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WORKING PAPER

Circular economy as a climate strategy: current knowledge and calls-to-action

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Executive Summary

Highlights

- Existing pledges and Nationally Determined Contributions (NDC) targets, even if fully achieved, are still not sufficient to meet the Paris climate goals. Considerable additional strategies and actions are urgently needed to close the emission gap.
- Built environment, transport, food system and clean energy are the most relevant sectors for circular economy strategies to deliver climate change mitigation benefits.
- Circular economy strategies can complement decarbonisation measures to further reduce greenhouse gas emissions[1] from material production, help lower emissions from operational energy use in the built environment and transport, and cut emissions from waste management.
- The largest potential greenhouse gas emission reductions through circularity come from consumption-side measures and product design measures.
- Circular economy strategies can support a sustainable clean energy transition by helping to relieve mineral supply pressure, increasing supply chain resilience, preventing new waste challenges, and accelerating the adoption of clean energy technologies as well as maximising their climate benefits.
- Furthermore, circular economy strategies can help enhance adaptation to climate change.
- Nine calls to action are put forward for government, business, and civil society leaders to accelerate circular economy strategies with the highest potential for climate benefits, and for the research community to close critical knowledge gaps.

Objective of this paper

The circular economy has been gaining increasing momentum as a compelling way to help meet the Paris climate goal. This paper aims to synthesise current knowledge on the potential role of the circular economy in climate change management, including mitigation and adaptation. Through review of prominent literature and extensive expert consultation, the paper identifies consensus, debates and critical knowledge gaps. It then suggests how the current knowledge landscape can be translated into actions, both for practitioners[2] to adopt and accelerate circular economy strategies where they can most effectively contribute to climate goals, and for the research community to advance the knowledge base and close critical knowledge gaps.

Key findings from the literature landscape

The circular economy can contribute to climate change management through three major mechanisms:

1) Reduce greenhouse gas emissions. Circular economy strategies can lessen demand for (virgin) raw materials and new products, and consequently reduce greenhouse gas emissions from the production phase. There is broad agreement that built environment, transport and the food system are the sectors with the highest greenhouse gas reduction potential through circular economy strategies, and the largest potential emissions reductions through circularity come from consumption-side measures and product design measures. In addition to reducing emissions from material production, circular economy strategies can also lower emissions from waste management, and can lead to reductions from operational energy use such as heating, cooling and fuel for transport.

2) Support a sustainable clean energy transition. A prominent part of global climate action is the transition to clean energy such as solar, wind and electric vehicles, which will allow us to reduce greenhouse gas emissions from energy production and use. Current clean energy technologies are often mineral-intensive. Therefore, proper material management on both the input (e.g., critical mineral supply) and output (i.e., waste streams from decommissioned equipment) ends of the sector will be crucial to support its sustainable scaling. Circular economy strategies can help relieve the material management pressure on both the input and output ends, hence making the clean energy transition more feasible and sustainable.

3) Enhance adaptation to climate change. Literature on this mechanism is still rather limited, but indicates that circular economy strategies may contribute in various ways such as by slowing down nature degradation, improving soil health, increasing flood resilience and many more.

In summary, important consensus is emerging from the knowledge community on how and where circular economy strategies can deliver the highest benefits for climate change management. On the other hand, the knowledge base still needs to be advanced to agree on the magnitude and timeline of these benefits, to assess and balance potential trade-offs, as well as to understand and manage the consumption side (including displacement rates and rebound effects) to reach an absolute reduction in global resource use and greenhouse gas emissions.

Calls-to-action:

Building on the literature- and consultation-based knowledge landscape, the following nine interconnected areas are identified for collective action:

1. **Shift consumption patterns.**
2. **Stimulate product circularity from the design phase.**
3. **Incorporate circularity across clean energy value chains.**
4. **Integrate circular economy strategies into national climate policies and plans.**
5. **Incentivise cross-border greenhouse gas emission reductions.**
6. **Connect circular economy metrics with climate change impacts.**
7. **Increase transparency and comparability in modelling methodologies.**
8. **Apply systemic and context-specific impact assessment to inform decision-making.**
9. **Investigate the role of the circular economy in climate change adaptation.**

We invite governments, businesses, philanthropies, NGOs, multilaterals and researchers to join the discussion and act collaboratively, to make circularity contribute most effectively towards climate goals.

