Circular Economy and Sustainability (2023) 3:1989–2008
https://doi.org/10.1007/s43615-023-00257-2

ORIGINAL PAPER

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

M. Sharmina[1] · D. Pappas[2,3] · K. Scott[4] · A. Gallego-Schmid[1]

Received: 10 October 2022 / Accepted: 6 February 2023 / Published online: 9 March 2023

Abstract

Environmental benefits of circular economy (CE) measures, such as waste reduction, need to be weighed against the urgent need to reduce CO_2 emissions to zero, in line with the Paris Agreement climate goals of 1.5–2 °C. Several studies have quantified CO_2 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 CO_2 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 CO_2 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 CO_2 savings from sector-wide estimates (mean 39.28 Mt CO_2 eq./year) slightly exceeded construction-element savings (mean 25.06 Mt CO_2 eq./year). We also find that a conservative estimate of 234 Mt CO_2 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

✉ M. Sharmina
maria.sharmina@manchester.ac.uk

1 Tyndall Centre for Climate Change Research, School of Engineering, The University of Manchester, M13 9PL Manchester, UK

2 Business School, Liverpool Hope University, L16 9JD Liverpool, UK

3 Tyndall Centre for Climate Change Research, Faculty of Science, University of East Anglia, NR4 7TJ Norwich, UK

4 Geography Department, The University of Manchester, M13 9PL Manchester, UK

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 CO_2) 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 CO_2/year.
- Reducing waste in the construction site, e.g. modular offsite construction can reduce waste by up to 90% compared with traditional onside construction [22]. The potential reduction of emissions by 2050 is 0.2 billion t of CO_2/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 CO_2/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 CO_2/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 CO_2 beyond 2050.

Although CE implementation can curtail overall CO_2 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 CO_2, 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 CO_2 eq./m^2 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 CO_2 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 CO_2 emissions are measured [25].

Exacerbating the challenges of assessing CO_2 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 CO_2 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 CO_2 emission savings or extra CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 estimates derived from a variety of methodologies, assumptions and models.

Selecting Our Sample of Quantitative CO_2 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 CO_2 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

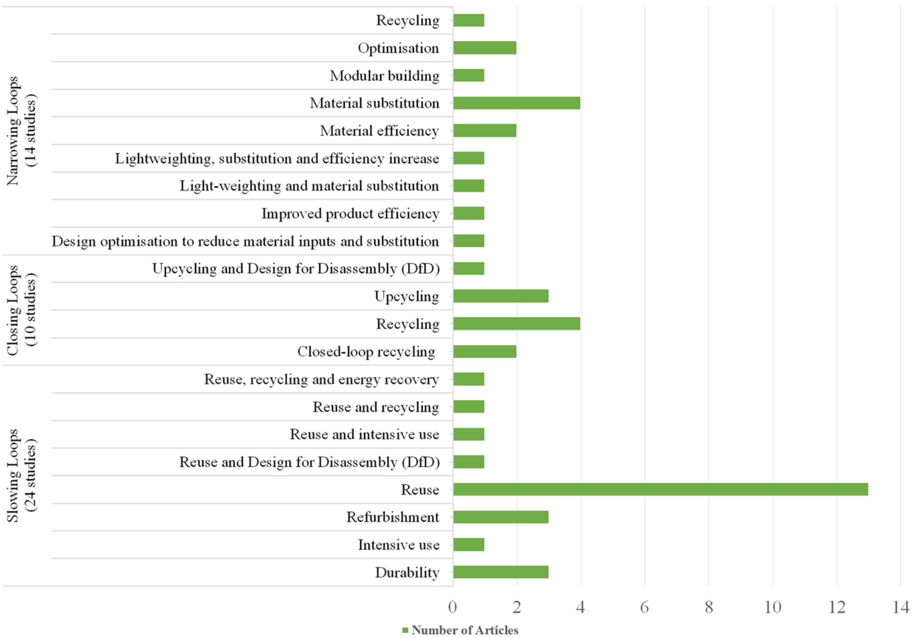

Fig. 1 The number of analysed studies by circular economy loop and by circular economy strategy. Note: some studies cover circular economy strategies from two loops and, hence, are counted in this figure twice

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 CO_2 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 CO_2 estimates provided per construction element (e.g. per brick, m^2, 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 CO_2 emissions per construction element.

