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

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

Jasmin Cantzler[1,*], Felix Creutzig[2,3], Eva Ayargarnchanakul[3,4], Aneeque Javaid[2], Liwah Wong[2], Willi Haas[5]

[1] *Gesellschaft für Internationale Zusammenarbeit GmbH, Friedrich-Ebert-Allee 32, 53113 Bonn*

[2] *Mercator Research Institute on Global Commons and Climate Change, Berlin*

[3] *Sustainability Economics of Human Settlements, Technical University Berlin*

[4] *Prince of Songkla University, Thailand*

[5] *Universität für Bodenkultur, Wien*

**Corresponding author, jasmincantzler@gmail.com*

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Abstract

Background

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).

Methods

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, whose results we summarized and present for six sectors (industry, waste, energy, buildings, transport, 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 of those of the Intergovernmental Panel on Climate Change (IPCC).

Results

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 highest saving potential is evidenced in the industry,energy and transport sector,mid-range savings in the waste and building sectorand lowest gains are to be expected in agriculture. A majority of studies investigates 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.

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 in 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, Preziosi and Acampora, 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, emissions need to reduce 7.6 per cent 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 as 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 invest into substantial demand reductions with focus on exergy concepts instead. There is a current lack of understanding of how much circular economy strategies can contribute to climate change mitigation.

While there is a widesprad expectation towards the CE to assist in achieving climate targets, there is to date no systematic review summarising the results of the scientific literature on the extent to which CE strategies can contribute to climate mitigation. What can be found is a multidute of reviews published in recent years on various aspects of the CE. The early review by Heshmati (2015)(2015) examines the rapidly growing literature on CE covering its concept and current practices and assesses its implementation. The review emphasises 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 circular economy 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, the basic principles, advantages and disadvantages, modelling and implementation of CE at the different levels (micro, meso and macro) worldwide. More than hundred definitions are analysed by Kirchherr et al. (2017). Drivers, barriers and practices that influence the implementation of the circular economy in the context of supply chains is the central issue of a review by Govonadan 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 one 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, Sadagopan and Rosado, 2018). In all these reviews climate change is hardly mentioned and any quantification of GHG emissions reductions are not in their scope.

Another review provides a critical assessment on current circularity metrics and selects only those metrics that fullfil 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), 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. Ingrao et al. (2018) review studies on food waste in a circular economy 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_2eq 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 these articles cover one or the other facette, they do not systematically provide a comprehenisve 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 what changes in household consumption patterns towards 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 to be key for climate mitigation. For food highest carbon savings come 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. Implicitely the review touches issues that overlap with circular economy strategies, however, explicitly no link to the circular economy is established. Nevertheless, it provides important reference points for the CE-climate nexus. Another recent topical review article (E. G. Hertwich *et al.*, 2019) that puts an emphasis on the suppy-side reviewed emissions reductions from material efficiency strategies applied to buildings, cars, and electronics. Specific material efficiency strategies, which overlap with CE strategies, were derived from literature and analysed. 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) resue, (5) recycling, upcycling, cascading and (6) improved yiels in production, fabrication and waste processing. The article concludes that there is a strong role for material efficiency strategie for material-intensive systems to contribute towards GHG emissions reductions. This study differes 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 quantitive 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 number 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 grey literature, obtained through expert solicitation.

Definining 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 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 (European Commission, no date; Yuan, Bi and Moriguichi, 2006; Government of Netherlands, 2016; Mathews and Tan, 2016; McDowall *et al.*, 2017) and a multitude of other actors alike (Sitra, no date; Ellen MacArthur Foundation, 2012; Preston, 2012; Nordic Council of Ministers, 2015; Stahel, 2016).

CE synthesizes and embodies a multitude of schools of thought with roots and relations to a number of related concepts (Ellen MacArthur Foundation, no date a; Blomsma and Brennan, 2017; Murray, Skene and Haynes, 2017) such as 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) order circular activities within the production chain according to their levels of circularity. Smarter product manufacturing and use is followed by lifetime extension, 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) identify an imbalance in which literature focuses on metrics and indicators as well as management systems and the like but leaves basic assumptions concerning values, social structures, cultures, underlying world-views and the paradigmatic potential of CE largely unexplored. A systematic review by Merli et al. (2018) finds CE to be an 'evolving concept that still requires development to consolidate its definition, boundaries, principles and associated practices'. An analysis of 114 CE definitions by Kirchherr et al. (2017) note that this '"circular economy babble" constitute a serious challenge for scholars' and offer a definition of CE developed 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, Reike and Hekkert, 2017).

Methods

Systematic reviews enable the collation of relevant evidence to a specifc 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 entail that the studies: (1) refer to 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 econonomy or cradle to cradle (see search query below for further information) ; and (2) refer to its quantitative mitigation potential in some regard (e.g. emissions estimates in % reductions, or tonnes of CO_2). 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 scientific literature, which we captured through the use of two databases, Web of Science and Scopus, relying on the search infrastructure provided by APSIS (see for comparable papers Minx et al. (2018)). We also included grey 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 these separately in the discussion section.

