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## TOPICAL REVIEW

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## Saving resources and the climate? A systematic review of the circular economy and its mitigation potential

Jasmin Cantzler<sup>1</sup>, Felix Creutzig<sup>2,3</sup> , Eva Ayargarnchanakul<sup>3,4</sup>, Aneeque Javaid<sup>2</sup> , Liwah Wong<sup>2</sup>   
and Willi Haas<sup>5</sup> 

<sup>1</sup> Gesellschaft für Internationale Zusammenarbeit GmbH, Friedrich-Ebert-Allee 32, Bonn 53113, Germany

<sup>2</sup> Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany

<sup>3</sup> Sustainability Economics of Human Settlement, Technical University Berlin, Berlin, Germany

<sup>4</sup> Faculty of Economics, Prince of Songkla University, Hatyai, Thailand

<sup>5</sup> Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna (BOKU), Austria

E-mail: [jasmincantzler@gmail.com](mailto:jasmincantzler@gmail.com)

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### Abstract

To achieve the temperature goal of the Paris Agreement, transformative actions are needed. The circular economy (CE) is one concept that gained popularity in recent years, with its proclaimed selling point to combine economic development with benefits to businesses, society, and the environment. However, definitions of CE diverge, applications appear across vastly different settings, and overall there is a lack of understanding of how much CE strategies can contribute to climate change mitigation (mitigation). We systematically screened 3244 records in Web of Science and Scopus, restricted to papers in English. We then selected studies against pre-determined eligibility criteria that had to (1) refer explicitly to CE or closely related concepts (e.g. performance economy, cradle-to-cradle, material or product efficiency); and (2) refer to a climate change mitigation potential. We identified 341 studies, summarized, and grouped into six sectors (industry, waste, energy, buildings, transport, and agriculture). These sectors are not completely mutually exclusive, but partially overlapping. Nonetheless, sectoral classifications relate to existing categorizations and map well with international assessments of climate change mitigations, such as those of the Intergovernmental Panel on Climate Change (IPCC). Our review sets out to summarize the results of the scientific literature on the extent to which CE strategies can contribute to mitigation. Even though our query explicitly required a consideration of climate change, only 10% of all studies contributed insights on how the CE can support mitigation. We find that the highest saving potential is evidenced in the industry, energy, and transport sector; mid-range savings in the waste and building sector; and lowest gains are to be expected in agriculture. The majority of studies investigate incremental measures claiming but not demonstrating climate change mitigation. Most studies indicate potential but implementation remains weak. Assessments should move from attributional to consequential analysis to avoid misleading policy makers.

### 1. Introduction

The circular economy (CE) is one concept that has been gaining increased popularity in recent years, with its proclaimed selling point to combine economic development with benefits to businesses, society, and the environment. Yet, the evidence base for its abatement potential remains somewhat elusive. Even the concept itself remains ambiguously defined and

only a recent systematic review approached the question about the definition and found CE an ‘evolving concept that still requires development to consolidate its definition, boundaries, principles and associated practices’ (Merli *et al* 2018). Yet, given that more and more actors are adopting CE principles and strategies, collecting and synthesizing the evidence on emissions savings becomes a vital contribution in the implementation of the Paris Agreement.

The Paris Agreement aims to avoid dangerous climate change by ‘holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels’ (United Nations 2015). To achieve this, countries have committed themselves to aim to peak global greenhouse gas emissions (GHG) ‘as soon as possible’, and to ‘undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century’ (United Nations 2015). Transformative policies and actions are needed to bend the emissions curve permanently and to the degree needed to put the world on the trajectory of 1.5 °C. Between now and 2030, we need to reduce 7.6% emissions per year to meet the 1.5 °C goal (UNEP 2019).

If it is true that there is a significant potential for emissions reductions through the adoption of CE principles, policy makers could accelerate and build on existing momentum to scale up climate action. If, however, CE is a rhetorical device that mispackages concepts of theoretical circular optimality in reality and potentially even ignores the costs of energy required for waste recovery (Cullen 2017), climate change mitigation (mitigation) efforts might be well advised to overcome the concept and to invest into substantial demand reductions with a focus on the exergy concepts instead. There is a current lack of understanding of how much CE strategies can contribute to climate change mitigation.

While there is a widespread expectation towards the CE to assist in achieving climate targets, there is to date no systematic review summarizing the results of the scientific literature on the extent to which CE strategies can contribute to climate mitigation. What can be found is a multitude of reviews published in recent years on various aspects of the CE. The early review by Heshmati (2015) examines the rapidly growing literature on CE covering its concept and current practices and assesses its implementation. The review emphasizes that even in China as a main practicing country of CE research, resources are allocated in a fragmented way and research is not conducted effectively for unified effort and progress. Another review asks what the approach of product service systems (PSS) can do for a resource-efficient and CE and finally structures it in research needs for PSS to become fruitful. Ghisellini and colleagues (2016) deal in their widely quoted review article with the origins of the notion, basic principles, advantages and disadvantages, modelling, and the implementation of CE at different levels (micro, meso and macro) worldwide. More than 100 definitions are analyzed by Kirchherr *et al* (2017). Drivers, barriers, and practices that influence the implementation of the CE in the context of supply chains are the central issues of a review by

Govindan and Hasanagic (2018). Korhonen and colleagues (2018) zoom in their review into the definitions of the CE and discuss missing research foci here while Merli *et al* (2018) ask how scholars approach the CE. A further review compiles two instruments to assist implementation. One instrument offers 45 CE strategies and the other presents 100 case studies. The review observes that the scope of current CE implementation considers selected products, materials, and sectors, while system changes to economy are rarely proposed (Kalmykova *et al* 2018). In all these reviews, climate change is hardly mentioned and any quantification of GHG emissions reductions is not in their scope.

Another review provides a critical assessment on current circularity metrics and selects only those metrics that fulfill certain sustainability requirements, amongst them the reduction of GHG emission levels (Corona *et al* 2019). A similar topic was chosen by a systematic review on performance assessment methods for the CE, which provides a comprehensive account on methods from e.g. data envelopment analysis (DEA), life cycle assessment (LCA), and material flow analysis (MFA) or multi-criteria decision methods (MCDM) and variables (Sassanelli *et al* 2019). While both provide a fair review of the conception of metrics, methods, and indicators, they do not deal with quantifications.

There are some CE review articles that deal with the link between circularity and climate change, albeit they are on specific issues. Ingraio *et al* (2018) review studies on food waste in a CE context. Authors argue that food waste has great potentials to be recovered through a set of technologies like anaerobic digestion (AD) into high-value energy, fuel, and natural nutrients and consequently can save CO<sub>2</sub>-eq emissions. Orsini and Marrone (2019) focus on the low-carbon production of building materials and identify seven low-carbon approaches (LEAs), amongst them some CE strategies (e.g. reusable materials and recycling). Another review is more explicit by linking the CE with climate change mitigation in the built environment (Gallego-Schmid *et al* 2020). While all of these articles cover one or the other facette, they do not systematically provide a comprehensive review across issues, technologies, and sectors. However, they are a rich source for this review.

Finally, there are two highly relevant reviews that provide quantifications regarding climate mitigation, but without a specific CE angle. There is one recent review on demand-side solutions for transitioning to low-carbon societies (Ivanova *et al* 2020). They assess how changes in household consumption patterns toward low-carbon alternatives present a great potential for emission reductions. For transport, they identify living car-free, shifting to a battery electric vehicle, and reducing flying as key for climate mitigation. For food, the highest carbon savings comes from dietary changes towards a vegan diet. Shifting to

renewable electricity and refurbishment and renovation are the options with the highest mitigation potential in the housing domain. Although, no link to the CE is established explicitly, the review touches issues that overlap with CE strategies implicitly by providing important reference points for the CE-climate nexus. Another recent topical review article (Hertwich *et al* 2019) that puts an emphasis on the supply-side reviewed emission reductions from material efficiency strategies applied to buildings, cars, and electronics. Specific material efficiency strategies, which overlap with CE strategies, were derived from the literature and the analysis. Quantifications are thus reviewed for the three areas and along the six strategies: (1) more intensive use, (2) lifetime extension, (3) light weight design and material choice, (4) reuse, (5) recycling, upcycling, cascading and (6) improving the yield in production, fabrication and waste processing. The article concludes that there is a strong role for material efficiency strategies for material-intensive systems to contribute towards GHG emission reductions. This study differs from our approach since it sets out with a material efficiency approach instead of a CE one, has a focus on three manufactured products instead of an all sector approach, and is a topical review instead of a systematic review.

The research question underpinning this review thus is: What is the reported quantitative potential of CE measures to reduce GHG emissions and in which sectors? We will present results that highlight possibly effective CE measures. However, we caution that the numbers must be interpreted against a diverse set of boundaries of analysis, and are not straight forward to generalize.

Main insights will be derived from the peer-reviewed literature. However, many studies are and were commissioned to consultancies and other research organizations and not published in scientific journals. Hence, we will compare our insights from the peer-reviewed literature with a sample from the gray literature, obtained through expert solicitation.