For example, if the CO_2 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 CO_2 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).

$$C_{EU} = \frac{P_{EU}}{P_i} \times N_{ji} \times C_j \tag{1}$$

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

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

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

To spatially scale up CO_2 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).

$$C_{EU} = \frac{P_{EU}}{P_i} \times C_{sec,i} \tag{3}$$

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 CO_2 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 CO_2 saving. Secondly, where studies provided cumulative estimates for CO_2 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).

$$C_{EU} = \frac{C_m}{Y_t - Y_0} \tag{4}$$

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 CO_2 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).

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

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 CO_2 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 CO_2 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 CO_2 to emission savings of 960.12 Mt CO_2 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 CO_2 eq. annual emission savings from intensive use of the stock. Our comparison shows that sector-wide emission savings (mean 39.28 Mt CO_2 eq.) were on average slightly higher than construction-element savings (mean 25.06 Mt CO_2 eq.). In particular, sector-wide estimates ranged between 0.01 Mt CO_2 eq./year from refurbishment, which did not include savings from operation energy [44], and 124.76 Mt CO_2 eq. from combined lightweighting, substitution and efficiency increase [41]. Construction-element estimates had a wider range: between 320.04 Mt CO_2 of extra emissions and 960.12 Mt CO_2 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 CO_2 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 CO_2 eq. in saved emissions from refurbishment [44] and up to 1.2 Mt CO_2 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 CO_2 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 CO_2 eq. In the studies focused on upcycling in isolation, emission savings reach 0.11–4.33 Mt CO_2 eq. [43, 52, 56], whereas upcycling with design for disassembly saves 12.39–19.48 Mt CO_2 eq. [57].

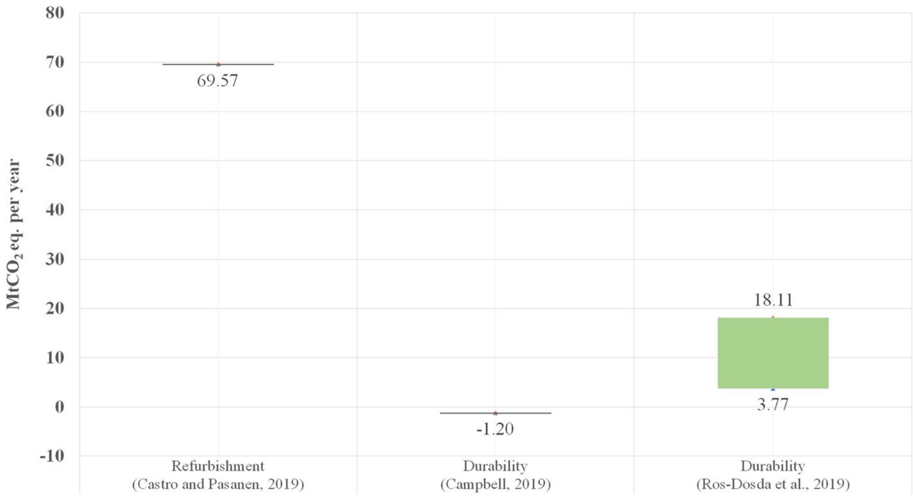

Fig. 2 Potential extra emissions and emission savings ($MtCO_2$ eq. per year) in the European Union from slowing resource loops per circular economy strategy. Note: reuse is excluded from this figure and, instead, explored in Figs. 2 and 3