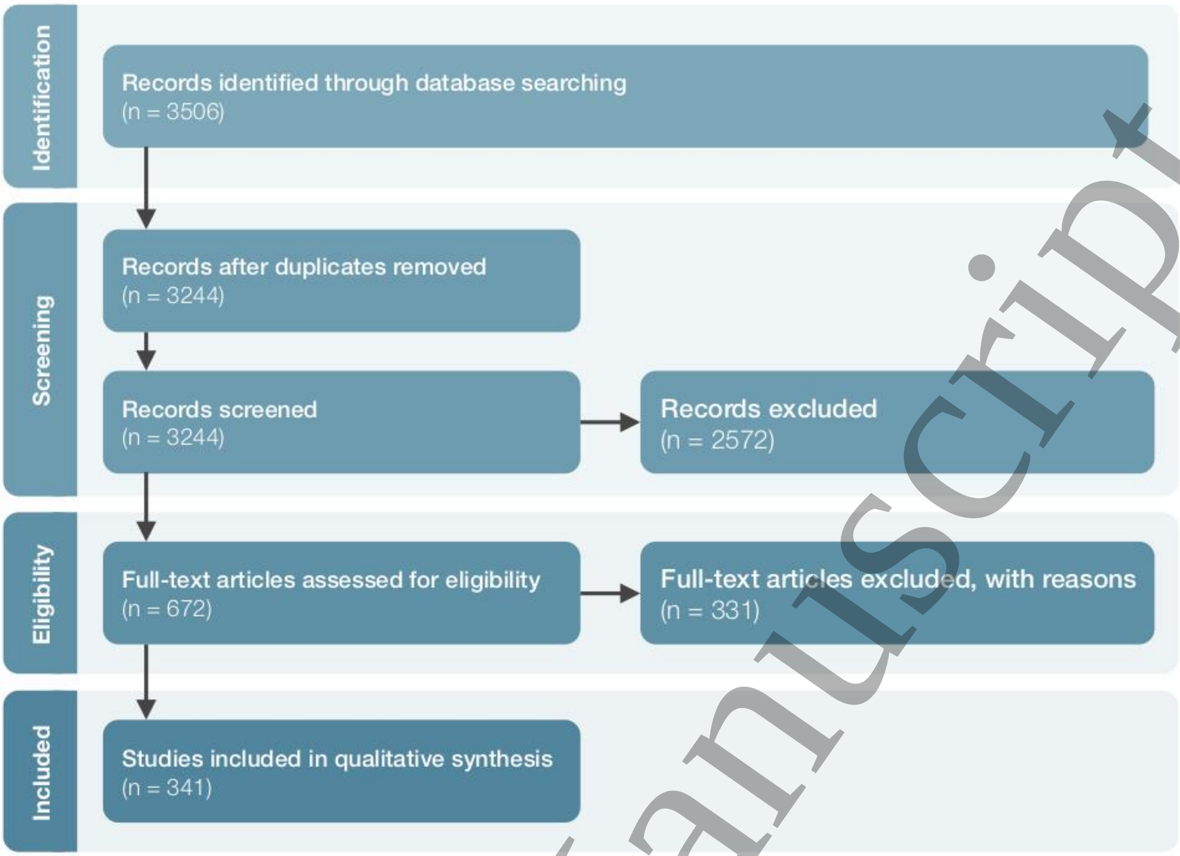

Figure 1: Workflow for selecting studies for review according to PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

We defined the literature query inter alia building on the mitigation query in Minx et al. (2018), which resulted into 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 ("CO2" 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 (2nd September 2019) yielded 3244 studies in 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 a first step a random sample of 50 studies was 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 elegibility (this was the case when an abstract suggested that a mitigation potential may be found in the full paper). After a first round of selection dismissed 2572 studies, the remainder was double checked by other authors to ensure consistency for inclusion. Ultimately, 341 studies (10% of the initial query result) were identified as relevant.

To synthesise the data of the studies, we agreed on the following nominal categories that were then populated: sector, geography (OECD, non-OECD and where available country), spatial 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, zero) to allow for a better grouping of the studies.