## 2. Defining circular economy

CE aims to transform our linear economic 'take-make-dispose' model to a circular one thereby 'decoupling economic activity from the consumption of finite resources, and designing waste out of the system' (Ellen MacArthur Foundation no date b). The notion of earth not as 'illimitable plane' but a 'closed sphere' can be dated back to the work of Boulding (1966), who used the term to highlight the exhaustibility of natural resources. CE gained a wave of supporters in the late 1970s and early 1980s. Today the concept is experiencing a renaissance and is promoted by governments (Yuan *et al* 2006, Government of Netherlands 2016, Mathews and Tan 2016,

Mcdowall *et al* 2017, European Commission no date) and a multitude of other actors-alike (Ellen MacArthur Foundation 2012, Preston 2012, Nordic Council of Ministers 2015, Stahel 2016, Sitra no date).

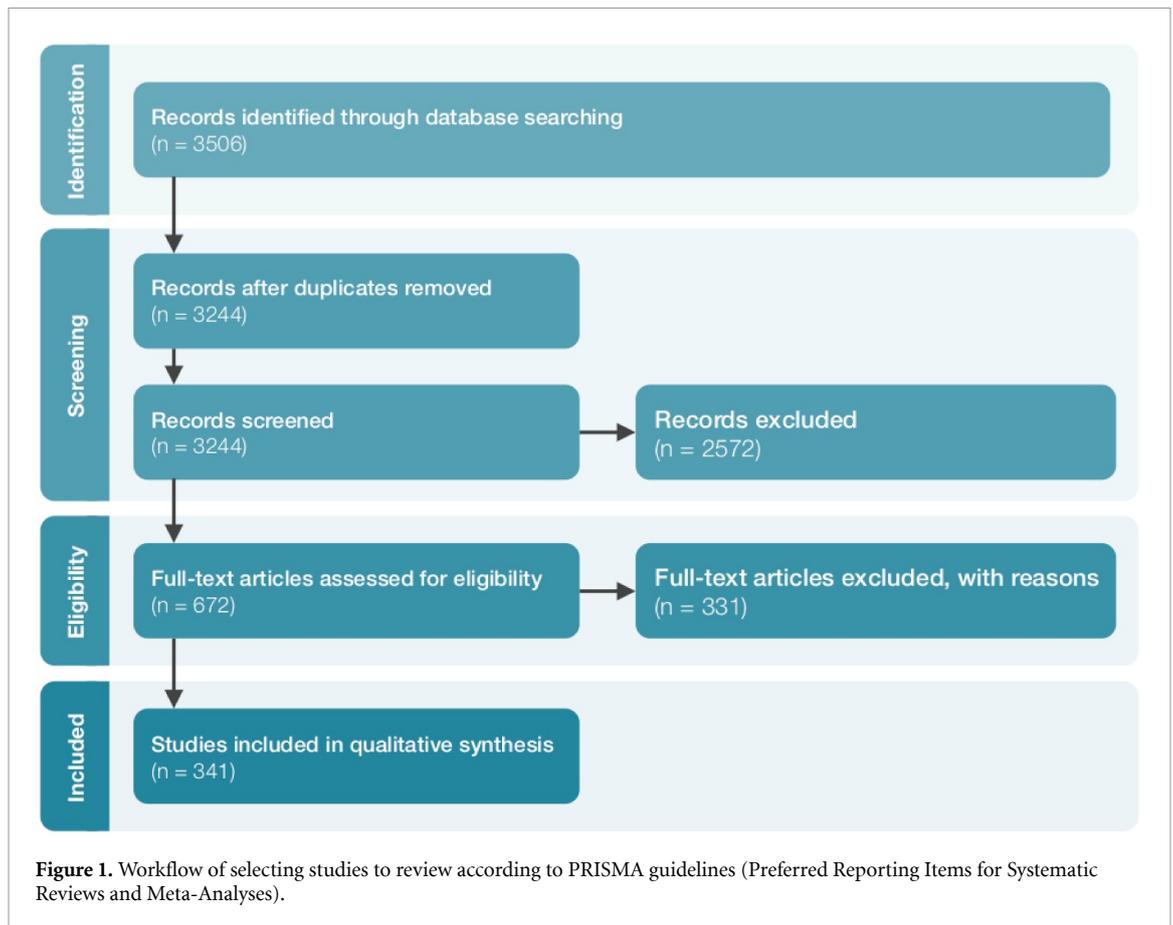
CE synthesizes and embodies a multitude of schools of thought with roots and relations to a number of related concepts (Blomsma and Brennan 2017, Murray *et al* 2017, Ellen MacArthur Foundation no date a) such as the cradle to cradle (Mcdonough and Braungart 2002), performance economy (Stahel and Reday-Mulvey 1981), biomimicry (Benyus 2002) and industrial ecology (Graedel 1994).

Since 'as a rule of thumb, more circularity equals more environmental benefits', Potting *et al* (2017) arranged circular activities within the production chain according to their levels of circularity. Smarter product manufacturing and use is followed by lifetime extension and recycling of materials through recovery. Incineration from which energy is recovered is considered a low-circularity strategy, 'because it means the materials are no longer available to be applied in other products' (Potting *et al* 2017).

Korhonen *et al* (2018) identified an imbalance of literatures that focus on metrics and indicators as well as management systems, but leaves the basic assumptions concerning values, social structures, cultures, underlying world-views, and the paradigmatic potential of CE largely unexplored. A systematic review (Merli *et al* 2018) found CE to be an 'evolving concept that still requires development to consolidate its definition, boundaries, principles and associated practices'. It was noted by Kirchherr *et al* (2017), from an analysis of 114 CE definitions, that this "circular economy babble" constitutes a serious challenge for scholars and offer a definition of CE development through multi-stakeholder discourse:

'A circular economy describes an economic system that is based on business models which replace the "end-of-life" concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations.'

In absence of a universal definition, this summary description offers the inclusion of various conceptual notions of CE while explicitly adopting a definition for our work, as recommended by several scholars (Kirchherr *et al* 2017).



### 3. Methods

Systematic reviews enable the collation of relevant evidence to a specific research question, using explicit systematic methods to minimize bias and enable the provision of reliable findings. To provide the necessary transparency of our systematic review, we employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, to the extent applicable (Liberati *et al* 2009) (figure 1).

Prior to embarking on the review, we developed a review protocol to guide the review procedure. At a minimum, the eligibility criteria entails that the studies refer to: (1) at least one CE activity or broadly related concept (e.g. a more narrow focus on resource or material efficiency), or related terms such as performance economy or cradle to cradle (see search query below for further information); and (2) its quantitative mitigation potential in some regard (e.g. emissions estimates in % reductions, or tonnes of CO<sub>2</sub>). We thus deliberately included also such papers, which did not mention CE as such but where the assessment of its principles was at the core of the study. No limitation was set to publication year. The publication language was limited to English.

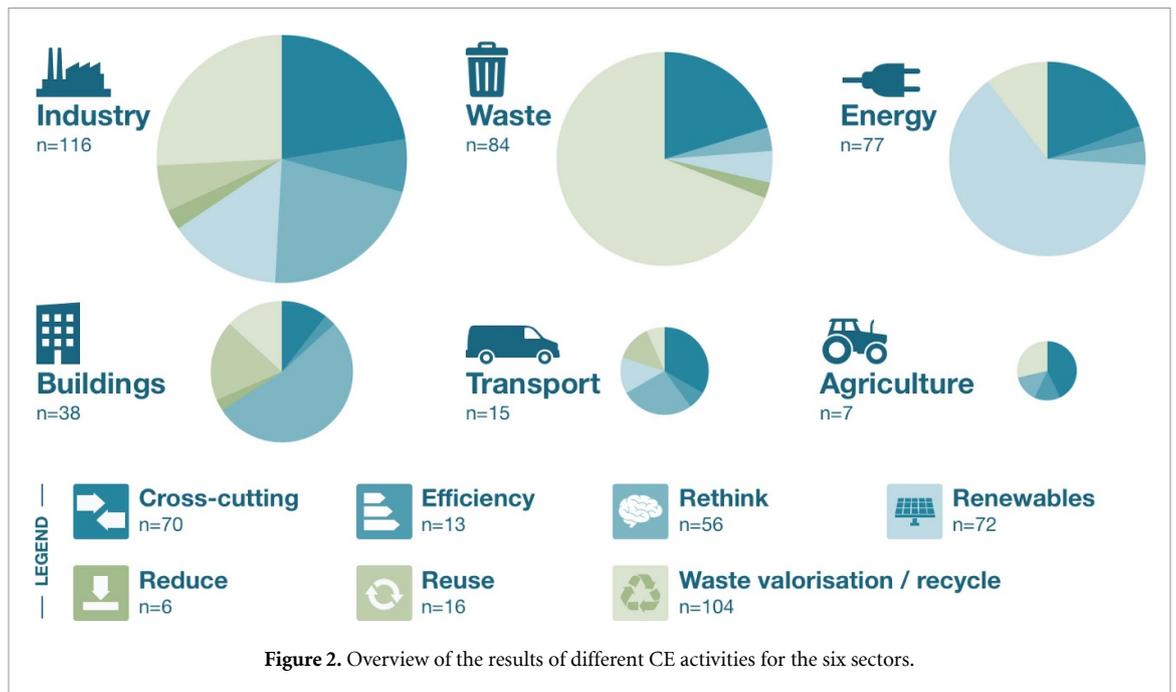
The information source first and foremost is the scientific literature, which we captured through the use of two databases, namely the Web of Science and

Scopus, relying on the search infrastructure provided by APSIS (see for comparable papers Minx *et al* (2018)). We also included the gray literature obtained through expert solicitation to identify the work of major think tanks and institutions concerned with CE and identify the most relevant papers. Since these were not obtained in a similarly transparent manner as the scientific studies, we included them separately in the discussion section.