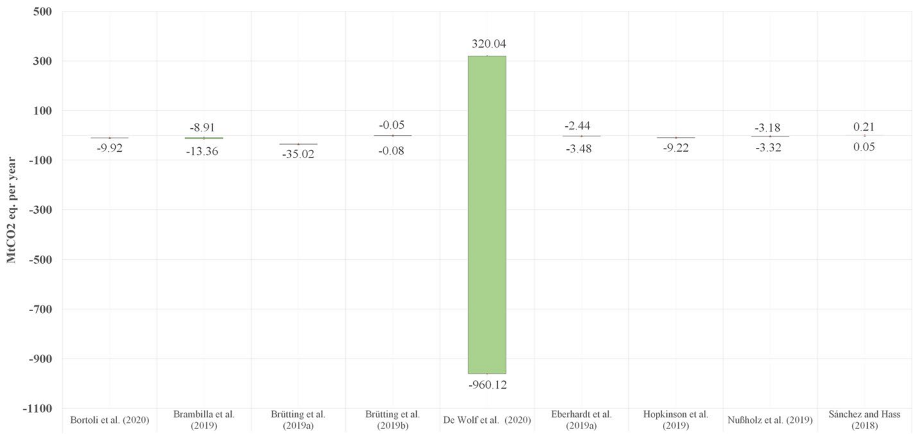

Fig. 3 Potential extra emissions and emission savings ($MtCO_2$ eq. per year) in the European Union from reuse across a range of studies. Note: reuse cases combined with other circular economy strategies are excluded from this figure and, instead, explored in Fig. 4

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 CO_2 eq. [30], followed by durability, which ranged from 3.77 to 18.11 Mt CO_2 eq. [29]. However, Campbell [55] highlights durability as cutting emissions by 1.2 Mt CO_2 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 CO_2 eq. [50] in extra emissions to 35.02

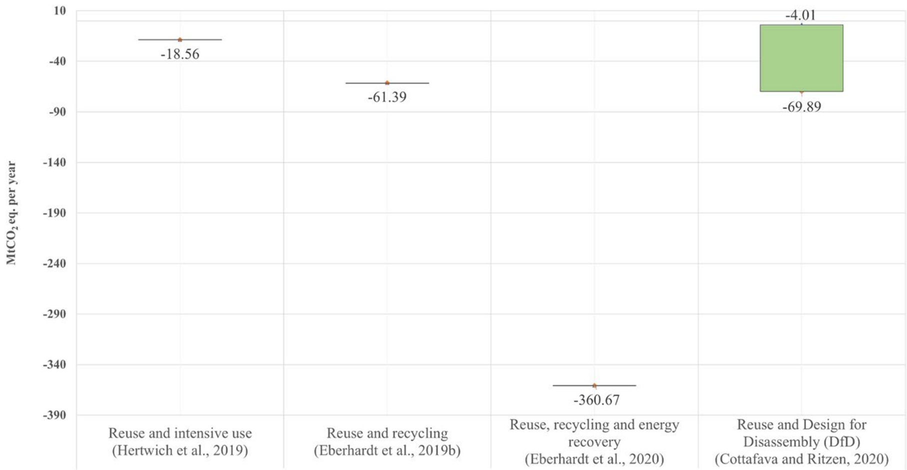

Fig. 4 Potential extra emissions and emission savings (MtCO_2 eq. per year) in the European Union from reuse cases combined with other circular economy strategies

Mt CO_2 eq. [58], 124.76 Mt CO_2 eq. [41] and 960.12 Mt CO_2 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 CO_2 eq. [50] to extra emissions of 0.21 Mt CO_2 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 CO_2 eq. of extra emissions [50] and emission savings of 9.92 Mt CO_2 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 CO_2 [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 CO_2 eq. at the lower bound when looking at reuse combined with design for disassembly [60], and up to 360.67 Mt CO_2 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 CO_2 eq. at the upper bound and 18.11 Mt CO_2 eq. at the lower bound [66–68], and closed-loop recycling with savings of 44.16 Mt CO_2 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

