



Impact of Circular Economy Measures in the European Union Built Environment on a Net-Zero Target

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Received: 10 October 2022 / Accepted: 6 February 2023
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Abstract

Environmental benefits of circular economy (CE) measures, such as waste reduction, need to be weighed against the urgent need to reduce CO₂ emissions to zero, in line with the Paris Agreement climate goals of 1.5–2 °C. Several studies have quantified CO₂ emissions associated with CE measures in the construction sector in different EU countries, with the literature's focus ranging from bricks and insulation products, to individual buildings, to the entire construction sector. We find that there is a lack of synthesis and comparison of such studies to each other and to the EU CO₂ emission reduction targets, showing a need for estimating the EU-wide mitigation potential of CE strategies. To evaluate the contribution that CE strategies can make to reducing the EU's emissions, we scale up the CO₂ emission estimates from the existing studies to the EU level and compare them to each other, from both construction-element and sector-wide perspectives. Our analysis shows that average CO₂ savings from sector-wide estimates (mean 39.28 Mt CO₂ eq./year) slightly exceeded construction-element savings (mean 25.06 Mt CO₂ eq./year). We also find that a conservative estimate of 234 Mt CO₂ eq./year in combined emission savings from CE strategies targeting construction elements can significantly contribute towards managing the EU's remaining carbon budget. While this is a significant mitigation potential, our analysis suggests caution as to how the performance and trade-offs of CE strategies are evaluated, in relation to wider sustainability concerns beyond material and waste considerations.

Keywords Carbon emissions · Construction sector · Carbon budget · Decarbonisation · Emission reduction · Climate change

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Introduction

The Paris Agreement aims to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels [1]. A sharp reduction in greenhouse gas emissions is needed in the following years to avoid the most severe consequences of climate change, including extreme droughts, heatwaves and floods [2]. To this end, the European Union (EU) has pledged to reduce greenhouse gas emissions by 55% by 2030 compared with 1990 levels and to become carbon neutral by 2050 [3]. The European Commission [4] has identified transport, agriculture and construction as the key sectors to focus on. All these sectors are high emitters, and the construction sector is particularly challenging to fully decarbonise due to increasing demand for buildings and infrastructure, the stock's long lifespan and reliance on carbon-intensive materials such as steel and cement [5].

The building sector currently accounts for more than a third of the total greenhouse gas emissions both worldwide [6] and in the EU [7]. Until recently, the reduction of operational emissions has been the main focus of policies such as the Energy Efficiency Directive [8] and research [9]. The subsequent improvement in energy efficiency and performance has reduced the level of operational emissions. However, less attention has been given to buildings-embodied emissions, and their relative contribution has become increasingly significant [5, 10]. It has been estimated that between 5 and 12% of total greenhouse gas emissions from the EU are associated with the extraction of raw materials, the manufacturing of construction products and the construction and renovation of the buildings [11]. Up to 80% of those greenhouse gas emissions could be saved by improving material efficiency [12]. As the urban population is expected to represent 68% of the total by 2050, adding 2.5 billion to the world's urban population [13], measures to increase material efficiency in the construction sector are key to achieving the goals set in the Paris Agreement [1].

Circular economy (CE) principles can play a crucial role in improving the material efficiency of the building sector and, therefore, influence embodied emissions [14, 15]. The CE can be defined as 'a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops' [16]. Slowing resource loops implies intensifying and expanding the use of products to prolong their value over time, whereas closing resource loops entails upcycling to create or restore new value from used materials [17]. Finally, narrowing resource loops implies reducing environmental impacts and resource consumption per unit of product [18]. However, studies have lamented a lack of empirical evidence that shows the contribution of CE to sustainability and the potential trade-offs [19, 20].

Material economics [21] has estimated that CE approaches can cut by 38% the greenhouse gas emissions (up to 2 billion t of CO₂) in the building sector by 2050 by reducing the demand for four key materials: aluminium, steel, plastic and cement. Examples of CE strategies that can be applied to achieve this reduction include the following:

- Increasing material efficiency with a better design, e.g. the same structural strength can be achieved using 50–60% of the amount of cement currently applied [21]. The potential reduction of emissions by 2050 is 1 billion t of CO₂/year.
- Reducing waste in the construction site, e.g. modular offsite construction can reduce waste by up to 90% compared with traditional onsite construction [22]. The potential reduction of emissions by 2050 is 0.2 billion t of CO₂/year.

- Increasing the use of building, e.g. by sharing offices or multi-purposed and repurposed buildings [23]. The potential reduction of emissions by 2050 is 0.3 billion t of CO₂/year.
- Reusing and recycling materials, e.g. the reuse of materials in the construction of 70 thousand new apartments could lead to reducing by 500,000 tonnes the amount of used materials [24]. The potential reduction of emissions by 2050 is 0.6 billion t of CO₂/year.
- Prolonging the functional lifetime of the buildings, e.g. durable, flexible and modular designs [25]. The potential reduction of emissions is 1 billion t of CO₂ beyond 2050.

Although CE implementation can curtail overall CO₂ emissions at the country level [26], particularly in the long term [27], evidence in the building sector is mixed [25, 28]. While some CE strategies in this sector can and do reduce CO₂, other strategies might in fact result in higher emissions. For example, increased durability of floor coverings through repair and maintenance can lead to 38.9 CO₂ eq./m² in additional emissions [29], while significantly refurbishing a building every 10 years can increase the building's embodied carbon by 67% [30]. Reuse almost consistently leads to lower CO₂ across several studies, whether focused on a single construction element such as rail track [31] or focused on the entire construction sector [32]. However, some studies do estimate extra emissions from reuse [33]. Such differences are due partly to how the CE strategies are implemented, and partly to how CO₂ emissions are measured [25].

Exacerbating the challenges of assessing CO₂ emissions, arising or saved as a result of CE strategies, are inadequate datasets that often lack consistency [34] or geographical specificity [35]; diversity of metrics for 'circularity' [36]; and absence of a unifying CE framework [37]. Another key challenge in this area includes the difficulty of comparing CE assessments to each other and to sectoral and national emission reduction targets, informed by the Paris Agreement climate change goal [25]. Consequently, reviews of CE's impact on CO₂ in construction so far have been qualitative [25, 38]. A multiplicity of locations, timeframes and other methodological assumptions points to a research need essential for informing low-carbon policy in the construction sector.