We defined the literature query inter alia building on the mitigation query in Minx *et al* (2018), which resulted in the following query:

((‘circular economy’ OR ‘cradle to cradle’ OR ‘material efficien\*’ OR ‘resource efficien\*’ OR ‘material productivity’ OR ‘material services’ OR ‘material footprint’ OR ‘closed-loop supply chain’ OR ‘functional service economy’ OR ‘performance economy’ OR ‘cradle to grave’ OR ‘product loop’ OR ‘material loop’) AND (‘CO<sub>2</sub>’ OR ‘carbon’ OR ‘GHG’ OR ‘greenhouse gas’ OR ‘climate change’ OR ‘global warming’ OR ‘warming climate’) NOT (‘catalyst\*’ OR ‘distill\*’ OR ‘super-critical’ OR ‘foaming’ OR ‘pore’))

The initial search query (September 2, 2019) yielded 3244 studies in the Web of Science and Scopus (once duplicates were removed). Having compiled a set of broadly relevant documents, the second stage of the scoping review was to manually exclude irrelevant articles. In the first step, a random sample of 50 studies were screened and cross-checked within

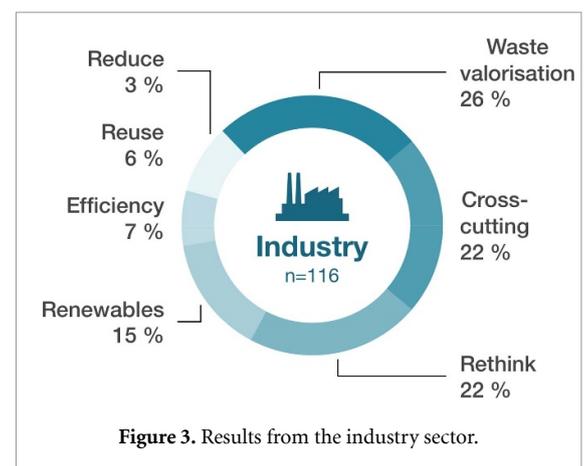


the author team until a good level of agreement was reached. The full screening of studies could then proceed. The abstracts were checked for the eligibility criteria described above, and where necessary the full paper was checked for eligibility (this was the case when an abstract suggested that a mitigation potential may be found in the full paper). After the first round of selection, 2572 studies were dismissed, and the remainder was double checked by other authors to ensure consistency of inclusion. Ultimately, 341 studies (10% of the initial query results) were identified as relevant.

To synthesize the data of the studies, we agreed on the following nominal categories: sector, geography (OECD, non-OECD and where available country), resolution (case study, global, national, regional, product), and CE principles (recycle, reduce, reuse, cross-cutting). We extracted the mitigation potential of the studies as described therein and added a category to state the mitigation potential in qualitative terms (high, medium, low, and zero) to allow for a better grouping of the studies.

#### 4. Results

Out of the 3244 studies initially identified as mentioning climate change and CE, only 341 (10%) contained a specific mitigation reference (for further information, please see the supplementary information, which can be found online 2020a at <https://stacks.iop.org/ERL/15/123001/mmedia>). This shows that a significant amount of studies do not include a decisive proof of their mitigation potential. In the majority of cases, emissions savings are assumed, not proved.



Synthesizing the 341 studies with regards to their mitigation potential posed significant challenges. Their mitigation potential was often given with regards to their own baselines, with no comparison of the order of magnitude within their sector or cost comparable measures.

The following sections summarize the results starting with the highest to lowest amount of results, sector-wise (figure 2). Each section provides results as described by key studies. Key studies were selected by identifying those studies which provide a specific aspect to the most substantial insights compared to the other studies dealing with the same aspect. Each of the key studies follows its own considerations and system boundaries and uses different metrics and indicators (see review articles on metrics Corona *et al* (2019) and Sassanelli *et al* (2019)). This diversity limits a unified comparison of quantified results. In the second step, we standardize the results regarding the potential reduction expressed as percentages.

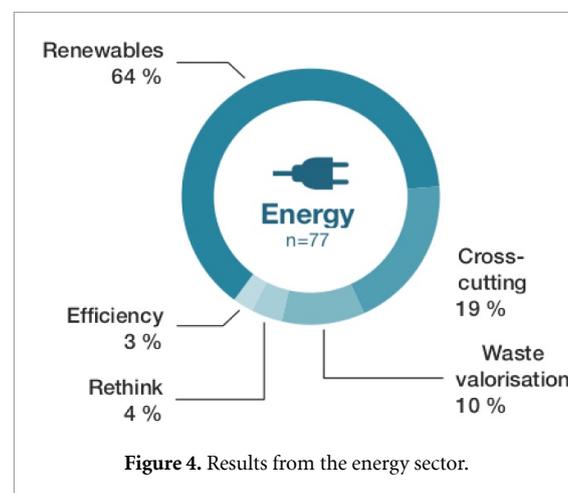
**Table 1.** Summary table of key studies in the industry sector and their reported mitigation potential.

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Industry	recycling	recycling of steel scrap and iron ore at end of its product life	Broadbent (2016)	–	–10%, –27%
		completely recyclable concrete	De Schepper <i>et al</i> (2014)	–	–66 to –70%
		production of 1 t marble-based geopolymer green cement paste vs. Portland cement	Lee <i>et al</i> (2017)	Taiwan	–54%
		producing clinker from red mud, desulfurization gypsum, and other industrial solid wastes vs. conventional preparation of sulfoaluminate clinker	Ren <i>et al</i> (2017)	–	–41%
	material substitution with bio-based products	replacing coal in cement manufacturing with saw-mill charcoal powder	Sjølie (2012)	Tanzania	–83%–91%
		closed-loop supply chains for automotive thermoplastic polymer waste recycling vs. forward supply chain	Chavez and Sharma (2018)	Mexico	–73%
		production of bioplastic PEF	Eerhart <i>et al</i> (2012)	–	–45 to –55%
		biomass-derived chemical products vs. fossil-derived	Adom <i>et al</i> (2014)	–	–39 to –86%

#### 4.1. Industry

Around 34% of the studies focused on industry. Broadly grouped, the majority of studies dealt either with (1) recycling, (2) reuse, or (3) material substitution (bio-based products) (figure 3).

Recycling presents multitudes of opportunities to save resources and emissions. In particular, steel and cement offer significant potential according to a wide range of literature. Broadbent (2016) found a saving of 1.5 kg CO<sub>2</sub>-eq emissions and 1.4 kg iron ore for every 1 kg of steel scrap that is recycled at the end of its product life, equating to a reduction of 27% and 10% compared to primary production. Completely recyclable concrete offers a reduction of global warming potential of 66%–70% (table 1) (De Schepper *et al* 2014). Using waste material for cement and concrete production is investigated as additional pathway for GHG emission reductions. Lee *et al* (2017) state that the production of 1 t marble-based geopolymer green cement paste saves around 54% CO<sub>2</sub> emissions compared to Portland cement paste. Producing clinker from red mud, desulfurization gypsum, and other industrial solid wastes potentially reduce resource consumption and global warming by 93% and 41% respectively, compared to the conventional preparation of sulfoaluminate clinker (Ren *et al* 2017). Replacing coal in cement manufacturing with saw-mill charcoal powder may reduce GHG emissions by



455–495 kg of CO<sub>2</sub>-eq MWh<sup>-1</sup>, corresponding to an 83%–91% decrease (Sjølie 2012).

Other recycling opportunities might also offer a high mitigation potential. A study shows that closed-loop supply chains for automotive thermoplastic polymer waste recycling generates 73% less CO<sub>2</sub> than the production of polyethylene terephthalate seats using a forward supply chain (Chavez and Sharma 2018).

**Table 2.** Summary table of key studies in the energy sector and their reported mitigation potential relative to their baseline emissions of the investigated topic. The biomass studies are subject to very high uncertainty, and additional land-use change effects are likely to reduce their mitigation potential.

