whether higher-order R-strategies (e.g., reuse vs. recycling) consistently yield greater mitigation benefits, several reuse-oriented measures involving minimal modification showed particularly high potential. At the same time, the review identified trade-offs between some interventions—such as between lightweighting and reus—suggesting the need for integrated assessment approaches. To strengthen the evidence base and support strategic decision-making, we also recommend that this preliminary work be expanded into a systematic review that can more robustly evaluate CE interventions and their climate change implications for the European industrial sector.

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