Results

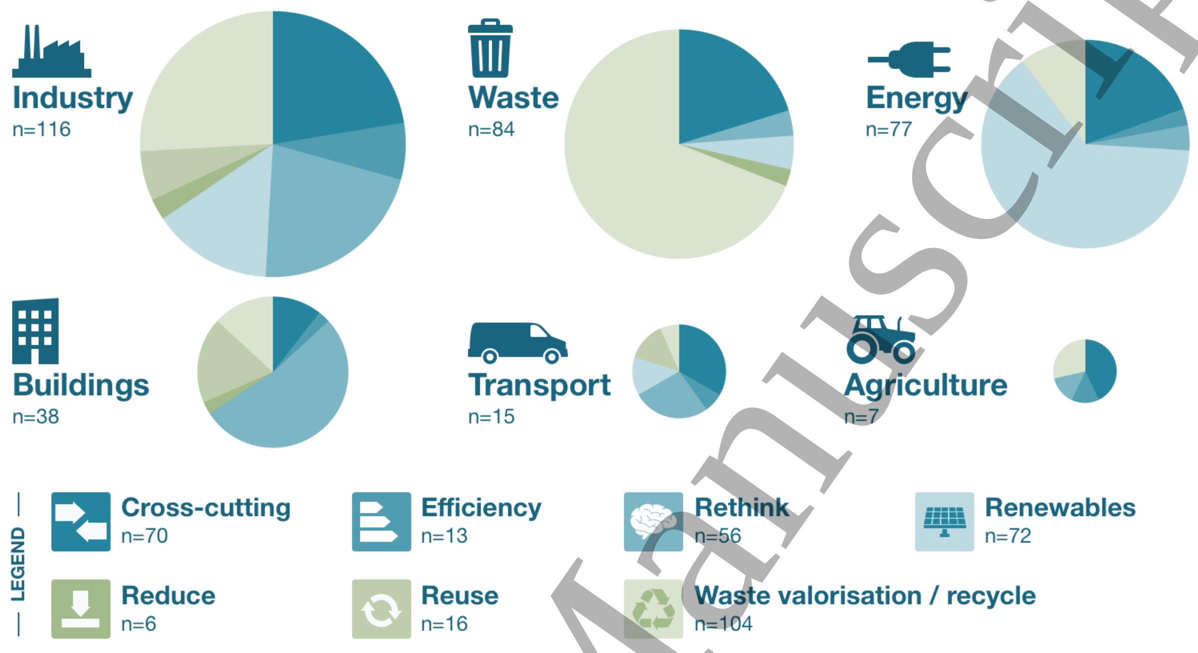

Figure 2: Overview of results different CE activities for six sectors

Out of 3244 studies initially identified as mentioning climate change and CE only 341 (10%) contained a specific mitigation reference. This shows a significant amount of studies do not include a decisive proof of their mitigation potential. In a majority of cases, emissions savings are assumed not proved.

Synthesing 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 amount of results, sector-wise, to the lowest amount (Figure 2). Each section first provides results as described by key studies. Key studies were selected by identfying those studies which provide for a specific aspect the most substantial insights compared to the other studies dealing with this 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 Sassanell et al. (2019)). This diversity limits a unified comparison of quantified results. In a second step we standardize results regarding the potential reduction expressed as percentage reduction relative to a reference state.

Industry

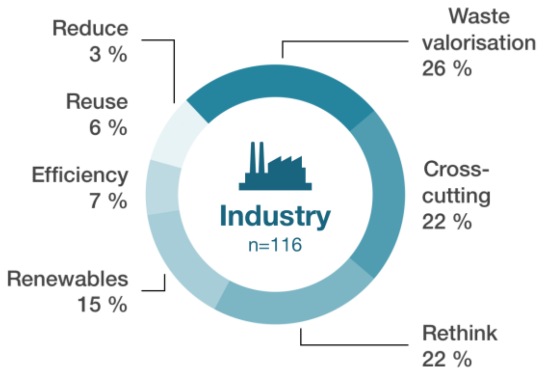

Figure 3: Results industry

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 according to a wide range of literature significant potential. Broadbent (2016) finds a saving of 1.5 kg CO_2-e emissions and 1.4 kg iron ore for every 1kg 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% (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. (Lee *et al.*, 2017) state that the production of 1t marble-based geopolymer green cement paste saves around 54% CO_2 emissions compared to Portland cement paste. Producing clinker from red mud, desulfurization gypsum, and other industrial solid wastes potentially reduces resource consumption and global warming by 93% and 41% respectively, compared with the conventional preparation of sulfoaluminate clinker (Ren *et al.*, 2017). Replacing coal in cement manufacturing with sawmill charcoal powder may reduce GHG emissions by 455-495 kg of CO_2-e MWh(-1), corresponding to a 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_2 than the production of polyethylene terephthalate seats using a forward supply chain (Chavez and Sharma, 2018).

Material substitution with bio-based products predominantly is discussed in the context of packaging. Producing bioplastic polyethylene furandicarboxylate can reduce GHG emissions about 45-55% compared to its petrochemical counterpart PET (Eerhart, Faaij and Patel, 2012).

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

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 et al. 2014	-	-66 to -70%
		production of 1t marble-based geopolymer green cement paste vs. Portland cement	Lee et al. 2017	Taiwan	-54%
		producing clinker from red mud, desulfurization gypsum, and other industrial solid wastes vs. conventional preparation of sulfoaluminate clinker	Ren et al. 2017	-	-41%
		replacing coal in cement manufacturing with sawmill charcoal powder	Sjølie 2012	Tanzania	-83-91%
		closed-loop supply chains for automotive thermoplastic polymer waste recycling vs. forward supply chain	Chavez & Sharma 2018	Mexico	-73%
	material substitution with bio-based products	production of bioplastic PEF	Eerhart et al. 2012	-	-45 to -55%
		biomass-derived chemical products vs. fossil-derived	Adom et al. 2014	-	-39 to -86%

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

Energy

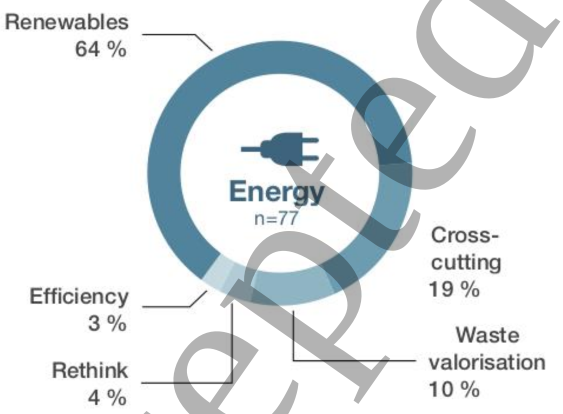

Figure 4: Results energy

Around 23% of 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 reuse 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_2-e. Comparing wood pellets and coal, a life cycle analysis (LCA) found wood pellets to equate to a 80-94% reduction in CO_2 emissions, depending upon whether the trees utilised for wood pellets are considered to be planted or harvested in year one, respectively, given a 100-year time horizon (Morrison, Daystar and Golden, 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_2 are used by microbes directly to synthesize fuel molecules, are promising pathways. However, a best case scenario for a hypothetical production plant for a n-butanol reached the study's sustainability requirement of at least 60% GHG savings compared to fossil fuels in a LCA assessment (Nilsson *et al.*, 2020).