Accordingly, this paper's aim is to estimate a range of trade-offs between CE measures and climate change mitigation (expressed in CO₂ emission savings or extra CO₂ emissions) in the EU construction sector, to inform the region's emission reduction targets. The main contribution of our study is in synthesising knowledge in this area in an interdisciplinary way by comparing existing CO₂ estimates for a range of CE strategies to one other and to the EU's remaining carbon budget for the first time. As an important contribution to comparing estimates at different scales, our study brings together the micro-level (construction elements and buildings), meso-level (neighbourhoods and the buildings sector as a whole) and macro-level (national and supra-national carbon budgets and emission reduction targets).

We achieve the aim of this paper through three objectives: we first extract CO₂ estimates from existing studies on CE measures in the construction sector in the European Union (plus the UK). We then scale up these estimates to the EU level where they refer to an individual country, and annualise them where a multi-year estimate is provided, to make them comparable. Finally, we compare the scaled-up annual CO₂ emission estimates to each other as well as to the EU's carbon budgets. In addition, we reflect on the challenges of comparing such estimates across studies that employ a variety of modelling approaches and assumptions.

Methods

This section explains the logic behind the process of scaling up the CO₂ estimates from the existing literature. We deliberately call the process ‘scaling up’ rather than ‘modelling’, as the intention is to use a simple and transparent method to gauge approximate CO₂ emissions and their orders of magnitude as estimated across the literature. The main advantages of our scaling-up method are its simplicity and transparency, as well as lower data intensity, compared to more complex modelling. These characteristics are particularly important for first-of-a-kind exploratory studies, like ours, that compare quantitative results from other studies based on different models, inputs and baselines. So, to achieve comparability and (as it were) to obtain the common denominator, we have developed a straightforward and easy-to-trace method to scale up the CO₂ estimates both temporally and spatially, while drawing attention to the challenges of evaluating circular economy strategies and measuring their impact on the climate.

Although this scaling-up exercise is the first synthesis of CE measures in the EU construction sector, the methodological approach itself is not uncommon: it is used widely in mitigation potential synthesis studies (see e.g. IPCC Working Group III assessment reports, or [39]). Throughout the paper, and particularly in the [Discussion](#) section, we acknowledge the challenges of comparing CO₂ estimates derived from a variety of methodologies, assumptions and models.

Selecting Our Sample of Quantitative CO₂ Emission Estimates

As a starting point, we used a sample of 24 studies shortlisted and reviewed by Gallego-Schmid et al. [25] on the co-benefits and trade-offs between CE measures in the built environment and climate change mitigation. We repeated the search on the same database (Scopus) and expanded the sample to 34 papers, grouping them by CE loop and CE strategy (Fig. 1). The relatively small number of studies covered here is due to the search terms used: understandably, some relevant studies might have slipped through the net. Although a more comprehensive list of search terms could yield a larger number of search results, the reviewed studies already provide a good spread of CO₂ estimates, as demonstrated in the [Results](#) section.

We applied a range of search strings that included ‘circular economy’ AND ‘construction OR buil*’ AND one of the following terms: durability, remanufacturing, refurbishment, product service systems, servitisation, sharing, closed-loop, material circularity, reuse, upcycling, maintenance, repair, upgrade, upgrading, circular supplies, reverse supply chains, reverse logistics, take back systems, cascading, by-product exchange, repurpose, recover, extended producer responsibility, cycling and industrial symbiosis [25]. Note that while material efficiency has been conceptualised by others [40] as broadly as the CE framework, here, we treat it as one of the CE strategies.

Supplementary Tables S1–3 summarise the full sample of analysed studies by their scale, country or region of focus, timeframe and CE strategy. The final column of each table provides our estimates of extra emissions (or emission savings) per year at the EU level, based on our scaling up of each study’s data. Note that where a study covers several CE strategies and thereby fits into different CE loops, it is listed in more than one Supplementary Table. For example, Cooper et al. [41] model both reuse (slowing

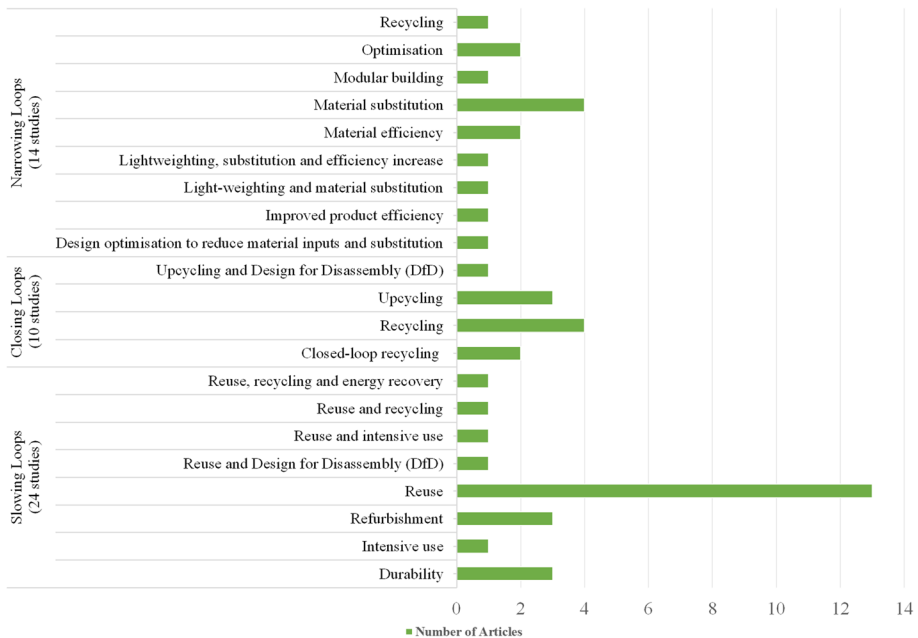


Fig. 1 The number of analysed studies by circular economy loop and by circular economy strategy. Note: some studies cover circular economy strategies from two loops and, hence, are counted in this figure twice

loops) and lightweighting (narrowing loops) and therefore appear in both Supplementary Tables S1 and S3.