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Energy	biomass for fossil fuels	pyrolysis of wood to substitute heavy fuel oil	Karvonen <i>et al</i> (2018)	–	–75%
		comparing wood pellets and coal	Morrison <i>et al</i> (2018)	USA and UK	–80%–94%
		third generation biofuels compared to fossil fuels	Nilsson <i>et al</i> (2020)	Sweden	–60%
		residual woody biomass to substitute jet fuel	Pierobon <i>et al</i> (2018)	US	–60%
		bagasse to jet fuel	Michailos (2018)	–	–47%
	recycling and reuse	syngas produced from algae feedstocks with solar energy in drying stage	Azadi <i>et al</i> (2015)	–	–60%
		AD bioelectricity replaced coal generation	Styles <i>et al</i> (2016)	UK	–131%
		repurposed batteries	Bobba <i>et al</i> (2018)	–	–58%
		contribution of CE approaches to energy savings in UK	Cooper and Hammond (2018)	UK	–5%–10%

Material substitution with bio-based products is predominantly discussed in the context of packaging. Producing bioplastic polyethylene furandicarboxylate can reduce GHG emissions by about 45%–55% compared to its petrochemical counterpart polyethylene terephthalate (PET) (Eerhart *et al* 2012).

Another study compared biomass-derived chemical products (bioproducts) to fossil-derived counterparts and found that bioproducts uniformly offer GHG emission reductions compared to their fossil counterparts, ranging from 39%–86% (Adom *et al* 2014).

#### 4.2. Energy

Around 23% of the identified studies focused on energy. The majority of studies dealt with substituting fossil fuel energy with some form of renewable primarily bio-based sources of energy (figure 4). Recycling and reusing were represented to a lesser extent. The opportunities of bio-based products and biomass were featured most prominently among the studies and included several applications.

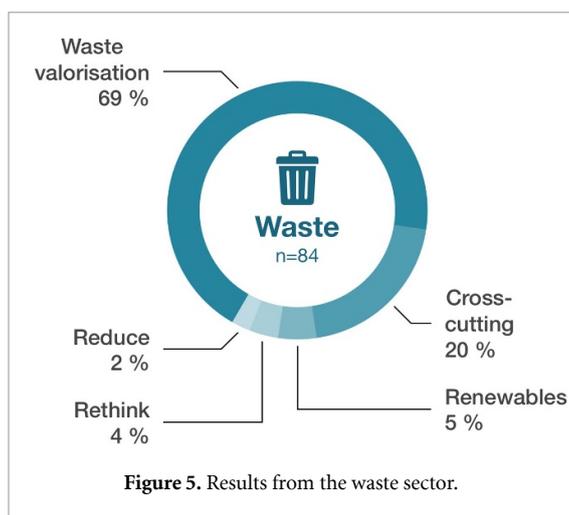
According to Karvonen *et al* (2018) using biomass as an alternative energy to fossil fuels could lead to a 75% reduction in CO<sub>2</sub>-eq (table 2). A life cycle analysis (LCA) of wood pellets show a 80%–94% reduction in CO<sub>2</sub> emissions compared to coal, depending upon whether the trees utilized for wood pellets are considered to be planted or harvested in year one, respectively, given a 100-year time horizon (Morrison *et al* 2018). Another study compared the cradle-to-grave impacts of thermochemical ethanol from loblolly pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass biomass

feedstock to gasoline. The use of cellulosic ethanol at the renewable fuel standards mandated production volume of 16 billion gallons of cellulosic ethanol per year by 2020 was found to result in 9–10 billion metric tons of GHG emissions avoided (Daystar *et al* 2015). Third generation biofuels, where sunlight and CO<sub>2</sub> are used by microbes directly to synthesize fuel molecules, are promising pathways. However, the best case scenario for a hypothetical production plant for an n-butanol reached the study's sustainability requirement of at least 60% GHG savings compared to fossil fuels in an LCA assessment (Nilsson *et al* 2020).

Biomass can also reduce emissions of jet fuel. Pierobon *et al* (2018) found a more than 60% reduction in the global warming potential by using residual woody biomass recovered from slash piles alternative to petroleum for the production of jet fuel. And an LCA of biojet fuel (farnesane) production from bagasse rather than edible feedstock (e.g. sugarcane) is estimated to reduce around 47% GHG emissions compared to fossil jet fuel (Michailos 2018).

The bioenergy LCA studies must be seen as a small part of a wider landscape of bioenergy climate change mitigation studies, ranging from attributional to consequential life-cycle assessment, to ecological and scenario modelling. A key concern is the direct and indirect consequential land use effects that reduce or overcompensate marginal attributional LCA-assessed mitigation savings. A comprehensive review with detailed accounting is provided in Creutzig *et al* (2015).

AD of algae, energy crops, and animal manure that are used as fertilizers and biogas also featured



dominantly in the studies. Annual cultivation and processing of 1 ton of seaweed (dry weight) evaluated over a time horizon of 100 years results in a net reduction of 34 ton CO<sub>2</sub> (Seghetta *et al* 2016); a carbon footprint declined to the values below 40 g CO<sub>2</sub> MJ<sup>-1</sup> for syngas utilizing solar energy in the drying stage, resulting in a 60% reduction compared to the carbon footprint of syngas produced via steam reforming of natural gas (i.e. similar to 100 g CO<sub>2</sub> MJ<sup>-1</sup>) (Azadi *et al* 2015). Other than seaweed, electricity produced by AD plants can save the carbon footprint by up to -1.07 kg CO<sub>2</sub>-eq kWh<sup>-1</sup> (Bacenetti and Fiala 2015) and the GHG abatement would increase 131% if all AD bioelectricity replaced coal generation (Styles *et al* 2016). Apart from AD plants, the biogas digestate from pig farms benefits 152.5 thousand tons (Gg) of CO<sub>2</sub>-eq (Tsai 2018).

Recycling and reusing is investigated to a lesser extent in the selected studies. Jensen (2019) found that recycling wind turbine materials at the end-of-service-life leads to emission reductions of 7351 ton CO<sub>2</sub> for a 60 MW wind park. Bobba *et al* (2018) found that using a repurposed battery in a grid-connected house to increase the rate of PV self-consumption, compared with a reference scenario in which a fresh battery is used in a grid-connected house, allows a 58% reduction of the life-cycle global warming potential. A UK study examined the extent to which certain CE interventions can contribute to reducing energy use and thus support the government's goal of achieving an 80% reduction in carbon dioxide emissions by 2050. For all energy saving approaches from reducing food waste, increasing higher steel material efficiency, expanding other material efficiency improvements, supporting product refurbishment and life extension, promoting vehicle refurbishment and lightweight, to constructing buildings as well as manufacturing other equipment enhance energy savings of 5%–10% within the UK and beyond were estimated (Cooper and Hammond 2018).

### 4.3. Waste

Around 25% of the studies focused on waste, with a majority on recycling and waste valorization, including waste-to-energy transformation (figure 5).

Portugal's national strategy for urban waste management was estimated to reduce 47% of the net GHG emissions by reducing the quantity sent to landfill and expected an increase in municipal solid waste recycling 'resulting from the increase of selective collection and more efficient treatment and recovery of mixed wastes' (table 3) (Ferrão *et al* 2015). Another case study in Ahmedabad (India) found similar emission reductions for cities: implementing sustainable waste management strategies, such as re-use, recycling, and decentralized composting bring down emissions by 58% compared to the BAU scenario (Mittal *et al* 2017).

Biogas production in wastewater treatment plants can play a decisive role in the reduction of CO<sub>2</sub> emissions. In one case study, converting biogas obtained from sewage sludge into biomethane by the use of biogas upgrading technologies decreases the CO<sub>2</sub> content by 43% (Batlle-Vilanova *et al* 2019).

Waste is used as a resource in a multitude of cases while simultaneously leading to GHG reductions. Producing urea from municipal solid waste saves approximately 0.1 tons of CH<sub>4</sub> and approximately 0.8 tons of CO<sub>2</sub> per ton of urea produced (Antonetti *et al* 2017). Other cases are reported in their specific sectors in the results of the other sectors.

The potential environmental impact of wasted food minimization is investigated based on a case study of Ireland and results in a reduction of -4.5 Mt CO<sub>2</sub>-e global warming potential (GWP) compared to business as usual (Oldfield *et al* 2016).

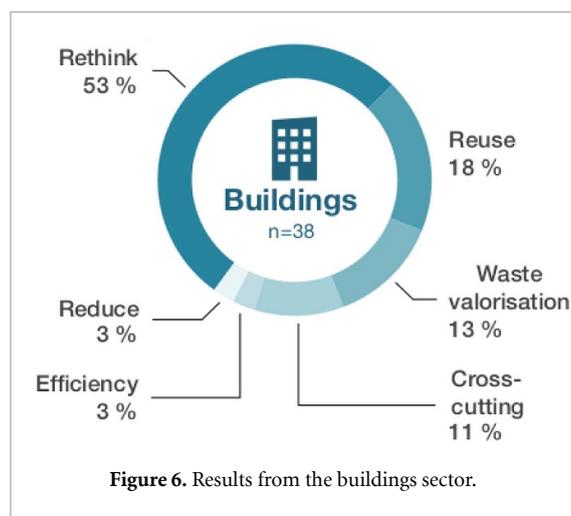
### 4.4. Buildings

Around 11% of the studies focused on the building sector with emphases on rethinking building materials, waste valorization, reuse, and to a lesser extent, other efficiency measures (figure 6).