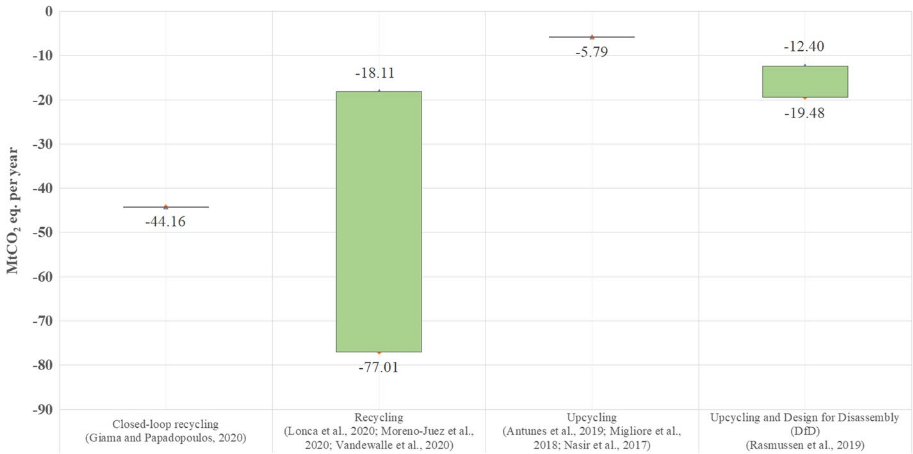

Fig. 5 Potential extra emissions and emission savings ($MtCO_2$ eq. per year) in the European Union from closing resource loops per circular economy strategy. Note: all of the closing-loop studies focus on construction elements rather than on sector-wide estimates

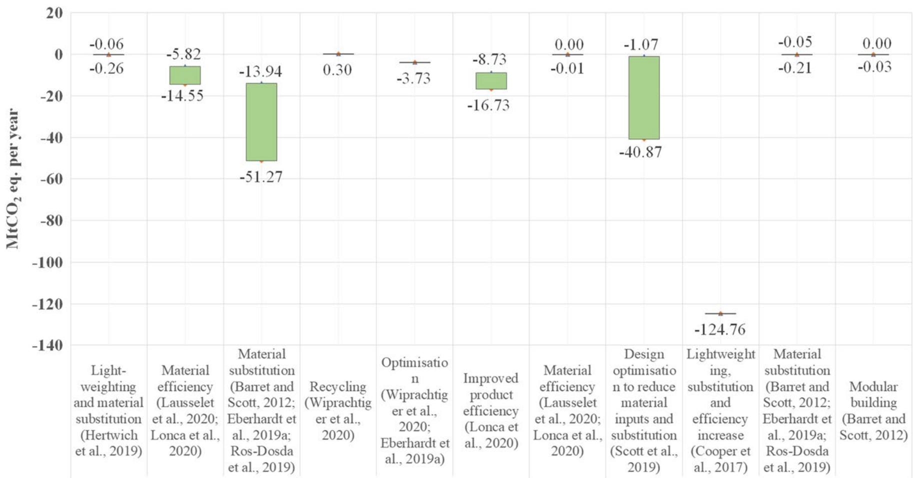

Fig. 6 Potential extra emissions and emission savings ($MtCO_2$ eq. per year) in the European Union from narrowing resource loops per circular economy strategy

contributors to emission savings, amounting to 124.76 Mt CO_2 eq. [41]. Design optimisation to reduce and substitute material inputs also leads to emission savings, with 40.87 Mt CO_2 eq. of savings at the upper bound of scaling up and 1.07 Mt CO_2 eq. at the lower bound [32]. Emission savings additionally come from improved construction products, reaching 16.73 Mt CO_2 eq. [66], while material substitution presents a range of 13.94 to 51.27 Mt CO_2 eq. of emission savings [29, 44, 46, 54].

Comparison with the EU-27 Remaining Carbon Budget

Before proceeding to the comparison of our CO_2 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 CO_2 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 CO_2 eq. per year would be more than twice compensated for by the upper bound 1671 Mt CO_2 eq. from construction element focused studies. However, as noted in the previous paragraph, this is an optimistic assessment. The lower bound of 234 Mt CO_2 eq. might give a more conservative estimate of potential annual CO_2 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 CO_2 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.