Biomass can also reduce emissions of jet fuel. Pierobon, Eastin and Ganguly (2018) find 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) estimated a reduction of around 47% GHG emissions compared to fossil jet fuel (Michailos, 2018).

The bioenergy LCA studies must be seen as 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 are 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).

Anerobic digestion (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_2 (Seghetta *et al.*, 2016); a carbon footprint decline to values below 40 g CO_2/MJ for syngas utilizing solar energy for the drying stage, resulting in a 60% reduction compared the carbon footprint of syngas produced via steam reforming of natural gas (i.e. similar to 100 g CO_2 MJ(-1)) (Azadi *et al.*, 2015). Other than seaweed, electricity produced by AD plants can save the carbon footprint by up to -1.07 kg CO_2-e/kWh (Bacenetti and Fiala, 2015) and the GHG abatement would increase 131% if all AD bioelectricity replaced coal generation (Styles, Dominguez and Chadwick, 2016). Apart from AD plants, the biogas digestate from pig farms benefits 152.5 thousand tons (Gg) of CO_2-e (Tsai, 2018).

Recycling and reuse is investigated to a lesser extend in the selected studies. Jensen (2019) finds that recycling wind turbine materials at end of-service-life leading to an emissions reductions of 7351 ton CO_2 for a 60 MW wind park. Bobba et al. (2018) find 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 a 80% reduction in carbon dioxide emissions by 2050. For all energy saving approaches from reducing food waste, higher steel material efficiency, other material efficiency improvements, product refurbishment and life extension, vehicle refurbishment and lightweight, construction as well as other equipment manufacture enhancements energy savings of 5 to 10% within UK and beyond were estimated (Cooper and Hammond, 2018).

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

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.

Waste

Figure 5: Results waste

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

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

Biogas production in wastewater treatment plants can play a decisive role in the reduction of CO_2 emissions. In one case study, converting biogas obtained from sewage sludge into biomethane by the use of biogas upgrading technologies decreases the CO_2 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_4 and approximately 0.8 tons of CO_2 per ton of urea produced (Antonetti *et al.*, 2017). Other use cases are reported in their specific sectors in the results of the other sectors.

The potential environmental impact of wasted food minimisation is investigated based on a case study of Ireland and results in a reduction of -4.5 Mt CO_2-e global warming potential (GWP) compared to business as usual (Oldfield, White and Holden, 2016).

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Waste	reduce waste	national strategy for urban waste management	Ferrão, Lorena, & Ribeiro 2015	Portugal	-47%
		sustainable waste management	Mittal et al. 2017	India	-58%
	waste as a resource	biogas production	Batlle-Vilanova et al. 2019	-	-43%
		production of urea	Antonetti et al. 2017	-	-1 t CH4, -0.8 tCO_2 per ton of urea

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

Buildings

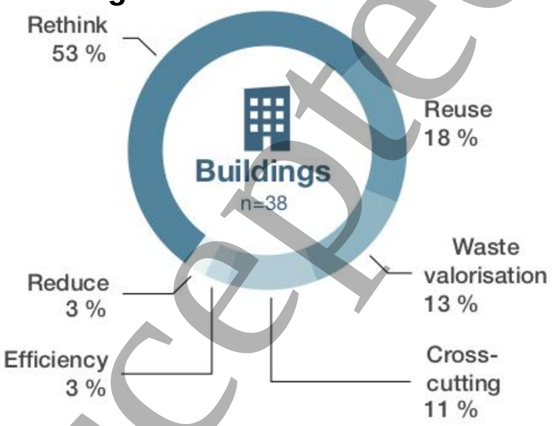

Figure 6: Results buildings

Around 11% of the studies focused on the building sector with a focus 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 circular economy (CE) and climate change in EU construction sector argues that CE solutions do not always result by default in emissions 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. Therefore case-by-case quantifications are crucial. A study investigating the replacement of primary with secondary materials for certain products at country level comes to the following saving potentials: 1) 0.95–1.42 kg CO_2-e avoided per kg wood plastic composite produced, 2) 0.008 kg CO_2-e avoided per kg aggregate prepared for concrete production, and 3) 0.025 kg CO_2-e avoided per kg brick manufactured. Applied to Denmark, at industry level, the brick case shows the highest carbon saving potential, with estimated annual savings of 25,300 tons CO_2-e. The annual carbon saving potential of the concrete case is around 7300 tons CO_2-e (Nußholz, Nygaard Rasmussen and Milios, 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/m3 foamed concrete with 40% fly ash resulted in a 65% reduction of the embodied carbon dioxide in comparison with 100% Portland cement 500 kg/m3 foamed concrete mix (Jones, Ozlutas and Zheng, 2017).