The review by Gallego-Schmid *et al* (2020) of CE and climate change in the EU construction sector argues that CE solutions do not always result by default in emission reductions. Though closing resource solutions can reduce emissions by 30%–50% per functional unit, results are dependent on recycling efficiencies and other factors such as transportation distances to recovery facilities (table 4). Therefore, case-by-case quantifications are crucial. A study investigating the replacement of primary with secondary materials for certain products at the country level comes to the following saving potentials: (1) 0.95–1.42 kg CO<sub>2</sub>-eq avoided per kg wood plastic composite produced, (2) 0.008 kg CO<sub>2</sub>-eq avoided per kg aggregate prepared for concrete production, and (3) 0.025 kg CO<sub>2</sub>-eq avoided per kg brick manufactured. Applied to Denmark, at the industry level,

**Table 3.** Summary table of key studies in the waste sector and their reported mitigation potential.

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Waste	reduce waste	national strategy for urban waste management	Ferrão <i>et al</i> (2015)	Portugal	−47%
		sustainable waste management	Mittal <i>et al</i> (2017)	India	−58%
	waste as a resource	biogas production	Battle-Vilanova <i>et al</i> (2019)	–	−43%
		production of urea	Antonetti <i>et al</i> (2017)	–	−1 t CH <sub>4</sub> , −0.8 t CO <sub>2</sub> per ton of urea



the brick case shows the highest carbon saving potential, with estimated annual savings of 25 300 tons CO<sub>2</sub>-eq. The annual carbon saving potential of the concrete case is around 7300 tons CO<sub>2</sub>-eq (Nußholz *et al* 2019).

The incorporation of fly ashes is an investigated option for cement substitution and a possible path to improve the environmental performance of the concrete industry. Replacing Portland cement with high volumes of fly ash significantly reduces the embodied carbon dioxide of the mixes. 300 kg m<sup>−3</sup> foamed concrete with 40% fly ash resulted in a 65% reduction of the embodied carbon dioxide in comparison with 100% Portland cement 500 kg m<sup>−3</sup> foamed concrete mix (Jones *et al* 2017).

Reusing parts of, or even the entire building also offers emissions reduction opportunities: a case study of a Danish office building, in which a concrete structure is designed for a disassembly for remanufacturing, showed that reusing twice and three times results in potential CO<sub>2</sub> emissions savings of 15% and 21% respectively compared to the reference scenario where all materials are disposed after use either by recycling, incineration, or landfill (Eberhardt *et al* 2019a). The more re-use cycles, the higher the potential impact savings of both the building and the concrete structure. The use of the prefabricated concrete structures twice and three times revealed potential savings of

40% and 55% respectively of embodied CO<sub>2</sub> emissions (Eberhardt *et al* 2019b).

In one study, a housing unit underpinned by the proposition that all the resources required to construct the building must be fully reusable, recyclable, or compostable reduced its GWP over its entire life cycle by 40% compared to the hypothetical reference unit in the same size and standard constructed out of the common building materials such as concrete (Kakkos *et al* 2019). Rethinking buildings material, either by substituting traditional materials such as cement all together or by blending in a certain percentage of recycled material offers a whole new array of mitigation reduction potentials. Cross laminated timber offers an attractive alternative to concrete and can result in significant GHG benefits, though trade-offs and limitations to the potential supply of timber need to be recognized (Hertwich *et al* 2019). A life-cycle assessment in China found cross laminated timber to reduce energy consumption by more than 30% and reduce CO<sub>2</sub> emissions by more than 40% compared to the conventional carbon intensive material (Liu *et al* 2016). Likewise, composite boards made by natural fiber and a bio-based epoxy resin could offer a reduction in CO<sub>2</sub> emissions of 50% compared to the traditional plasterboard used for drywall applications (Quintana *et al* 2018). Using the end-of-life shipping containers for buildings can be considered nearly zero energy buildings (Schiaivoni *et al* 2017).

Rethinking the way we live and use space also offers emission reductions opportunities, including counteracting the movement towards more floor space. This could be achieved not just through smaller residences, but also ‘larger household sizes, fewer second homes, dual-use spaces, and shared or multi-purpose office spaces’. In Norway, a more intense use of residential buildings could reduce the climate impact of buildings by 50% (Hertwich *et al* 2019).

Retrofitting is another studied option to reduce emissions. The CO<sub>2</sub> reductions from energy-efficient windows equate to a reduction of about 3% of the CO<sub>2</sub> emissions from the Atlanta residential sector when natural gas provides heating or 6%–9% when heating comes from electricity. (Minne *et al* 2015).

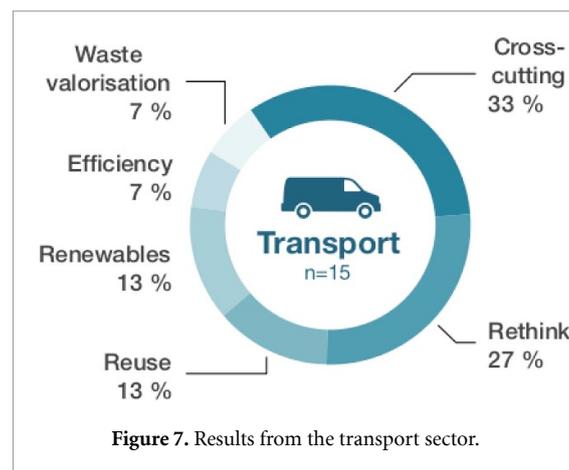
**Table 4.** Summary table of key studies in the building sector and their reported mitigation potential. The percentage reduction refers to embodied energy and GHG emissions. The entry on 'reduce need for larger/new buildings' includes in-use emissions, as specified. The retrofitting strategy is only about in-use emissions from heating.

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential	
Buildings	replacing primary with secondary materials	wood plastic composite	Nußholz <i>et al</i> (2019)	Sweden,	−0.95–1.42 kg CO <sub>2</sub> -e per kg	
		concrete production		Denmark	−0.008 kg CO <sub>2</sub> -e per kg	
	reuse	brick manufacturing				−0.025 kg CO <sub>2</sub> -e per kg brick manufactured
		replacing Portland cement with high volumes of fly ash	Jones <i>et al</i> (2017)	–	−65%	
		office building whose concrete structure is designed for disassembly for subsequent reuse	Eberhardt <i>et al</i> (2019a)	Denmark	−15% and −21%	
		use of the prefabricated concrete structures for two and three times	Eberhardt <i>et al</i> (2019b)	Denmark	−40% and −55%	
	rethinking building materials	housing unit whose materials are fully reusable, recyclable or compostable	Kakkos <i>et al</i> (2019)	–	−40%	
		cross laminated timber vs. conventional carbon intensive material	Liu <i>et al</i> (2016)	China	−40%	
		composite boards made by natural fiber and a bio-based epoxy resin vs. traditional plasterboard used for drywall applications	Quintana <i>et al</i> (2018)	–	−50%	
	retrofitting	more intense use for residential buildings	(Hertwich <i>et al</i> 2019)	Global	−50%	
energy efficient window retrofits		(Minne <i>et al</i> 2015).	US	−3% to −9%		

#### 4.5. Transport

Only a very small fraction (<5%) of the studies focused on transport. The majority of the studies can be broadly categorized as: (1) those focusing on fuel alternatives, ranging from algae-based biofuels to EVs and hydrogen fuel cell powered cars; (2) those dedicated to the design of vehicles and mitigation potential, including material substitution and alternative means of production, such as additive manufacturing; and (3) those dealing with the reuse of materials, such as battery packs of end-of-life electric vehicles or recycling of vehicles (figure 7).