Scaling Up the Estimates to the EU Level

For each study, we extracted estimates of CO₂ savings or extra emissions arising from CE strategies. Where a range of estimates was provided in a study, we recorded the minimum of the range as a ‘lower bound’ and the maximum of the range as an ‘upper bound’, to get an idea of the spread. For comparability of results within the boxplots presented in this paper, where a study provided only one estimate, this value was assumed to represent both the upper and lower bounds.

For the purposes of our paper, the studies’ estimates often needed to be scaled up spatially (i.e. from one country or one construction element to the entire EU level) and in some cases scaled down temporally (i.e. from a multi-year lifecycle emission estimate to an annual estimate). Both types of scaling required a number of assumptions and additional data and statistics outside the sample of studies. The assumptions are explained in this section, while information on additional data and sources used in this paper can be found in Supplementary Table S4.

To spatially scale up CO₂ estimates provided per construction element (e.g. per brick, m², or wall assembly), we used the following steps:

- 1 Searched for available numbers for, or estimated, how many of such construction elements are likely to be in Europe or, if an estimate at the European level was not available, in one or several European countries.
- 2 Scaled up the number of the construction elements from the country level to the EU level in proportion to the country's share in the EU population.
- 3 Multiplied the number of construction elements in the EU by the CO₂ emissions per construction element.

For example, if the CO₂ emission estimate was given per cantilever truss [42], we estimated how many cantilever trusses there are in the EU, or at least in one of the EU countries, and then scaled it up proportionately based on the country-vs-EU population numbers (see Eq. 1). In another example, Migliore et al. [43] estimated emission savings from using recycled material in bricks, providing CO₂ eq. per tonne of bricks. Here, we arrived at EU-wide emission savings from this CE strategy by combining it with data on the number of bricks used annually in the EU and the average weight of a brick (see Eq. 2 and Supplementary Table S4).

$$C_{EU} = \frac{P_{EU}}{P_i} \times N_{ji} \times C_j \quad (1)$$

where

C_{EU} = carbon emissions from EU's construction sector;
 P_{EU} = EU population;
 P_i = i country's population;
 N_{ji} = number of j infrastructures in i country;
 C_j = carbon emissions from one infrastructure of type j

$$C_{EU} = \frac{P_{EU}}{P_i} \times N_{ji} \times W_j \times C_w \quad (2)$$

where

W_j = weight of one infrastructure of type j ;
 C_w = carbon emissions per unit of weight

To spatially scale up CO₂ estimates provided per sector in a particular EU country (e.g. for the entire construction sector in the UK), we again used the country-vs-EU population ratio. For example, Barrett and Scott [44] estimated emission savings from modular buildings and the substitution of cement at the construction sector level in the UK. As the UK population is around 13% of that of the EU [45], we scaled up this estimate to the EU level in proportion to the population (see Eq. 3).

$$C_{EU} = \frac{P_{EU}}{P_i} \times C_{sec,i} \quad (3)$$

where

$C_{sec,i}$ = carbon emissions from country i 's construction sector

In relation to the temporal scaling up, we came across two types of studies. Firstly, some studies presented CO₂ estimates that are one-off actions [30, 46], for example cavity wall insulation, so such savings could not be implemented annually or multiple times on the same building stock; hence, we treated them as a one-off CO₂ saving. Secondly, where studies provided cumulative estimates for CO₂ savings within their own timeframe (e.g. up

to 2032 in [32]), we divided the savings by their provided timeframe to obtain an annual estimate (see Eq. 4).

$$C_{EU} = \frac{C_m}{Y_t - Y_0} \quad (4)$$

where

C_m = multiyear carbon emission estimate;

Y_t = target year;

Y_0 = base year

Calculating the EU's Remaining Carbon Budget

After scaling up the estimates from the studies, we compared them to the remaining EU-27 carbon budget, using 2019 as a baseline year. To calculate the latter, we deducted the 2019 global annual emissions [47] from the 2018 global carbon budget [48], to derive the budget remaining after 2020. We then divided this remaining global carbon budget by the world population for 2019 [49] and multiplied it by the EU-27 population for the same year [45]. We then assumed that this remaining EU-27 carbon budget would be spent linearly before 2050, with the same annual amount of CO₂ emitted (i.e. the same annual amount of the carbon budget spent). We, therefore, divided the budget by 31 years covering the period between 2019 and 2050 (see Eq. 5).

$$CB_{EU,t} = \frac{CB_G}{P_{G,0}} \times P_{EU,0} \div (Y_t - Y_0) \quad (5)$$

where

$CB_{EU,t}$ = EU's remaining annualised carbon budget before target year;

CB_G = global carbon budget remaining between base year and target year;

$P_{G,0}$ = global population in base year;

$P_{EU,0}$ = EU population in base year

Results

Here, we present our analysis of the scaled-up emission estimates by their scope (studies covering the entire construction sector, a neighbourhood, or construction elements such as bricks or tarmac), by CE loop (slowing, closing or narrowing) and by CE strategy (e.g. reuse, upcycling or material substitution). We then compare the emission estimates to the EU-27 carbon budget remaining before 2050, to put them into perspective. All estimates presented in this paper are our scaled-up numbers, rather than the original numbers from the literature.

Mitigation Potential by Scope

There are only three studies [29, 50, 51] in the sample estimating both savings and extra emissions from CE measures in the construction sector within the same study. Emission savings of, for example, using ceramic tiles instead of synthetic carpet around Europe

would be around 4.52 to 41.85 Mt CO₂ eq. per annum [29]. By contrast, more intensive use, repair, maintenance and replacement of flooring surfaces would lead to extra emissions of 3.77–18.11 Mt CO₂ eq. per annum at the EU level (ibid.). Among the studies estimating both extensive extra emissions and emission savings, De Wolf et al. [50] demonstrate large uncertainty: from extra emissions of 320.04 Mt CO₂ to emission savings of 960.12 Mt CO₂ eq. per annum. The construction elements in this study include exterior and interior walls, floors and intermediate floors, roofs, fire protection elements and windows.