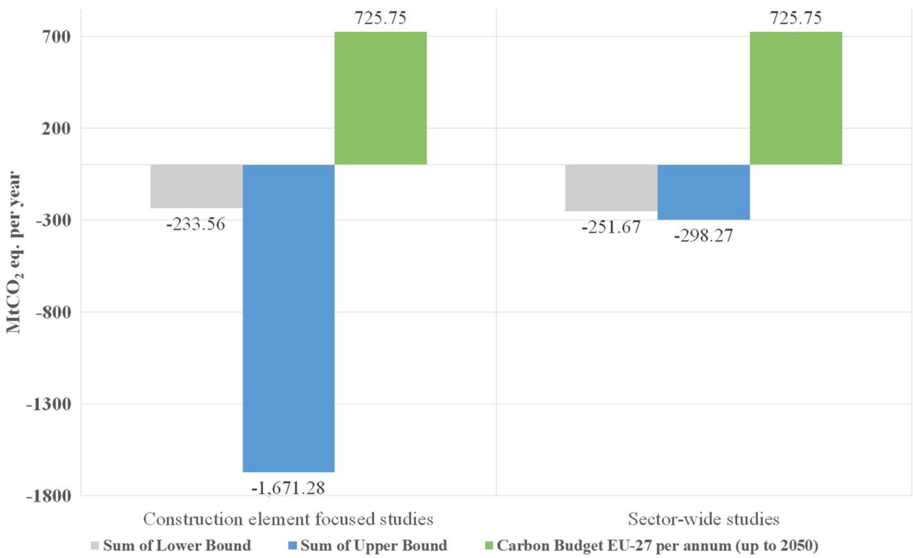

Fig. 7 Extra emissions and emission savings ($MtCO_2$ eq. per year) from the circular economy strategies in the European Union's construction sector compared to the remaining EU-27 carbon budget per annum. The carbon budget was divided by the number of years between 2019 and 2050

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 CO_2 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 CO_2 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 CO_2 eq., yet the range of savings across elements was large (+320 to −1200 Mt CO_2 eq.). Without consistent data, it is difficult to understand how much these differences relate to data and modelling, or different building and material contexts.

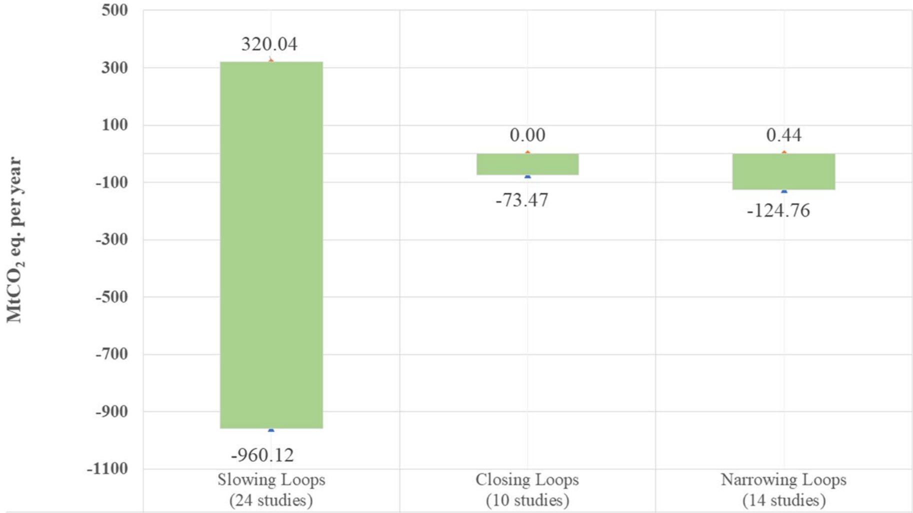

Fig. 8 Extra emissions and emission savings ($MtCO_2$ eq. per year) from the circular economy loops in the European Union's construction sector. Note: some studies cover circular economy strategies from two loops and, hence, are counted in this figure twice

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 CO_2 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 CO_2 eq. There was a wide range of emission estimates for reuse (+35 to −960 Mt CO_2 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 CO_2 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 CO_2 eq.).