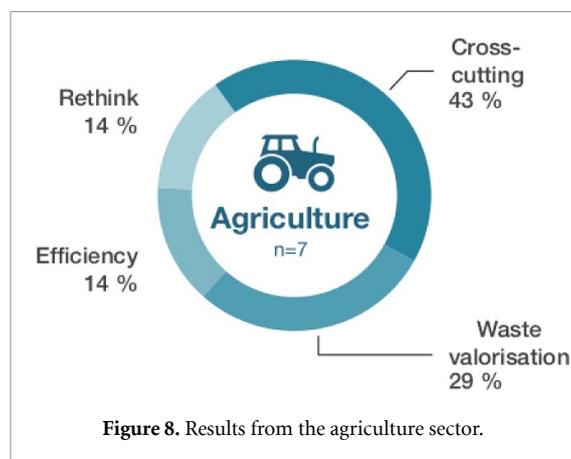
The most significant mitigation potential on the operation side lies in fuel alternatives. Importantly, there is an issue with the boundaries of analysis here. Most fuel substitution publications on new energy vehicles, such as battery electric vehicles (BEV), do not explicitly refer to the CE, and are therefore outside the scope of our search query, similar to the literature on biomass. A few studies, however, do, and report high potentials, though they may not be completely representative of the overall fuel substitution literature. For example, one CE-related study reports that EVs (269 g CO<sub>2</sub> km<sup>−1</sup>) or hydrogen fuel power cells



(235 g CO<sub>2</sub> km<sup>−1</sup>) generate substantially lower full life-cycle emissions than fossil fuel powered cars, such as an internal combustion engine (ICE) Diesel (738 g CO<sub>2</sub> km<sup>−1</sup>) (table 5) (Baptista *et al* 2011). There is general agreement that battery electric vehicles outperform ICEs in terms of life-cycle GHG emissions, with key factors including electricity used for battery production and car use and the overall lifetime of

**Table 5.** Summary table of key studies in the transport sector and their reported mitigation potential.

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Transport	fuel alternatives	EVs	Baptista <i>et al</i> (2011)	London	−64%
	changes in design	a ship vessel designed and manufactured for 100% hull reuse	Gilbert <i>et al</i> (2017)	–	−29%
	recycling/reuse	remanufacturing of a diesel engine	Hertwich <i>et al</i> (2019)	Global	−69%
	ownership	green procurement of road markings	Cruz <i>et al</i> (2016)	US	−50%
	car sharing	changing ownership models such as car sharing	Chen and Kockelman (2016)	US	−50%



vehicles (Helmers *et al* 2017, Hill *et al* 2019). Also, from a personal carbon footprint perspective, substituting an ICE with a BEV is a major opportunity to reduce emissions (Ivanova *et al* 2020).

Aside from efficiency and technology measures, the design of vehicles can significantly alter its emissions profile. A review of material efficiency strategies by Hertwich *et al* (2019) revealed the largest potential emission reductions in the light-weight and reduced-size of vehicles. Gilbert *et al* (2017) compared a business as usual design of a ship vessel with a 100% hull reuse design and manufacture and found a 29% reduction of emissions (from 222 t CO<sub>2</sub> to 158 t CO<sub>2</sub>). Additive manufacturing technologies for light-weight metallic aircraft components through the year 2050 could save 92–215 million metric tons and save thousands of tons of aluminum, titanium and nickel alloys (Huang *et al* 2016).

The recycling and reuse of end-of-life vehicles can also lead to emission reductions. The remanufacturing of a diesel engine can save 69% of embodied GHG emissions compared to producing a new diesel engine (Hertwich *et al* 2019). Ahmadi *et al* (2017) found that GHG advantages of vehicle electrification can be doubled by extending the life of the EV batteries, for example, through reuse in stationary

applications as part of a ‘smart grid’ and enabling better use of off-peak low-cost clean electricity or intermittent renewable capacity.

Other studies focused on the green procurement of road infrastructure (road markings) and found a 50% mitigation potential throughout the entire lifetime (Cruz *et al* 2016). Changing ownership models such as car sharing could reduce the average individual transportation energy use and GHG emissions by half (Chen and Kockelman 2016).

#### 4.6. Agriculture

A very limited number of identified studies (2%) dealt with agriculture, mostly interrelated to energy and waste and with a focus on waste valorization and efficiency measures (figure 8).

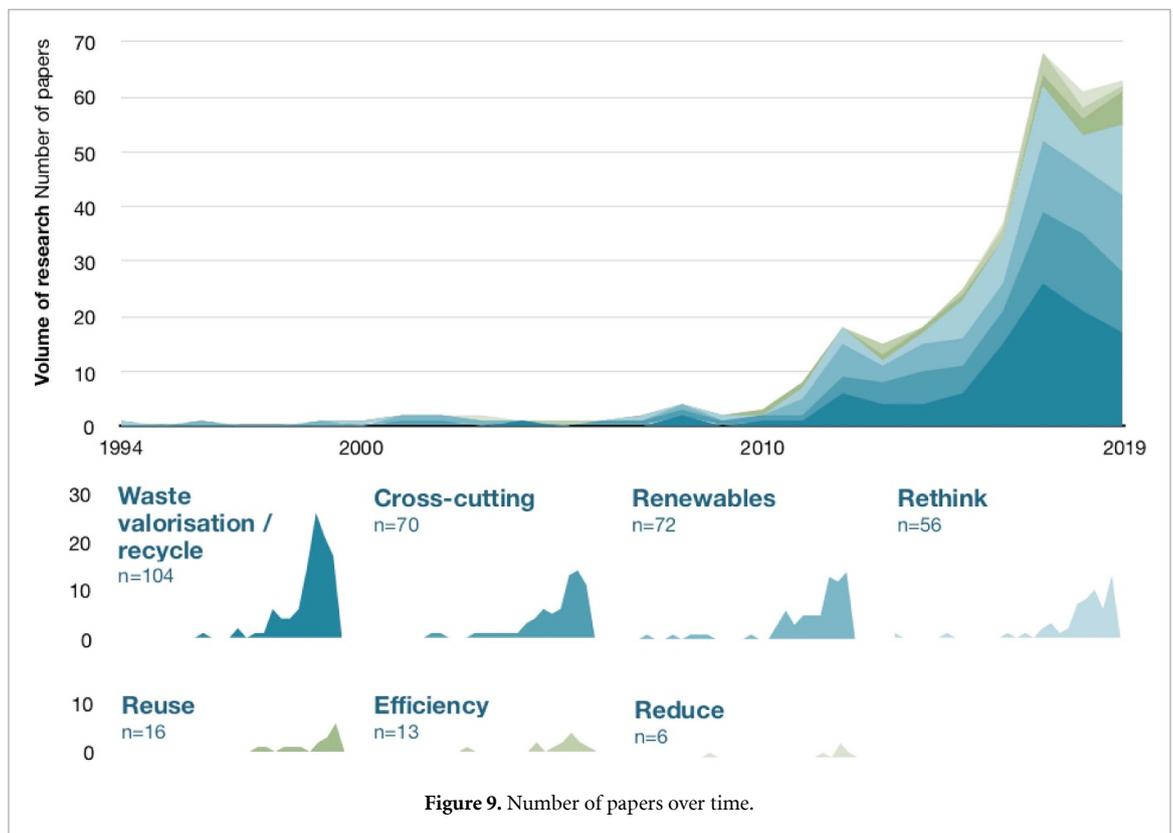
Life cycle analyses were conducted on pork (Noya *et al* 2017), fish canning (Laso *et al* 2018), and cassava starch (Pingmuanglek *et al* 2017) production. The impact of the change in each product on CO<sub>2</sub> emissions varies. A GHG emission reduction of 11% compared to the base scenario was an advantage of pork production under CE activities, such as a closing loop production system, where resource efficiency and waste valorization were prioritized over final disposal options. Anchovy residues from the fishing and canning process were disposed in a landfill with biogas (table 6) recovery, incinerated, and valorized into fishmeal for aquaculture. The landfill scheme gained the highest mitigation potential of 2.68 kg CO<sub>2</sub>-eq per functional unit. Recovering cassava pulp for the ethanol production led to an increased net GHG benefit of about 85% compared to the base scenario of using cassava pulp as animal feed. The AD of cow dung with new feedstock residues to increase biogas can lower the impact on climate change by 13% (Sfez *et al* 2017).

Recycling phosphorus from meat and bone meal, sewage sludge, and compost instead of fossil-phosphorus fertilizers could lead to a 28% decline of emissions to water bodies (Zoboli *et al* 2016).

With regards to efficiency measures, one study of 15 enterprises found that by just replicating the

**Table 6.** Summary table of key studies and their reported mitigation potential for the agriculture sector.

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Agriculture	closed-loop	pork production with closed-loop production system	Noya et al (2017)	Spain	-11%
	waste-to-energy	landfill with biogas recovery	Laso et al (2018)	Spain	-2.68 kg CO <sub>2</sub> -e per functional unit
		recovering cassava pulp for the ethanol production	Pingmuanglek et al (2017)	Thailand	-85%
		AD of cow dung to increase biogas	Sfez et al (2017)	India	-13%
	recycling	recycling phosphorus from meat and bone meal, sewage sludge, and compost	Zoboli et al (2016)	Austria	-28%
	efficiency	applying the efficiency levels of the least-emitting producers of beef and lamb	Hyland et al (2016)	-	-15% and -31%