Among the analysed studies, only three focused on modelling the entire construction sector [32, 41, 44], while the rest focused on separate construction elements such as bricks [43], train station roofs [42] or asphalt [52]. Note that ‘construction elements’ in this context could be rather substantial, for example, reuse, recycling and energy recovery from building materials in schools, offices and residential buildings [53]. Only one study focused on the neighbourhood building stock [51] rather than on either the sector or construction element, with an estimate of 0.01 Mt CO₂ eq. annual emission savings from intensive use of the stock. Our comparison shows that sector-wide emission savings (mean 39.28 Mt CO₂ eq.) were on average slightly higher than construction-element savings (mean 25.06 Mt CO₂ eq.). In particular, sector-wide estimates ranged between 0.01 Mt CO₂ eq./year from refurbishment, which did not include savings from operation energy [44], and 124.76 Mt CO₂ eq. from combined lightweighting, substitution and efficiency increase [41]. Construction-element estimates had a wider range: between 320.04 Mt CO₂ of extra emissions and 960.12 Mt CO₂ of emission savings when looking at the reuse case, with both estimates scaled up from the same study [50].

Extra emissions (rather than emission savings) only appeared among the studies focused on construction elements, and not among the sector-wide studies. Estimates in the sector-wide studies could exceed the larger positive impacts of other CE strategies, resulting in the overall emission savings. It is plausible that the more aggregated nature of economy-wide models makes it difficult to distinguish between impacts of alternative sources of steel such as high strength or recycled.

Mitigation Potential by CE Strategy

Extra emissions are present among studies focused on slowing (using products for longer or more intensively) and closing resource loops (upcycling and closed-loop recycling), but not among studies on narrowing loops (e.g. lightweighting and material substitution). Castro and Pasanen [30], Ros-Dosda et al. [29] and Sánchez and Hass [33] focusing on slowing loops and Wiprachtiger et al. [54] focusing on closing loops estimate exclusively extra emissions between 0.05 [33] and 63.31 Mt CO₂ eq. [30] per annum. Other studies exploring slowing loops show that refurbishment and durability can result in small to moderate emission savings, for example, up to 5.8 kt CO₂ eq. in saved emissions from refurbishment [44] and up to 1.2 Mt CO₂ eq. in saved emissions from durability [55].

The studies where a combination of CE strategies was explored, such as both reuse and recycling, present greater emission savings at the lower bound when compared to studies exploring an isolated CE strategy. We find that among studies focused on slowing resource loops, Eberhardt et al. [53] estimate savings of 360.67 Mt CO₂ eq. At the upper bound, the reuse case explored in isolation by De Wolf et al. [50] presents the greatest emission savings among all studies, at 960.12 Mt CO₂ eq. In the studies focused on upcycling in isolation, emission savings reach 0.11–4.33 Mt CO₂ eq. [43, 52, 56], whereas upcycling with design for disassembly saves 12.39–19.48 Mt CO₂ eq. [57].

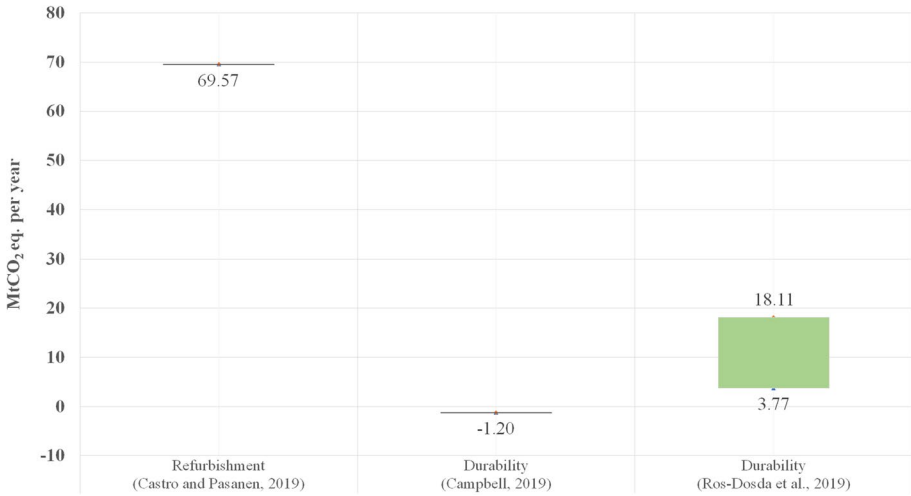


Fig. 2 Potential extra emissions and emission savings (MtCO₂ eq. per year) in the European Union from slowing resource loops per circular economy strategy. Note: reuse is excluded from this figure and, instead, explored in Figs. 2 and 3

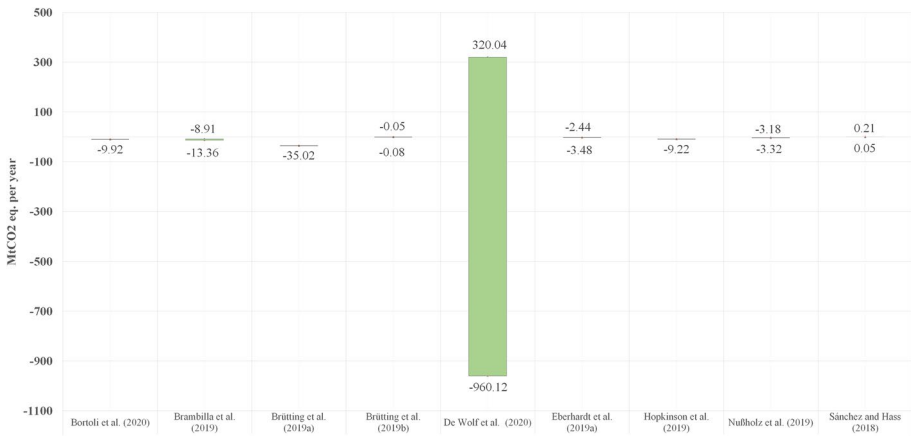


Fig. 3 Potential extra emissions and emission savings (MtCO₂ eq. per year) in the European Union from reuse across a range of studies. Note: reuse cases combined with other circular economy strategies are excluded from this figure and, instead, explored in Fig. 4

Among the slowing resource loops for the studies focused on construction elements (Fig. 2), refurbishment is the leading contributor to extra emissions, at 69.57 Mt CO₂ eq. [30], followed by durability, which ranged from 3.77 to 18.11 Mt CO₂ eq. [29]. However, Campbell [55] highlights durability as cutting emissions by 1.2 Mt CO₂ eq. The combined range of emission estimates for durability adds up to extra emissions, rather than to emission savings.