Reusing parts of, or even the entire building also offers emissions reduction opportunities: A case study of a Danish office building whose concrete structure is designed for disassembly for subsequent reuse finds that reuse two and three times results in potential CO_2 emissions savings of 15% and 21% respectively compared with a reference scenario where all materials are disposed of after use either by recycling, incineration or landfill (Eberhardt, Birgisdóttir and Birkved, 2019a). The more use cycles the higher the potential impact savings of both the building and the concrete structure. Use of the prefabricated concrete structures for two and three times revealed potential savings of 40% and 55% respectively of embodied CO_2 emissions (Eberhardt, Birgisdóttir and Birkved, 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 a hypothetical reference unit in same size and standard constructed out of 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 (E. 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_2 emissions by more than 40% compared to 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_2 emissions of 50% compared to traditional plasterboard used for drywall applications (Quintana *et al.*, 2018). Using end-of-life shipping containers for buildings can be considered nearly zero energy buildings (Schiavoni *et al.*, 2017).

Rethinking the way we live and use space also offers emissions 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 for residential buildings could reduce the climate impact of buildings by 50% (E. Hertwich *et al.*, 2019).

Retrofitting is another studied option to reduce emissions. The CO_2 reductions from energy-efficient windows equates to a reduction of about 3% of the CO_2 emissions from the Atlanta residential sector when natural gas provides heating or 6–9% when heating comes from electricity. (Minne, Wingrove and Crittenden, 2015).

Sector	Sub-field	Description	Authors	Geographical Scope	Mitigation potential
Buildings	replacing primary with secondary materials	wood plastic composite concrete production brick manufacturing	Nußholz, Nygaard Rasmussen, & Milios 2019	Sweden, Denmark	-0.95–1.42 kg CO_2-e per kg -0.008 kg CO_2-e per kg -0.025 kg CO_2-e per kg brick manufactured
		replacing Portland cement with high volumes of fly ash	Jones, Ozlutas, & Zheng 2017	-	-65%
	reuse	office building whose concrete structure is designed for disassembly for subsequent reuse	Eberhardt, Birgisdóttir, & Birkved 2019a	Denmark	-15% and -21%
		use of the prefabricated concrete structures for two and three times	Eberhardt, Birgisdóttir, & Birkved 2019b	Denmark	-40% and –55%
		housing unit whose materials are fully reusable, recyclable or compostable	Kakkos, Heisel, Hebel, & Hischier 2019	-	-40%
	rethinking building materials	cross laminated timber vs, conventional carbon intensive material	Liu, Guo, Sun, & Chang 2016	China	-40%
		composite boards made by natural fiber and a bio-based epoxy resin vs. traditional plasterboard used for drywall applications	Quintana, Alba, del Rey, & Guillén-Guillamón 2018	-	-50%
		more intense use for residential buildings	(E. Hertwich *et al.*, 2019)	Global	-50%
	retrofitting	energy efficient window retrofits	(Minne, Wingrove and Crittenden, 2015).	US	-3 to -9%

Table 4: Summary table of key studies in the building sector and their reported mitigation potential. The percentage reduction refer 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.

Transport

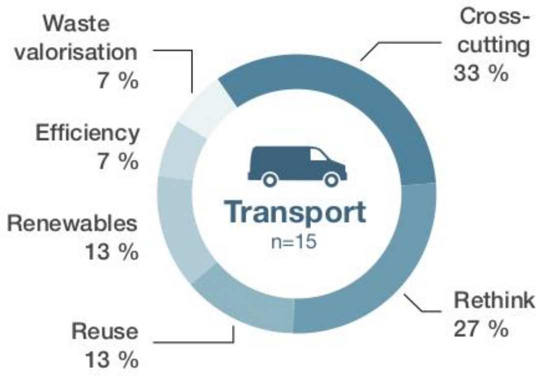

Figure 7: Results transport

Only a very small fraction (<5%) of the studies focused on transport. The majority of the studies can be broadly categorized threefold: (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 derived thereof, 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 analyis here. Most fuel substitution publications on new energy vehicles, such as BEVs, do not explicitly refer to the circular economy, 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 gCO_2/km) or hydrogen fuel power cells (235 gCO_2/km) generate substantially lower full life-cycle emissions than fossil fuel powered cars, such as an ICE Diesel (738 gCO_2/km) (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 overall lifetime of vehicles (Helmers, Dietz and Hartard, 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) finds the largest potential emission reductions in the light-weighting and reduced size of vehicles. Gilbert et al. (2017) compared a business as usually design of a ship vessel with designing and manufacturing for 100% hull reuse and found a 29% reduction of emissions (from 222 t CO_2 to 158 t CO_2). Additive manufacturing technologies for lightweight 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 emissions reductions. The remanufacturing of a diesel engine can save 69% of embodied GHG emissions compared to producing a new diesel engine (E. Hertwich *et al.*, 2019). Ahmadi et al. (2017) find 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 life time (Cruz, Klein and Steiner, 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).