1 Introduction

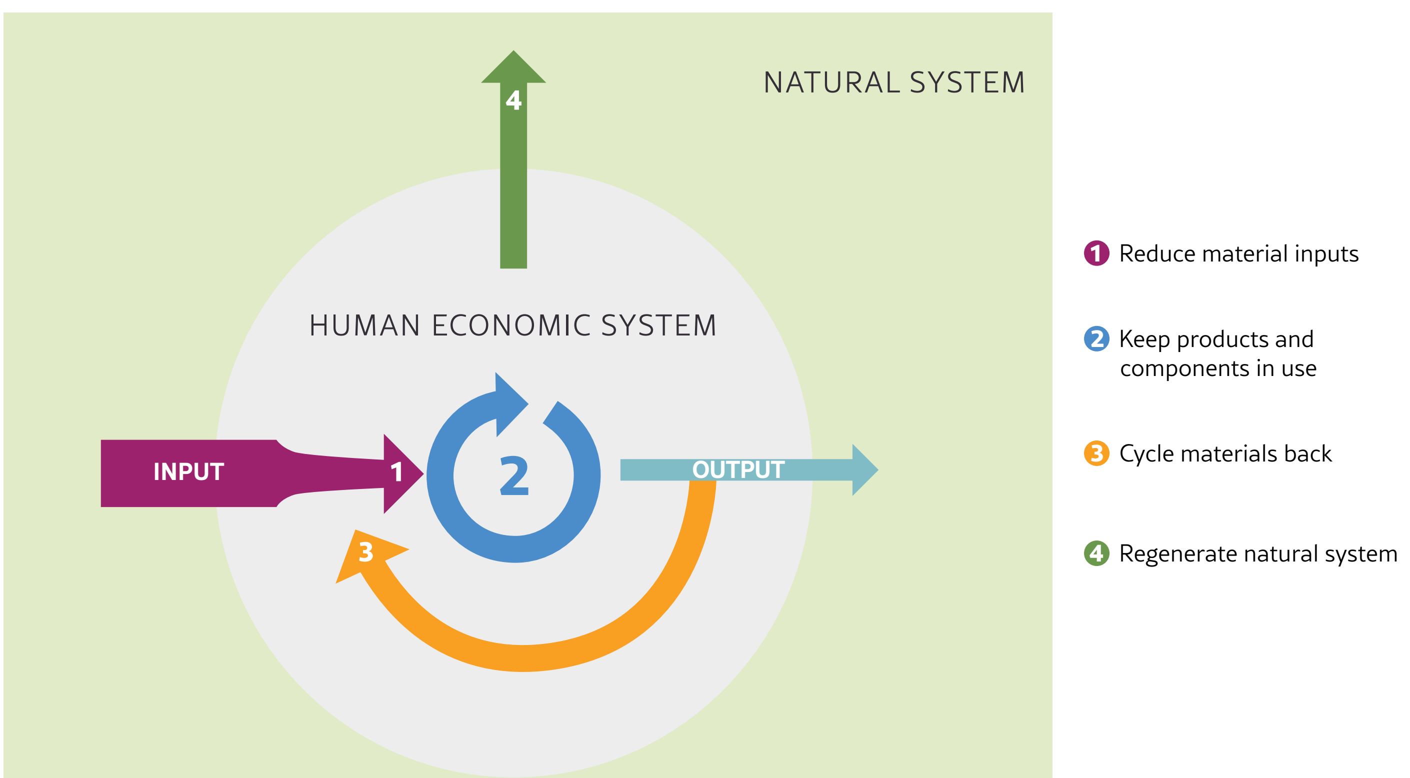
The 2015 Paris Agreement established a goal to limit global warming to "well below" 2˚C, and to pursue efforts to limit it to 1.5˚C. To stay below the 1.5˚C limit, global net greenhouse gas emissions must be cut in half from 2010 levels by 2030, and reach net zero by the early 2050s. This will require far-reaching system changes at an unprecedented scale. As of 2021, it is estimated that even if all existing pledges and targets in the latest NDC submissions are fully achieved, in 2030 there will still be a substantial gap of 25 Gt CO_2e between actual emissions and those required to meet the 1.5˚C goal (UNEP 2021). Considerable additional strategies and actions are urgently needed to close the gap.

The circular economy has been gaining increasing momentum as a proposed pathway to help meet the Paris climate goal. For instance, in the latest Assessment Report by the Intergovernmental Panel on Climate Change (IPCC 2022), the circular economy was mentioned for the first time as a solution for climate change mitigation.

This paper summarises current knowledge on the role of circular economy strategies in climate change management, including mitigation and adaptation, based on literature and consultations. This is not an exhaustive academic literature review. Instead, it focuses largely on several highly influential reports with primary research results widely quoted by practitioners,[3] complemented with related academic literature as well as consultations with over 30 experts through interviews and reviews (see Acknowledgements). The paper examines three mechanisms through which the circular economy can contribute to climate change management (Sections 2-4). It identifies where consensus, debates and critical knowledge gaps are by comparing literature and consultation inputs across specific topics. It then suggests how the current knowledge landscape can be translated into actions (Section 5), both for practitioners to adopt and accelerate circular economy strategies where they can most effectively contribute to climate goals, and for the research community to close critical knowledge gaps.