While some CE strategies that closed resource loops led to negligible additional emissions (less than 0.5 Mt CO_2 eq.), these were outweighed by potential savings. The highest mitigation potential was reported for recycling (−18 to −77 Mt CO_2 eq.), then closed-loop recycling (−44 Mt CO_2 eq.) and upcycling combined with design for disassembly (−12 to −19 Mt CO_2 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 CO_2 eq.) in one sector-wide study. When taking CE strategies in isolation, material substitution (−14 to −51 Mt CO_2 eq.) and material efficiency (−6 to −15 Mt CO_2 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 CO_2 savings together, the lower bound estimates from the sector-wide studies indicate CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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.

References

1. United Nations. The Paris Agreement (2015) [cited 2021 21st Oct]; Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
2. IPCC (2021) Summary for policymakers. In: Masson-Delmotte et al (eds) Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change V. Cambridge University Press, Cambridge
3. European Commission (2019) A European Green Deal. European Commission, Brussels
4. European Commission (2020) Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. European Commission, Brussels
5. Giesekam J, Tingley DD, Cotton I (2018) Aligning carbon targets for construction with (inter)national climate change mitigation commitments. Energy Build 165:106–117
6. UNEP (2020) 2020 global Status Report for buildings and construction: towards a Zero-emission, efficient and resilient buildings and Construction Sector. United Nations Environment Programme (UNEP): Nairobi, Kenya
7. European Commission. Energy performance of buildings (2019) [cited 2021 20th Oct]; Available from: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performanceof-buildings
8. European Parliament and, Council (2012) Directive 2012/27/EU of the European parliament and of the Council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC. European Parliament and Council: Strasbourg, France
9. Ng ST, Wong JMW, Skitmore M (2013) Challenges facing carbon dioxide labelling of construction materials. Proc Inst Civ Eng - Eng Sustain 166(1):20–31
10. Ingrao C et al (2019) Sustainability issues of by-product and waste management systems, to produce building material commodities: a comprehensive review of findings from a virtual special issue, vol 146. Resources, Conservation and Recycling, pp 358–365
11. European Commission, Circular economy action plan. For a cleaner and more competitive Europe 2020, European Commission, Brussels
12. Hertwich EG et al (2020) Resource Efficiency and Climate Change: material efficiency strategies for a Low-Carbon Future. A report of the International Resource Panel. United Nations Environment Programme Nairobi, Kenya
13. Nations U (2019) World urbanization prospects: the 2018 Revision (ST/ESA/SER.A/420). United Nations, New York