As illustrated in Figs. 3 and 4, there is much variability in the emission estimates for the CE strategy of reuse, ranging from 320.04 Mt CO₂ eq. [50] in extra emissions to 35.02

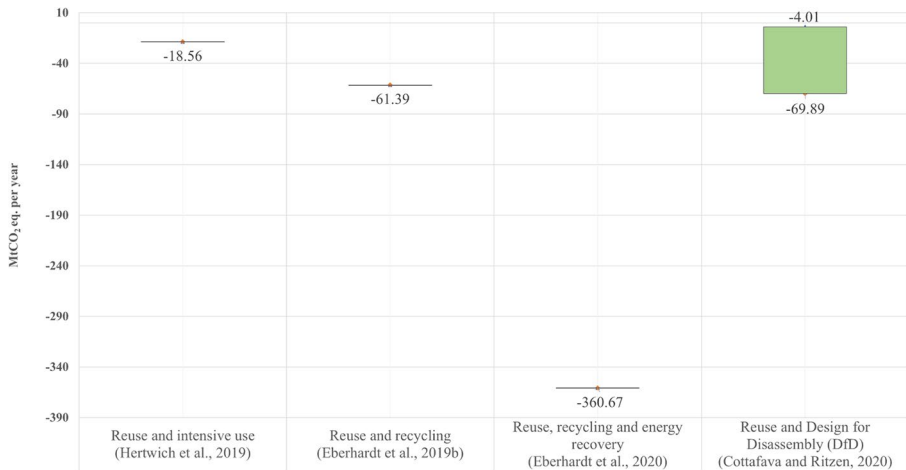


Fig. 4 Potential extra emissions and emission savings (MtCO₂ eq. per year) in the European Union from reuse cases combined with other circular economy strategies

Mt CO₂ eq. [58], 124.76 Mt CO₂ eq. [41] and 960.12 Mt CO₂ eq. in emission savings. This variability can be partly explained by the large number of studies exploring reuse, compared to other CE strategies. Specifically, thirteen studies focus on reuse as a single strategy (Fig. 3) and four more focus on reuse in combination with other strategies (Fig. 4) such as optimisation and material substitution [46], recycling [59], design for disassembly [60] and intensive use [61]. The dominance of studies on reuse (along with recycling) is consistent with findings by other researchers [14].

Focusing on the reuse case further, when assessing emissions from reuse of construction elements (i.e. after excluding sector-wide studies), we observe significant variability between the estimates, ranging from emission savings of 960.12 Mt CO₂ eq. [50] to extra emissions of 0.21 Mt CO₂ eq. [33] (Fig. 3). By contrast, when scaling up at the lower bound for the reuse cases, we observe lower emission savings and higher extra emissions, with 320.04 Mt CO₂ eq. of extra emissions [50] and emission savings of 9.92 Mt CO₂ eq. [31]. All other reuse options result in emission savings [e.g. 62–65], with combined reuse, recycling and recovery saving the largest amount of carbon dioxide at 360.67 Mt CO₂ [53].

While reuse is largely discussed in our literature sample as a single strategy, four studies discuss it in conjunction with other CE strategies. We present scaled-up estimates from these sources in Fig. 4. We exclusively find emission savings across these combined strategies, ranging from 4.01 Mt CO₂ eq. at the lower bound when looking at reuse combined with design for disassembly [60], and up to 360.67 Mt CO₂ eq. from reuse combined with recycling and energy recovery [53].

Among the studies on closing loops, emission savings mainly derive from recycling, with 77.01 Mt CO₂ eq. at the upper bound and 18.11 Mt CO₂ eq. at the lower bound [66–68], and closed-loop recycling with savings of 44.16 Mt CO₂ eq. [69]. Further emission savings come from upcycling and design for disassembly [43, 52, 56] and from upcycling [57], as Fig. 5 presents.

When examining the narrowing resource loops by CE strategy in the sector-wide studies (Fig. 6), it is evident that the lightweighting, substitution and efficiency are leading

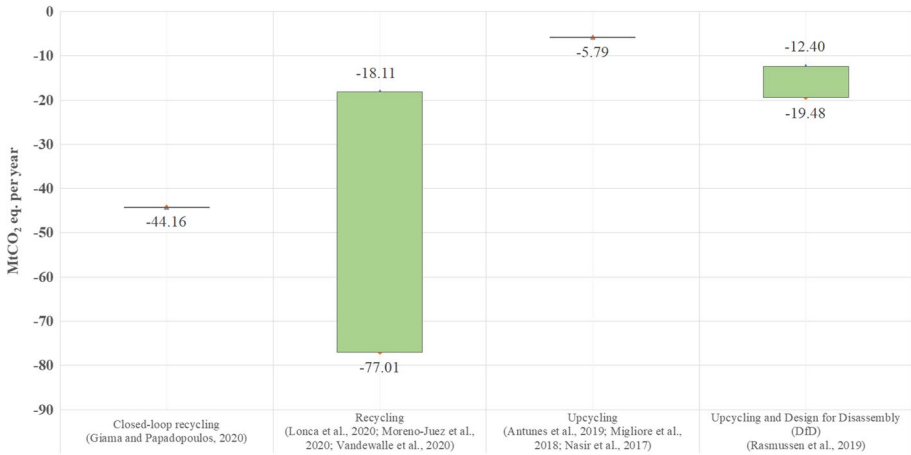


Fig. 5 Potential extra emissions and emission savings (MtCO₂ eq. per year) in the European Union from closing resource loops per circular economy strategy. Note: all of the closing-loop studies focus on construction elements rather than on sector-wide estimates