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

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

Agriculture

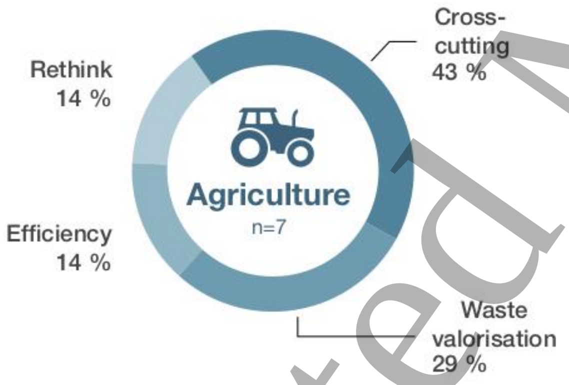

Figure 8: Results agriculture

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, Jakrawatana and Gheewala, 2017) production. The impact of the change in each product on CO_2 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 valorisation were prioritised over final disposal options. Anchovy residues from the fishing and canning process were disposed in a landfill with biogas recovery, incinerated, and valorized into fishmeal for aquaculture. The landfill scheme gained the highest mitigation potential of 2.68 kg CO_2-e 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, De Meester and Dewulf, 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, Zessner and Rechberger, 2016).

With regards to efficiency measures, one study of 15 enterprises found that even just replicating the efficiency levels of the least-emitting beef and lamb producers (use of inputs such as fertisilier, concentrate feed, bedding, etc.), enterprises could reduce their carbon footprint by 15% and 31%, respectively (Hyland *et al.*, 2016).

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_2-e per functional unit
		recovering cassava pulp for the ethanol production	Pingmuanglek, Jakrawatana, & Gheewala 2017	Thailand	-85%
		AD of cow dung to increase biogas	Sfez, De Meester, & Dewulf 2017	India	-13%
	recycling	recycling phosphorus from meat and bone meal, sewage sludge, and compost	Zoboli, Zessner, & Rechberger 2016	Austria	-28%
	efficiency	applying the efficiency levels of the least-emitting producers of beef and lamb	Hyland, Styles, Jones, & Williams 2016	-	-15% and -31%

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

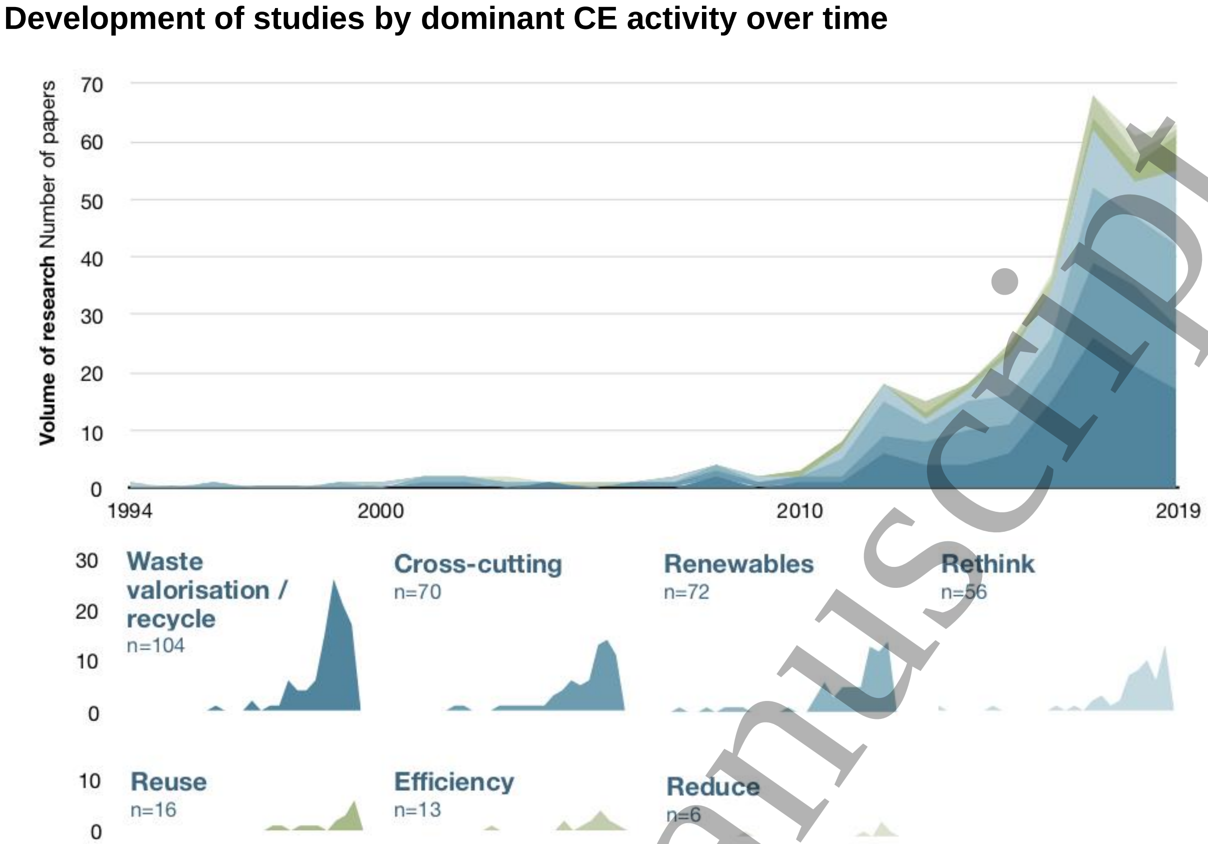

Figure 9: Number of papers over time

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 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 empirical analysis. Also these activites 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 is to circulate resources within the economy so that 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; Moraga *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 one to depart from a linear economy to a CE, indicating a considerable misalignment.