14. Caldas LR et al (2022) How different tools contribute to climate change mitigation in a circular building environment? - a systematic literature review. Sustainability 14(7):3759
15. Parece S et al (2022) A methodology to qualitatively select upcycled building materials from Urban and Industrial Waste. Sustainability 14(6):3430
16. Geissdoerfer M et al (2017) The Circular economy – a new sustainability paradigm? J Clean Prod 143:757–768
17. Bocken NMP et al (2016) Product design and business model strategies for a circular economy. J Industrial Prod Eng 33(5):308–320
18. Mendoza JMF, Gallego-Schmid A, Azapagic A (2019) Building a business case for implementation of a circular economy in higher education institutions. J Clean Prod 220:553–567
19. Kirchherr J, van Santen R (2019) Research on the circular economy: a critique of the field Resources. Conserv Recycl 151:104480
20. Korhonen J, Honkasalo A, Seppälä J (2018) Circular economy: the concept and its limitations. Ecol Econ 143:37–46
21. Economics M (2019) Industrial Transformation 2050 - pathways to net-zero emissions from EU Heavy Industry. University of Cambridge Institute for Sustainability Leadership (CISL), Cambridge
22. WRAP, Case study: Waste minimisation through offsite construction 2004. Waste & Resources Action Programme (WRAP), Banbury
23. Waste L, Board R (2015) Towards a circular economy – context and opportunities. London Waste and Recycling Board, London
24. Circle, Economy (2016) Circular Amsterdam: a vision and action agenda for the city and metropolitan area. Circle Economy, Amsterdam
25. Gallego-Schmid A et al (2020) Links between circular economy and climate change mitigation in the built environment. J Clean Prod 260:121115
26. Hailemariam A, Erdiaw-Kwasie MO (2022) Towards a circular economy: Implications for emission reduction and environmental sustainability. Bus Strat Env bse.3229. https://doi.org/10.1002/bse.3229
27. Mongo M et al (2022) Assessment of the impact of the circular economy on CO2 emissions in Europe. J Innov Econ Manag 39(3):15–43
28. Ma W et al (2023) Evaluating carbon emissions of China's waste management strategies for building refurbishment projects: contributing to a circular economy. Environ Sci Pollut Res 30:8657–8671. https://doi.org/10.1007/s11356-021-18188-6
29. Ros-Dosdá T et al (2019) Environmental comparison of indoor floor coverings. Sci Total Environ 693:133519
30. Castro R, Pasanen P (2019) How to design buildings with Life Cycle Assessment by accounting for the material flows in refurbishment. IOP Conf Ser: Earth Environ Sci 225:012019. https://doi.org/10.1088/1755-1315/225/1/012019
31. de Bortoli A, Bouhaya L, Feraille A (2020) A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France. Int J Life Cycle Assess 25(4):814–830
32. Scott K et al (2019) Bridging the climate mitigation gap with economy-wide material productivity. J Ind Ecol 23(4):918–931
33. Sanchez B, Haas C (2018) A novel selective disassembly sequence planning method for adaptive reuse of buildings. J Clean Prod 183:998–1010
34. Wu P-Y et al (2021) A data-driven approach to assess the risk of encountering hazardous materials in the building stock based on environmental inventories. Sustainability 13(14):7836
35. Mukoro V, Gallego-Schmid A, Sharmina M (2021) Life cycle assessment of renewable energy in Africa. Sustain Prod Consum 28:1314–1332
36. Corona B et al (2019) Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour Conserv Recycl 151:104498
37. Mendoza JMF et al (2017) Integrating backcasting and eco-design for the circular economy: the BECE framework. J Ind Ecol 21(3):526–544
38. Bleischwitz R et al (2022) The circular economy in China: achievements, challenges and potential implications for decarbonisation. Resour Conserv Recycl 183:106350
39. Ivanova D et al (2020) Quantifying the potential for climate change mitigation of consumption options. Environ Res Lett 15(9):093001
40. Allwood JM et al (2011) Material efficiency: a white paper. Resour Conserv Recycl 55(3):362–381
41. Cooper SJG et al (2017) Thermodynamic insights and assessment of the 'circular economy'. J Clean Prod 162:1356–1367
42. Brütting J et al (2019) Design of truss structures through reuse. Structures 18:128–137