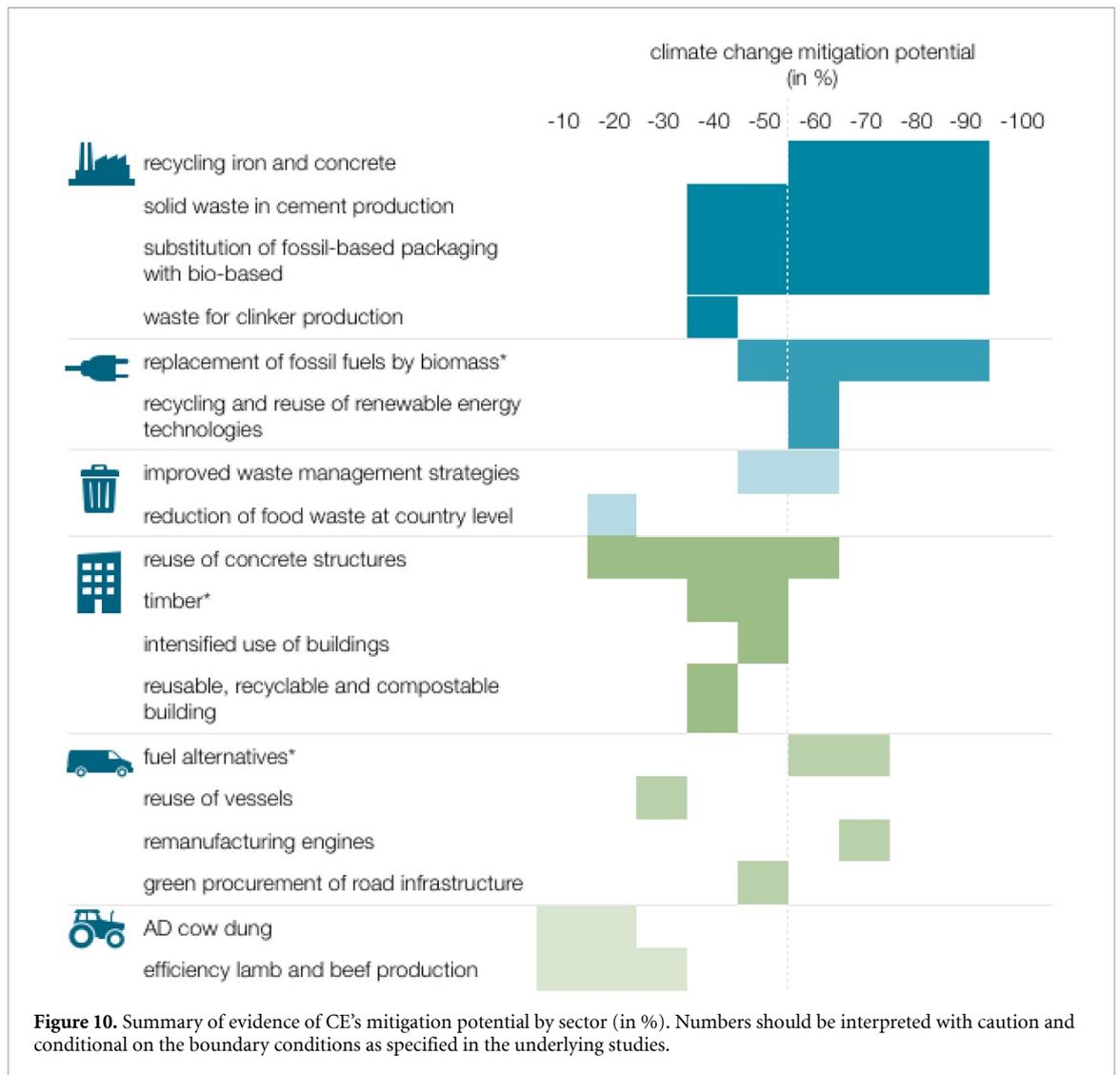


efficiency levels of the least-emitting beef and lamb producers (use of inputs such as fertilizer, concentrate feed, bedding, etc.), enterprises could reduce their carbon footprint by 15% and 31%, respectively (Hyland et al 2016).

**4.7. Development of studies by dominant CE activity over time**

Studies at the intersection of CE and climate change mitigation continuously increased from 2010 onwards with a preliminary saturation in 2017

(figure 9). Studies on waste valorization and recycling present the largest part, which had its biggest increase after 2015. Together with the studies on cross-cutting issues and renewables, they constitute about three quarters of the studies. Studies on reuse, efficiency, and reduce play a minor role. The low number in reuse and reduce studies might be explained by their more challenging nature in terms of the empirical analysis. Also, these activities are more difficult to reconcile with CE’s promise to foster economic growth. Efficiency studies might be a minority group of studies here since



they have a complementary focus with too little overlaps. Most efficiency studies relate environmental burden of a resource to the value of output (Di Maio *et al* 2017), which consequently encourages decoupling GDP and resource use (Haberl *et al* 2020). In contrast, the CE circulates resources within the economy so that the repeated use of resources in the shape of consecutive products can deliver their services and therefore, one and the same resource can generate more value (Di Maio *et al* 2017).

Interestingly, a considerable number of studies on rethink show a long-term growth trend. This indicates that conceptual consideration and sustainability intentions find their way into empirical studies.

The distribution of papers over the different circularity strategies is inverse to the order of priority, scholars suggest (Potting *et al* 2017, Morga *et al* 2019, Morseletto 2020). Conceptual academic thinkers argue that refuse, rethink, and reduce have the highest priority, while recycle and recover (including waste valorization) present the lowest

depart from a linear economy to a CE, indicating a considerable misalignment.

#### 4.8. Summary of evidence on CE's reported mitigation potential

The review provides a rather fragmented picture of the literature. Many studies fail to provide specific emissions savings, and when they do so, they are not well contextualized in the wider scope, lack a standardized language as well as units, and are unclear to what circularity concept they refer to. Consequently, studies are not well suited to be compared or interpreted for aggregated conclusions. Considering these challenges, we summarize the findings of the review on what the literature reports on the potential CE measures to reduce GHG emissions in different sectors (figure 10).

The industry sector studies have revealed high GHG savings for the recycling of iron and concrete in the range of 60%–90%. Various uses of solid waste in the cement production reduce GHG emissions by 40%–90%. The substitution of fossil-based by bio-based packaging materials can yield reductions

by 40%–90%. The use of waste for clinker production shows a roughly 40% reduction regarding global warming potential.

Energy related studies often investigated the replacement of fossil fuels by biomass and show a reduction of roughly 50%–90% for different options. Recycling and reuse of renewable energy technologies can yield 60% GHG savings.

In the waste sector, improved waste management strategies can save around 50%–60% of GHG emissions. Reduction of national food waste is reported to reduce a significant amount, roughly 8% of GHG emissions at the country level.

Applying CE measures in the building sector shows that the reuse of concrete structures can save 20%–60% of GHG emissions. Using timber instead of carbon intensive materials reduces GHG emissions by roughly 40%–50%. Intensified use of buildings shows a 50% reduction potential as well. Making building to be reusable, recyclable, and compostable might save 40% of the GWP.

Studies in the transport sector have proclaimed a 65% reduction potential from using fuel alternatives, 30% from reusing vessels, 70% from remanufacturing engines, and 50% from organizing green procurement of road infrastructure.

CE measures in the agricultural sector have shown around 10%–15% reduction for pork production and for anaerobic digestion of cow dung. If selected enterprises reduce to low-emitting production level, 15% beef and 30% lamb could be saved.

In sum, according to the studies, the highest savings can be assumed in the industry, energy, and transport sectors, mid-range savings in the waste and building sectors and lowest gains are to be expected in agriculture.

While most studies are at the product or case study level, we can contrast this with the studies at the national or global levels. Here, the studies are highly diversified in their estimates. While Material Economics (2018) estimated a 36% reduction for the most significant value chains of steel, plastics, aluminum, and cement by 2100, the IRP calculated 19% reduction by 2050. A study by Cooper and Hammond (2018), which only focuses on energy savings, suggested a potential of 5%–10% savings. Similar results are reported by Wijkman *et al* (2016); Finland, France, the Netherlands, Spain, and Sweden might cut carbon emissions by 3%–10% in the material efficiency scenario, whereas a 30% cut in the energy efficiency scenario, and by 50% in the renewable scenario. All scenarios combined could achieve a reduction by two thirds.

## 5. Discussion and concluding remarks

### 5.1. Comparison with gray literature

Past studies (Geissdoerfer *et al* 2017, Merli *et al* 2018) have recommended to also include the gray literature

when investigating CE. Since the inclusion of gray literature is not easily conductible in a systematic manner, we dedicate a separate section to the studies we obtained through expert solicitation. We reached out to five leading CE experts in the private sector and asked them for their top reports on the CE and its mitigation potential.

As other reviews (Gallego-Schmid *et al* 2020) postulated before, the results vary widely depending on the measures adopted, the rigor of them, as well as the system boundaries and sectors considered. Wijkman *et al* (2016) found that a CE (enhanced energy and material efficiency and increased renewable energy in the energy mix), would have less than one-third (up to almost minus 70%) of the emissions compared to a business-as-usual economy (fossil fuel based and resource-inefficient) of the same size. Based on the outcomes of a material flow analysis and related carbon, water, and land footprints, food and building materials have the greatest opportunities for carbon, water, and land footprint reductions (Kerkhof *et al* 2017), though other studies also consider the opportunities in other sectors, such as transport.

According to the Ellen MacArthur Foundation (2019), if CE were applied to the way we produce and manage food by designing out waste and keep materials in use, coupled with the expansion of regenerative agriculture practices, emissions could be reduced by 49% or 5.6 billion tons CO<sub>2</sub>-eq in 2050. A report by Deloitte (2016) focused on the EU food sector and found that reducing food waste and recycling nutrients from organic waste by applying CE measures could reduce emissions between 55 and 64 Mt CO<sub>2</sub>-eq (12%–14% respectively).