Summary of evidence on CE's reported mitigation potential

The review provides a rather fragmented picture of literature. Many studies fail to provide specific emissions savings, and if 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 of CE measures to reduce GHG emissions in the different sectors (Figure 10).

In the industry sector studies reveal high GHG savings for recycling of iron and concrete in a range of 60-90%. Various uses of solid waste in the cement production reduces 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, roghly 8%, of GHG emissions at 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 emisisons by roughly 40-50%. Intensified use of buildings shows a 50% potential as well. Making building to be reusable, recyclable and compostable might save 40%.

Studies in the transport sector estimate a 65% reduction potential for fuel alternatives, see a potential of 30% the reuse of vessels, 70% for remanufacturing engines and 50% in green procurement of road infrastructure.

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

In sum, according to studies highest savings can be assumed 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.

While most studies are at product or case study level, we can contrast this with studies at national or global levels. Here the studies are highly diverse in their estimates. While Material Economics (2018) estimate a 36% reduction for the most significant value chains steel, plastics, aluminum and cement by 2100, the IRP calculates 19% reduction by 2050. A study by Cooper and Hammond (2018), which only focuses on energy savings, suggest a potential of 5-10% savings. Similar results in range are reported by Wijkman and Scanberg (2016) who estimated for Finland, France, the Netherlands, Span and Sweden that in all countries a materials efficiency scenario might cut carbon emissions by 3-10%, whereas an energy efficiency scenario cuts it by 30% and a renewable scenario by 50%. All scenarios combined could achieve a reduction by two thirds.

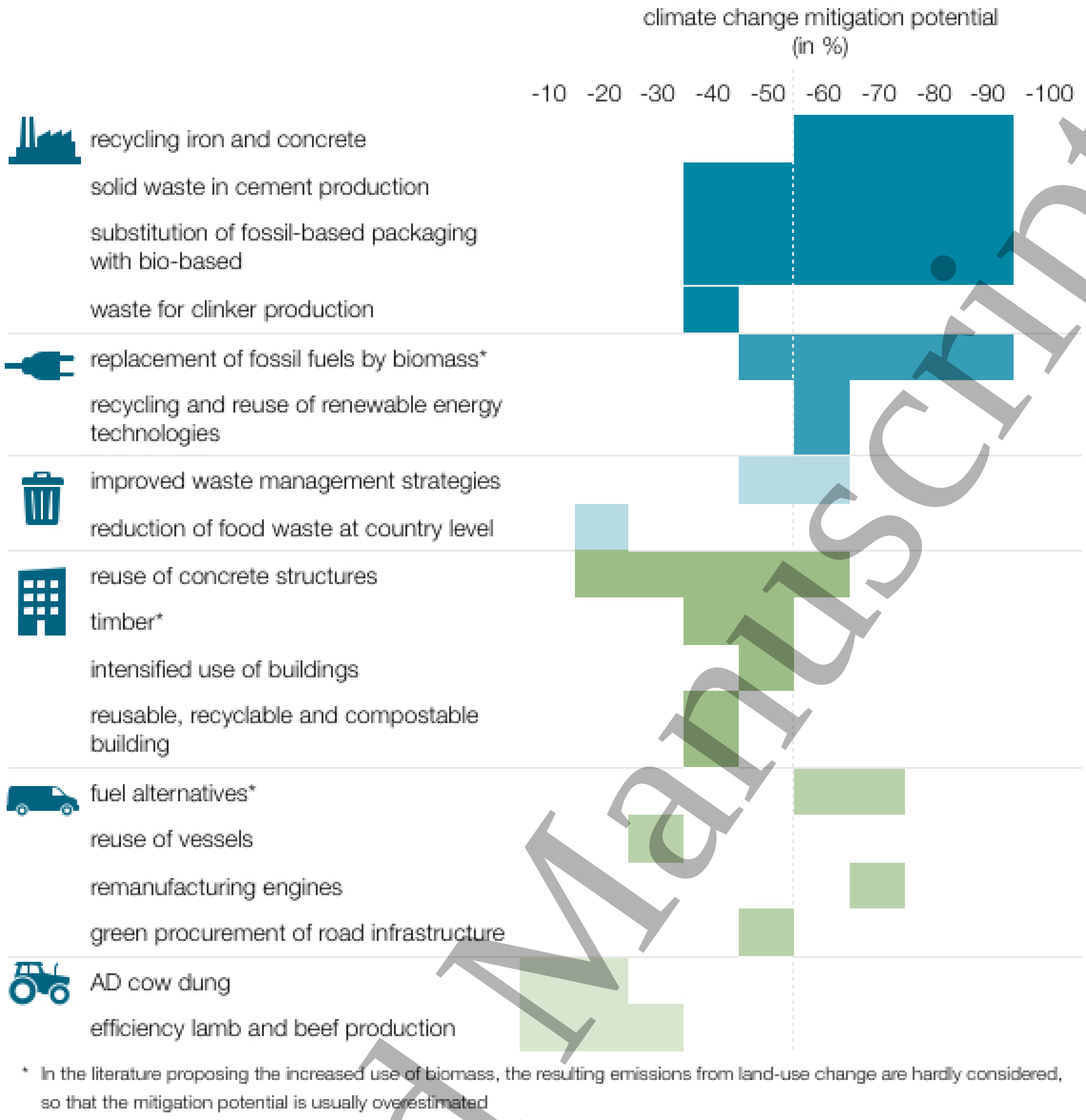

Figure 10: summary of evidence of CE's mitigation potential by sector (in %). Numbers should be interpreted with caution and conditional on the boundary conditions as specified in the underlying studies.