43. Migliore M et al (2018) Innovative use of scrap and waste deriving from the stone and the construction sector for the manufacturing of bricks. Review of the international scenario and analysis of an Italian case study. Environ Eng Manag J 17:2507–2514. https://doi.org/10.30638/eemj.2018.249
44. Barrett J, Scott K (2012) Link between climate change mitigation and resource efficiency: a UK case study. Glob Environ Change 22(1):299–307
45. Eurostat (2020) Population & demography. Online, Eurostat, Editor
46. Eberhardt LCM, Birgisdóttir H, Birkved M (2019) Comparing life cycle assessment modelling of linear vs. circular building components. IOP Conf Ser: Earth Environ Sci 225:012039
47. IEA. Global CO2 emissions in 2019 (2020) [cited 2021 28th Sept]; Available from: https://www.iea.org/articles/global-co2-emissions-in-2019
48. IPCC (2018) Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, et al., Editors
49. United, Nations (2020) The 2019 revision of World Population prospects D.o.E.a.S.A. United Nations, Population Division Editor. Online
50. De Wolf C, Hoxha E, Fivet C (2020) Comparison of environmental assessment methods when reusing building components: a case study. Sustainable Cities and Society 61:102322
51. Lausselet C et al (2021) Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. J Ind Ecol 25(2):419–434
52. Antunes V, Freire AC, Neves J (2019) A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling. Constr Build Mater 211:453–469
53. Eberhardt LCM et al (2021) Circular economy potential within the building stock - mapping the embodied greenhouse gas emissions of four danish examples. J Building Eng 33:101845
54. Wiprächtiger M et al (2020) A framework for sustainable and circular system design: development and application on thermal insulation materials. Resour Conserv Recycl 154:104631
55. Campbell A (2019) Mass timber in the circular economy: paradigm in practice? Proc Inst Civ Eng - Eng Sustain 172(3):141–152
56. Nasir MHA et al (2017) Comparing linear and circular supply chains: a case study from the construction industry. Int J Prod Econ 183:443–457
57. Rasmussen FN, Birkved M, Birgisdóttir H (2019) Upcycling and design for disassembly – LCA of buildings employing circular design strategies. IOP Conf Ser: Earth Environ Sci 225:012040
58. Brütting J, De Wolf C, Fivet C (2019) The reuse of load-bearing components. IOP Conf Ser: Earth Environ Sci 225:012025
59. Eberhardt LCM, Birgisdóttir H, Birkved M (2019) Life cycle assessment of a Danish office building designed for disassembly. Build Res Inf 47(5):666–680
60. Cottafava D, Ritzen M (2021) Circularity indicator for residential buildings: addressing the gap between embodied impacts and design aspects. Resour Conserv Recycl 164:105120
61. Hertwich EG et al (2019) Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environ Res Lett 14(4):043004
62. Brambilla G et al (2019) Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resour Conserv Recycl 141:133–142
63. Cooper DR, Allwood JM (2012) Reusing steel and aluminum components at end of product life. Environ Sci Technol 46(18):10334–10340
64. Hopkinson P et al (2019) Recovery and reuse of structural products from end-of-life buildings. Proc Inst Civ Eng - Eng Sustain 172(3):119–128
65. Nußholz JLK, Nygaard Rasmussen F, Milios L (2019) Circular building materials: carbon saving potential and the role of business model innovation and public policy. Resour Conserv Recycl 141:308–316
66. Lonca G, Bernard S, Margni M (2019) A versatile approach to assess circularity: the case of decoupling. J Clean Prod 240:118174
67. Moreno-Juez J et al (2020) Treatment of end-of-life concrete in an innovative heating-air classification system for circular cement-based products. J Clean Prod 263:121515
68. Vandewalle D et al (2020) Assessment of Eco-Friendly Pavement construction and maintenance using multi-recycled RAP mixtures. Recycling 5(3):17
69. Giama E, Papadopoulos AM (2020) Benchmarking carbon footprint and circularity in production processes: the case of stonewool and extruded polystyrene. J Clean Prod 257:120559
70. Çimen Ö (2021) Construction and built environment in circular economy: a comprehensive literature review. J Clean Prod 305:127180

71. Corvellec H, Stowell AF, Johansson N (2022) Critiques of the circular economy. J Ind Ecol 26(2):421–432
72. Korhonen J et al (2018) Circular economy as an essentially contested concept. J Clean Prod 175:544–552
73. Huysman S et al (2016) Quantifying the environmental impacts of a european citizen through a macro-economic approach, a focus on climate change and resource consumption. J Clean Prod 124:217–225
74. Hobson K et al (2021) Consumption work in the circular economy: a research agenda. J Clean Prod 321:128969