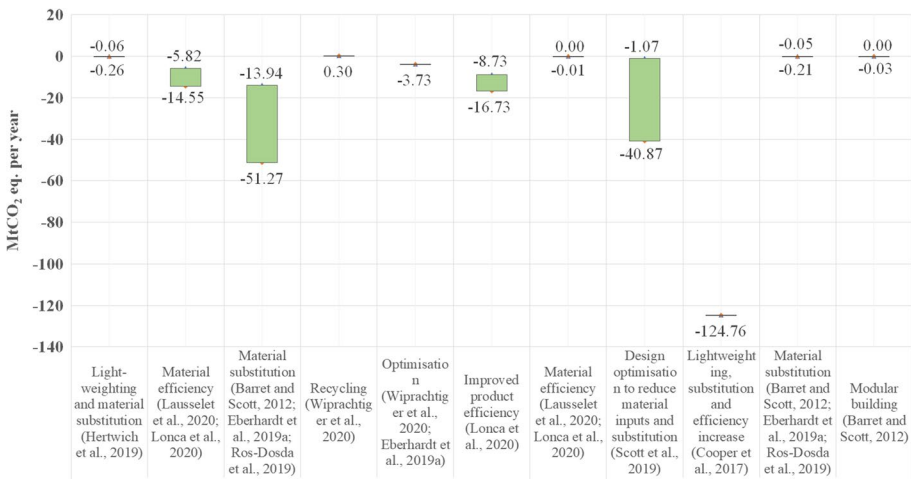


Fig. 6 Potential extra emissions and emission savings (MtCO₂ eq. per year) in the European Union from narrowing resource loops per circular economy strategy

contributors to emission savings, amounting to 124.76 Mt CO₂ eq. [41]. Design optimisation to reduce and substitute material inputs also leads to emission savings, with 40.87 Mt CO₂ eq. of savings at the upper bound of scaling up and 1.07 Mt CO₂ eq. at the lower bound [32]. Emission savings additionally come from improved construction products, reaching 16.73 Mt CO₂ eq. [66], while material substitution presents a range of 13.94 to 51.27 Mt CO₂ eq. of emission savings [29, 44, 46, 54].

Comparison with the EU-27 Remaining Carbon Budget

Before proceeding to the comparison of our CO₂ estimates with the EU-27 carbon budget, it is worth noting several points. First, for this part of the analysis, we have added up the estimates from all of the analysed studies, which raises several thorny methodological issues discussed in the next section. Second, some of the CE strategies are one-off or take place at long intervals, so cannot be repeated annually until 2050. Such CE strategies, e.g. refurbishing the building skin and interiors every 10 or 20 years [30], are mainly evident among the slowing loop studies in our sample (see Supplementary Tables S1–3 for more information on the timescales of the CE strategies). Therefore, the summed-up values in Fig. 6 are more optimistic than the CO₂ emission reductions from the construction sector that would in practice be available year on year. Third, note that in this section, as the summed-up values are relatively high compared to those in the preceding sections, the values are rounded up to whole numbers for ease of reading.

When comparing the emission estimates to the EU-27 carbon budget remaining before 2050 (Fig. 7), the potential of CE in the construction sector to manage this budget is remarkable. The remaining carbon budget of around 726 Mt CO₂ eq. per year would be more than twice compensated for by the upper bound 1671 Mt CO₂ eq. from construction element focused studies. However, as noted in the previous paragraph, this is an optimistic assessment. The lower bound of 234 Mt CO₂ eq. might give a more conservative estimate of potential annual CO₂ emission savings from the CE strategies applied to individual construction elements such as bricks [43] or cantilever trusses [58]. The aggregated range for the sector-wide studies is between 252 and 298 Mt CO₂ eq. For this comparison, we have not summed up the sector-wide estimates with those from the construction element focused studies, as the latter would then likely be double-counted.

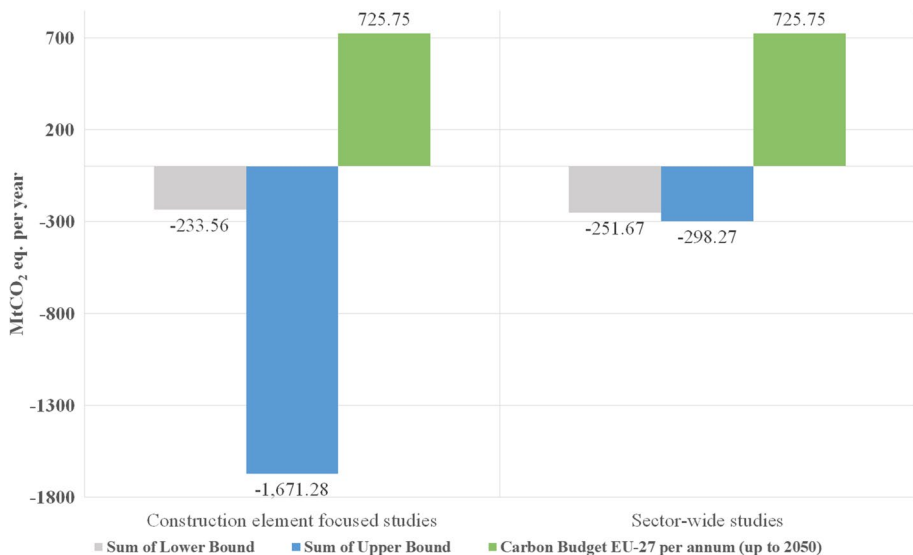


Fig. 7 Extra emissions and emission savings (MtCO₂ eq. per year) from the circular economy strategies in the European Union's construction sector compared to the remaining EU-27 carbon budget per annum. The carbon budget was divided by the number of years between 2019 and 2050

Discussion

The current literature on the circular economy has been criticised for its lack of empirical work, its bespoke, case-specific nature of studies and limited focus on service-based strategies such as sharing and leasing [19]. These limitations can be at least in part attributed to the absence of a unifying framework [20] and a prevalent focus on China [70], restricting analyses of the mitigation potential of EU-wide CE strategies. We start to address this in our analysis of the construction and use-patterns of the building sector in the EU. Given the significance of greenhouse gas emissions from the sector, our study provides a first and vital attempt to estimate the total mitigation potential of CE strategies in the EU's built environment.