Discussion and concluding remarks

Comparison with grey literature

Past studies (Geissdoerfer *et al.*, 2017; Merli, Preziosi and Acampora, 2018) have recommended to also include grey literature when investigating CE. Since the inclusion of grey literature is not easily conductable 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 circular economy 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 and Skånberg (2016) find 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 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_2-e in 2050. A report by Deloitte (2016) focused on the EU food sector and finds that reducing food waste and recycling nutrients from organic waste by applying circular economy measures could reduce emissions between 55 and 64 MtCO_2eq (12-14% respectively).

Making better use of product and material within key sectors such as built environment and mobility could reduce global CO_2 emissions from cement, steel, plastic, and aluminium by 40% or 3.7 billion tons CO_2-e compared to a 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 more intensive use of homes, designing buildings using less material, use of sustainably harvested timber. Specifically for the EU, Deloitte finds a potential of 17-32%, depending on the measures adopted. The report considers 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 demand-side measures to be able to reduce emissions by more than half, or 123 Mt CO_2 , by the second half of this century. Key suggested measures include improvded design of buildings and components to increase buildings' longevity and adaptability; disassembly at the end of life; and 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 29-62% and 39-53% in India. For the EU, Deloitte concludes that the increase of recycling of materials could decrease emissions by 45%. Focusing on the reuse of components and repair activities to extent the lifetime of vehicles could divide them by 3. Interventions with the largest reductions include changing patterns vehicle use (ride-sharing, car-sharing) and shifting towards smaller vehicles. A report by Material Economics (2018) finds that in a scenario where shared vehicles account for two-thirs of travel in the EU, materials requirements could fall by as much as 75%, reducing annual CO_2 emissions from materials production by 43 Mt by 2050.

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 literature that did not entail these in their title, abstract or key words. Further, we have excluded the search terms "recycling", "reduce", "reuse", etc., as these terms also appear in a wide array of non-CE literature. 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 decidated section on grey 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 a 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 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. Differing level (micro, meso, macro) and varying scale of interventions hinder the aggregation of potentials.

Concluding remarks

Kirchherr et al.'s (2017) conclusions that this '"circular economy babble" constitute 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 or no proper reference 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, underneath policy makers and researchers alike should adhere to 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, but without systematic mitigation effect, it is clear that the CE label alone is insufficient to serve as guide post for climate action. Instead, CE strategies must be checked against three additional criteria: 1) has climate change mitigation effects been quantified? 2) is quantification of 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 positive 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 climate change mitigation literature, mostly considered outside the CE framing. CE-related literature mostly take a narrow attributional life-cycle approach that underestimates problematic upstream effects, such as land-use change emissions, thus overestimating mitigation potential (Plevin, Delucchi and Creutzig, 2014).

Second, our review reveals that a majority of CE studies focus on recycling, not on more transformative reduce, reuse, and rethink concepts. With 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, if 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 mostly marginal concepts are considered that don't deliver on larger GHG emission reduction. This is reflecting political science observation that in international politics, CE is mostly specified in terms of technological solution that keep accelerating consumption trends (Isenhour, 2019).

Third, CE approaches are multifold, and some of them very promising. However, there is more talk than walk. We document mostly studies on potential emission reduction, but few studies that document actual emission reductions at scale. Nonetheless, as table 10 evidences, there is substantial potential. This must be interpreted against boundary conditions of analysis. For example, in the building sectormany 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 (Table 10), probably because material substitution and avoided material use plays the largest role here. Second, reduce and reuse strategies, avoiding emissions to start with, are particular 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 scarcely, if at al, studied by CE practitioners.

A main question asks for the reason of this bias in the literature. Possibly, 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 lobby. It is hence important to foster new business models but also to find reduce and reuse strategies that match the interests of incumbents.

Our review is timely and addresses a cornerstone of the circular economy claim for relevance: that CE is crucial for mitigating climate change. Previous high-quality reviews, (Tukker, 2015; Ghisellini, Cialani and Ulgiati, 2016; Kirchherr, Reike and Hekkert, 2017; Govindan and Hasanagic, 2018; Kalmykova, Sadagopan and Rosado, 2018; Merli, Preziosi and Acampora, 2018) have sorted the CE literature, and have consolidated CEs relevance and limits for business 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), who systematically material efficiency strategies for reducing GHG emissions. Tellingly, this study avoids using the concept of the circular economy. Our review is different in explicitly and only drawing from studies that draw on the circular economy as a concept. This allows us to not only identify the potential of specific strategies in 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 and that is contextualized in the higher levels of scales, reductions in absolute and relative terms, clear time frames, showing the option space with its benefits and trade-offs.

Acknowledgements

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