Making better use of the product and material within key sectors such as built environment and mobility could reduce global CO<sub>2</sub> emissions from cement, steel, plastic, and aluminium by 40% or 3.7 billion tons CO<sub>2</sub>-eq compared to the baseline scenario in 2050. The International Resource Panel (2020) finds that G7 countries alone could reduce their GHG emissions from the material cycle of residential buildings by 80%–100% in 2050 through material efficiency strategies. Reductions in China could amount to 80%–100% and 50%–70% in India. Interventions with significant mitigation potential include increasing the intensive use of homes, designing buildings using less material, and using sustainably harvested timber. Specifically for the EU, Deloitte found a potential reduction of 17%–32%, depending on the measures adopted. The report considered a significant increase, on average, from 22% to 70% in the integration of recycled materials used for the construction of buildings (leading to a reduction in emissions of –17%). The other scenario adds an increased reuse of material, assuming steel and aluminium can be reused up to 50% and a reuse rate of 30% for other materials. Material Economics find the demand-side measures to be able to reduce emissions by more than

half, or 123 Mt CO<sub>2</sub>, by the second half of this century. Key suggested measures include the improved design of buildings and components to increase buildings' longevity and adaptability; the disassembly at the end of life; and the reuse of intact structural components.

Additional opportunities (Hertwich *et al* 2020) are found in the transportation sector, in particular for passenger cars: material efficiency strategies could reduce GHG emissions from the material cycle of passenger cars in 2050 by 57%–70% in G7 countries. Reductions in China could amount to a reduction of 29%–62% and 39%–53% in India. For the EU, Deloitte concluded that the increase of material recycling could decrease emissions by 45%. A third of resources could be saved by focusing on the reuse of components and repair activities to extend the lifetime of vehicles. Interventions with the largest reductions include changing the patterns of the vehicle use (ride-sharing, car-sharing) and shifting towards smaller vehicles. A report by Material Economics (2018) revealed that, in a scenario where shared vehicles meet two-thirds of travel demand in the EU, material requirements could fall by as much as 75%, reducing annual CO<sub>2</sub> emissions from material production by 43 Mt by 2050.

## 5.2. Limitations

This systematic review is limited to studies written in English. Surely, more evidence could be captured if the scope were extended to other languages, especially Japanese and Chinese. While we tested our search terms carefully, there is a risk that we missed the literatures that did not entail these in their title, abstract or keywords. Further, we have excluded the search terms 'recycling', 'reduce', 'reuse', etc, as these terms also appear in a wide array of non-CE literatures. Since the CE reference in CE articles was already at best elusive at times, including articles with no CE reference or related concept (see search query in methods section) would have blurred the picture even more and would have gone beyond the scope of this study. To mitigate the focus on peer-review literature at least to some extent, we included a dedicated section on the gray literature.

In many cases, the selected studies do not report sufficient methodological details to judge the rigor of the primary data included. Additionally, most studies only calculate the marginal reduction, thereby neglecting absolute reduction and rebound effects. Moreover, the studies differ greatly in their methods and system boundaries, which complicated any planned aggregation and comparison of their mitigation potential. Initially, the paper was set out to investigate the mitigation potential of CE. Coming out the other end of this research, it is evident that an aggregation is not possible. Different levels (micro, meso, and macro) and various scales of interventions hinder the aggregation of potentials.

## 5.3. Concluding remarks

Kirchherr *et al's* (2017) concluded that this “circular economy babble” constitutes a serious challenge for scholars” resonates with the author team of this study. While all studies reviewed refer to the CE and GHG emissions, most of them do not provide any proper references to what they understand by a CE. Once the veil is lifted, a potpourri of measures hides underneath without any standards in terms of assumptions or presentation of results. CE offers a new and shiny dress to old concepts, from recycling to efficiency measures. Boundaries to other realms of mitigation options are fuzzy, and while some CE scholars use the concept broadly, many other researchers analyzing similar issues, refrain from referring to CE. If it works as a communication concept to accelerate policy action, it certainly supports mitigation and emissions reduction efforts. Yet, policy makers and researchers should adhere to the principles of transparency and call things by their name in order to avoid an uncanny disconnection between CE talk and reality.

What does this mixed-use of CE labeling imply for the use of CE strategies for climate change mitigation? Should strategies be scaled up? Given the incoherent use of CE, including both serious and scalable action and greenwashing strategies with marginal improvements, it is clear that the CE label alone without the systematic mitigation effect is insufficient to serve as a guide post for climate action. CE strategies must be checked against three additional criteria: (1) has climate change mitigation effects been quantified? (2) is the quantification of the effect comprehensive (including indirect effects)? And (3) is the quantitative effect meaningful and consistent with coherent action to stay within remaining carbon budgets? A focus on studies that answer positively to these three requests helps to identify those part of the CE literature that help decision-makers in upscaling climate change mitigation action.

There are three specific additional considerations for further understanding of the CE literature.

First, key strategies refer to technological substitution such as biomass instead of fossil fuels and electric vehicles instead of ICEs. These substitution technologies are a major staple of the climate change mitigation literature, mostly considered outside the CE framing. CE-related literature mostly takes a narrow attributional life-cycle approach that underestimates problematic upstream effects such as land-use change emissions, thus overestimating mitigation potential (Plevin *et al* 2014).

Second, our review reveals that a majority of CE studies focus on recycling, not on more transformative reduce, reuse, and rethink concepts. In other words, articles pre-dominantly focus on lower circularity priorities, while issues of higher priorities are far less addressed. This needs countersteering by scholars and funding agencies, scholars' insights

on the priorities are not to be ignored. Possibly, many practitioners adopt the transformative mantle of CE, greenwashing underlying business interest, even when most marginal concepts are considered that do not deliver on larger GHG emission reduction. This reflects the political science observation that, in international politics, CE is mostly specified in terms of technological solution that keeps accelerating consumption trends (Isenhour 2019).

Third, CE approaches are multifold and some of them are very promising. However, there is more talk than walk. We document most studies on potential emission reduction, but few studies that document actual emission reductions at scale. Nonetheless, as figure 10 evidences, there is substantial potential. This must be interpreted against boundary conditions of analysis. For example, in the building sector, many studies mostly focus on embodied emissions of buildings, not on their operational emissions (which are in turn captured by the non-CE literature). Two specific insights are worth pointing out: the industry sector witnesses the largest potential in CE-related emission reductions (figure 10), probably because material substitution and avoided material use plays the largest role here. Second, reduce and reuse strategies, avoided emissions to start with, are particularly effective and cost-efficient, if they are studied (for example, avoiding new building constructions or avoiding cars by increased sharing). However, these options, while highlighted by the International Resource Panel, are scarce, if at all, studied by CE practitioners.

The main reason for this bias in the literature is possibly because recycling and efficient processing strategies are more consistent with existing business models, whereas reduce and reuse strategies require a new set of practitioners and businesses, and thus have less lobbying power. It is hence important to foster new business models and to also find reduce and reuse strategies that match the interests of incumbents.

Our review is timely and addresses a cornerstone of the CE claim for relevance: that CE is crucial for mitigating climate change. Previous high-quality reviews, (Tukker 2015, Ghisellini *et al* 2016, Kirchherr *et al* 2017, Govindan and Hasanagic 2018, Kalmykova *et al* 2018, Merli *et al* 2018) have sorted the CE literature and have consolidated CEs' relevance and limits for businesses and as resource use strategies. However, ours is the first to systematically assess the contribution of CE for climate change mitigation. The closest review to ours is Hertwich *et al* (2019), which systematically gathered material efficiency strategies to reduce GHG emissions. Tellingly, this study avoids using the concept of the CE. Our review is different in explicitly and only drawing from studies that draw on the CE as a concept. This allows us to not only identify the potential of specific strategies in the six sectors, but also to critically assess the lack of meaningful contribution of large parts of the CE literature that claims to address climate change mitigation.

In conclusion, substitution of material and processes in cement, steel, and vehicle production, together with a shift to renewable energies, are core and essential strategies to decarbonize economies. To become effective, CE strategies require broad implementation. They also should make best use of refuse, reduce, and rethink strategies that are poorly represented in the applied literature.

Future research would benefit from a clear reference to the conceptual CE base by referring to the appropriate literature as well as from a transparent presentation of results regarding CE measures mitigation potential that allows for comparison with other cases, products, or countries, that is contextualized in a higher level of scales, a reduction in absolute and relative terms, a clearer time frame, and an option space with its benefits and trade-offs.

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## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

## ORCID iDs

Felix Creutzig  <https://orcid.org/0000-0002-5710-3348>

Aneeque Javaid  <https://orcid.org/0000-0003-0453-2701>

Liwah Wong  <https://orcid.org/0000-0002-7571-8581>

Willi Haas  <https://orcid.org/0000-0001-5599-9227>

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