We have calculated the upper and lower bounds of possible emission savings from analysed CE strategies from a systematic review of the literature (including studies on the UK). Spatial and temporal scaling techniques have been applied to construction elements and countries to evaluate the CO₂ mitigation potential at the EU level. A realistic emission reduction potential is likely to lie somewhere within those boundaries.

Most studies focused on specific construction elements, as critically observed by Kirchherr and van Santen [19], with three looking across the construction sector more broadly. Studies focusing on one element risk neglecting trade-offs between alternative strategies, and provide less validation for practitioners working across the sector. Studies looking across the sector estimated slightly greater mean emission savings of 14 Mt CO₂ eq.; however, one study on reuse of multiple construction elements, including walls, floors, roofs and windows (which we categorised as construction elements), reported the highest mitigation potential of 960 Mt CO₂ eq., yet the range of savings across elements was large (+320 to -1200 Mt CO₂ eq.). Without consistent data, it is difficult to understand how much these differences relate to data and modelling, or different building and material contexts.

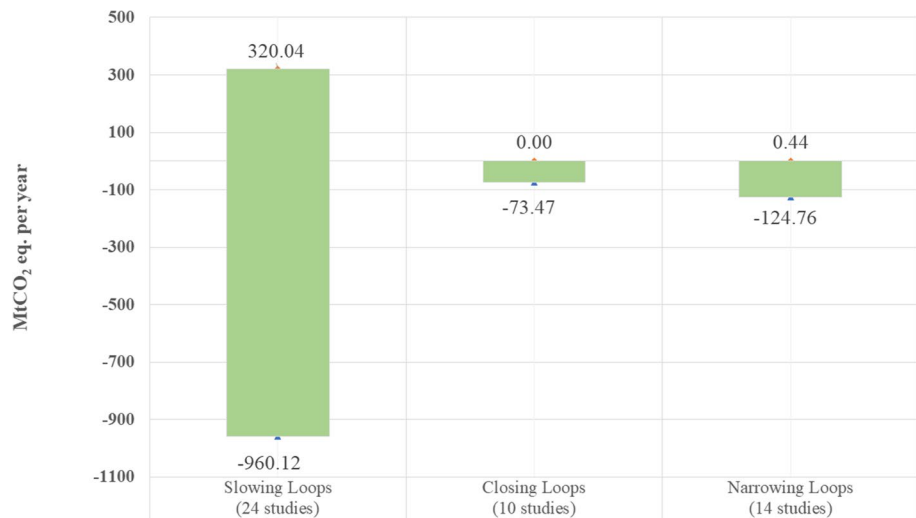


Fig. 8 Extra emissions and emission savings (MtCO₂ eq. per year) from the circular economy loops in the European Union's construction sector. Note: some studies cover circular economy strategies from two loops and, hence, are counted in this figure twice

Comparing the CE strategies by loop (Fig. 8), we found some studies that considered slowing and closing resource loops estimated exclusively extra emissions of up to 63 Mt CO₂ eq. It is important to acknowledge that not all circularity strategies are inherently ‘win-win’ [71]. Strategies sitting outside of this ‘win-win’ paradigm that address trade-offs become at risk of being overlooked, and oversimplifying circularity solutions. Slowing loops focused on refurbishment and durability of construction elements. Sector-wide studies looking at the same CE strategies however estimated moderate emission savings in the region of up to 1 Mt CO₂ eq. There was a wide range of emission estimates for reuse (+35 to −960 Mt CO₂ eq.), also categorised here as slowing resource loops. This perhaps reflected the large number of studies focused on this strategy (11 focused solely on reuse), yet all but one study that focused on construction elements showed emission savings within a smaller range of 0 to 35 Mt CO₂ eq. When reuse was combined with additional strategies including recycling and energy recovery, overall savings were on average higher, albeit without the extremes (−4 to −361 Mt CO₂ eq.).

While some CE strategies that closed resource loops led to negligible additional emissions (less than 0.5 Mt CO₂ eq.), these were outweighed by potential savings. The highest mitigation potential was reported for recycling (−18 to −77 Mt CO₂ eq.), then closed-loop recycling (−44 Mt CO₂ eq.) and upcycling combined with design for disassembly (−12 to −19 Mt CO₂ eq.). Considering the narrowing of resource loops, only emission savings were reported, with lightweighting, substitution and efficiency in combination contributing the highest savings potential (−125 Mt CO₂ eq.) in one sector-wide study. When taking CE strategies in isolation, material substitution (−14 to −51 Mt CO₂ eq.) and material efficiency (−6 to −15 Mt CO₂ eq.) showed the greatest savings. On balance, our analysis suggests that, at the upper bound, a combination of CE strategies where possible (for example upcycling and design for disassembly) would lead to higher emission savings per strategy than if they were implemented individually.

We compared summed-up annual emission savings, at both upper and lower bounds, with an available carbon budget for the EU-27 annualised from 2019 to 2050, finding a significant potential for CE strategies in the construction sector to stay within the EU’s remaining carbon budget. While the upper bound is optimistic as it inevitably includes some double counting when adding estimated CO₂ savings together, the lower bound estimates from the sector-wide studies indicate CO₂ savings equivalent to a third of the EU’s remaining budget. While our search terms covered CE strategies in the building or construction sector, not all construction elements and CE strategies will have been considered in the analysed studies, indicating additional potential savings exist elsewhere.

Despite the EU’s CE Action Plan providing a prerequisite to achieve climate neutrality by 2050 [11], some measures presented in the literature as circular resulted in extra emissions, for example, the repair and maintenance of more intensively used floor surfaces. While this relates to both how CE strategies are implemented and how emissions are measured (a methodological challenge identified in e.g. Korhonen et al. [72]), it leads to wider debates about whether these circular strategies are environmentally sustainable. Although arguably complete circularity is theoretically possible [72], context is important, such as the energy used in the recycling process. While these strategies were incorporated in our study because ‘circular’ was one of the key search terms, it highlights the need to consider carefully how the sustainability of CE strategies is measured, to avoid and address unintended consequences.

Limitations and Future Research

Limitations of this work arise from the need to provide a harmonised dataset from a diverse and inconsistent evidence base. The scaling up of construction elements using an estimate of their quantity in the EU-27 and emission estimates in proportion to the country's share in the EU-27 population required several assumptions and additional data and statistics outside the sample of studies. However, countries can use very different building materials and in different amounts depending on design and standards. For example, not all countries will use predominantly bricks, or the same construction elements. In addition, population shares will not be fully representative of building demands due to different house sizes and occupancy rates. These factors could over- or underestimate the emissions associated with different construction elements, depending on how the case country compares to the European average.

There is a large variation in methods, functional units, location and timeframe, system boundary, assumptions about uptake rate and other potential sources of heterogeneity, which will affect the scaling up of mitigation potentials. Input-output-based studies, for example, do not generally consider end-of-life impacts and the associated emissions, but have a wider system boundary compared to life cycle assessments, which include only the main processes albeit at a more detailed product level. Studies have shown that LCA analyses often underestimate emission savings [73]. Broader socio-economic assumptions within the analysed studies are also determining factors in estimating emission savings. For example, Barrett and Scott [44] assume certain levels of economic growth, consumption and decarbonisation of power in their emissions baseline, which will differ compared to other studies. The scaling-up process assumes similar emission savings will be realised in other EU countries (in proportion to the share of population), yet rates of economic development, population growth and decarbonisation will differ. Going forward, more advanced comparisons of CE-focused studies could consider replacement rates across the nations, including the lifetimes of buildings and construction elements, as well as differences between new builds and existing building stock.

While we have added CO₂ emission estimates from construction elements separately to sector-wide estimates when evaluating the total contribution of CE strategies to staying within the EU-27's remaining carbon budget, the addition of the estimates is likely to lead to double counting. For example, we have summed the results of all reuse studies, some of which will consider reuse of the same construction element (not always specified in an underlying analysed study). Additionally, presenting these savings as annual does not recognise that some CO₂ emission estimates, for example from refurbishment, will not result in extra emissions or emission savings annually but e.g. once a decade.

Although a comparison of studies needs to be performed with caution and we have undoubtedly missed papers as a result of our search terms, such cross-study comparisons are common, for example as part of regular overviews of state-of-the-art research by the Intergovernmental Panel on Climate Change and other reviews [39]. This study provides a starting point to evaluate the contribution of CE strategies towards carbon neutral targets at scale, while future research in this area needs to focus on more sophisticated modelling and comparison. Future research could look at the standardisation of methods for assessing CE strategies. For example, there is merit in conducting large ensemble studies similar to those in the areas of climate change and integrated assessment modelling, alongside critical studies on participation in a CE, for example, new business models and consumption norms [74].

We have also not discussed the social and economic dimensions of CE and the redesign of existing consumption cultures and linear business models. There are a variety of critiques and limitations of the CE concept, its implementation and outcomes [20, 71, 72]. These demonstrate the enormity of the shift and extra research needed in how the economy operates and society behaves; in the need to thoroughly and carefully assess the sustainability outcomes; and in how to govern the transition in a very interlinked yet uneven global economy.

Conclusion

Decarbonising the construction sector is challenging given the rising demand for buildings and infrastructure, their long lifespan and their reliance on carbon-intensive steel and cement. Given the need for urgent and ambitious emission reductions to achieve the Paris Agreement climate goals of 1.5–2 °C, circular economy strategies provide an additional policy lever for improving the energy efficiency of buildings and decarbonising heating and cooling. While many studies have started quantifying the mitigation potential of slowing, closing and narrowing resource loops in the built environment in specific local and national contexts, the combined potential to meet the EU's climate goals remains underexplored.

Our study is the first to estimate the trade-offs between circular economy strategies and climate change mitigation at the EU level. We applied a scaling-up process to a systematic review of the mitigation potential of circular economy strategies in construction across the EU (including the UK) to compare alternative strategies to each other and to the EU's carbon budgets. While we found a significant potential for the circular economy to contribute to a low-carbon economy, we also found the need to prioritise methods that enable similar analyses at scale, an appraisal of what counts as circular (since many strategies add CO₂ emissions instead of reducing them), alongside a critical assessment of the circular economy's wider environmental and related socio-economic impacts.

To ensure well-informed policies, our analysis highlights the need for better quality data to measure circularity contributions towards decarbonisation. Otherwise, the lack of monitoring and evaluation of construction sector choices towards achieving carbon budgets would limit policymakers in this area. Improved data on material and carbon intensities and on material flows would support a broader assessment of the impact of circular economy measures in the European Union built environment on a net-zero target. Accordingly, we recommend that European Union policy in the construction sector should include assessing the potential trade-offs, synergies and unintended consequences of implementing circular economy. In addition, policy incentives are needed for combining circular economy strategies (e.g. upcycling and design for disassembly), as this unification would likely lead to higher CO₂ emission savings per strategy than if they were implemented individually. Such trade-off assessments and incentives would lead to more systemic thinking across policy domains.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s43615-023-00257-2>.

Author Contribution Conceptualisation: Maria Sharmina; methodology: Maria Sharmina, Dimitrios Pappas, Kate Scott, Alejandro Gallego-Schmid; formal analysis and investigation: Maria Sharmina, Dimitrios Pappas; writing—original draft preparation: Maria Sharmina, Dimitrios Pappas, Kate Scott, Alejandro Gallego-Schmid; writing—review and editing: Maria Sharmina, Dimitrios Pappas, Kate Scott, Alejandro Gallego-Schmid; funding acquisition: Maria Sharmina.

Funding This work has been funded by the Sustainable Consumption Institute (grant reference: 118206) at the University of Manchester.

Data Availability Available on request.

Declarations

Ethics Approval and Consent to Participate Not applicable

Consent for Publication Not applicable

Competing Interests Alejandro Gallego-Schmid is an Editorial Board member of the *Circular Economy and Sustainability* Journal.

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