Several definitions exist for the circular economy,[4] some with different breadth of scope. To avoid duplicating discussions on the roles of energy, water, land and other resources in climate change management, this paper will focus on the circularity of material resources, which include biomass, fossil fuels, metals and non-metallic minerals (IRP 2019)[5] and will highlight where different resource scopes are used in referenced literature. Most circular economy strategies can be clustered into the following four categories (Figure 1): 1) reduce material inputs, which can be achieved through e.g., refuse, material-efficient product design and manufacturing, dematerialisation and substitution; 2) keep products and components in use, which can be achieved through e.g., increased durability, upgrading, sharing, reusing, repairing, resale, refurbishing, remanufacturing, repurposing; 3) cycle materials back into the economy, usually through recycling;[6] 4) regenerate natural systems, which is particularly relevant for biomass materials.

Figure 1 | **The four categories of circular economy strategies**



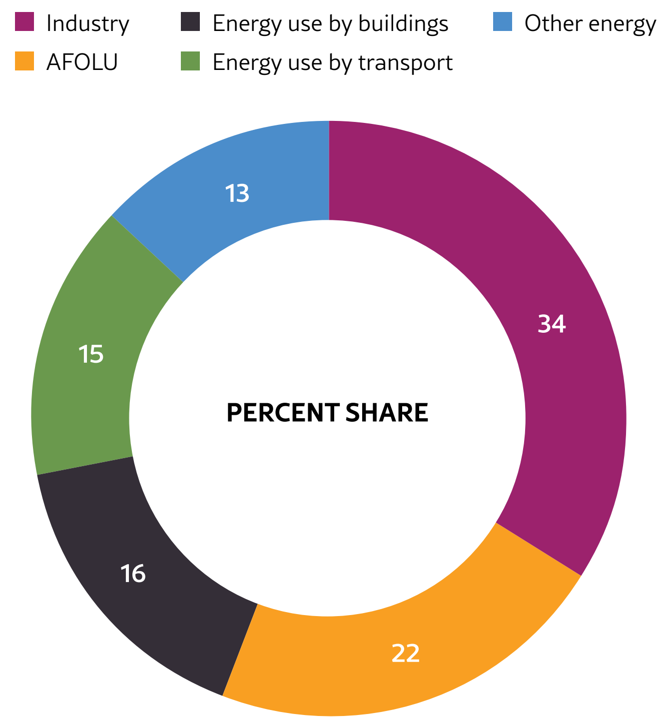
While this paper focuses on the role of the circular economy in climate change management, it is important to emphasise that climate change is not the only relevant impact category for the circular economy. Other environmental and socio-economic impact categories, such as biodiversity, decent work and social equity, are just as relevant and important.

Furthermore, this paper mainly examines ways in which, and to what extent, a circular economy, if achieved, may help manage climate change. Readers interested in how to accelerate the transition to a circular economy are referred to abundant existing literature from e.g., Ellen MacArthur Foundation, UNEP, Circle Economy and PACE.

2 Circular economy strategies can reduce greenhouse gas emissions

Reducing greenhouse gas emissions is a relatively well-studied pathway for the circular economy to contribute to climate goals. After reviewing global emissions related to both industrial and biomass materials (Section 2.1), this section synthesises projections of potential reductions through circular economy strategies in six sectors from the literature (Section 2.2), and then proceeds to discuss the most outstanding debates or attention points arising from comparing the literature findings as well as from the expert consultations (Section 2.3).

Figure 2 | **Global greenhouse gas emissions per sector (direct and indirect combined) in 2019 for a total of 59Gt CO_2e**



Note: AFOLU: Agriculture, Forestry and Other Land Use.
Source: IPCC 2022.

2.1 Materials-related greenhouse gas emissions

Annual global material extraction has more than tripled since 1970 to 92 billion tons in 2017 (IRP 2019) and is projected to double again by 2050 (IRP 2017). This increased material consumption has contributed to economic development and rising living standards, but has also become a root cause of the triple planetary crisis (climate change, biodiversity loss and pollution) the world is facing today.

The International Resource Panel estimates that about half of global greenhouse gas emissions come from material resource extraction and processing[7] (IRP 2020). These emissions occur in many different ways, including the energy used to power machinery and industrial facilities that extract and process the materials, emissions released during the process of extracting or transporting fossil fuels, those released from chemical reactions in production (e.g., the transformation of limestone into calcium oxide in cement production), and energy used to transport materials and manufacture them into their final form.

According to the IPCC sixth assessment report, emissions attributed to industry[8] accounted for about 34% of total global greenhouse gas emissions in 2019 (IPCC 2022). The materials that contribute most emissions are metal (accounting for 7.8% of global total emissions), cement (2.6%[9]) and chemicals (6.3%). These materials are also often referred to as “harder to abate”, since their decarbonisation requires technologies that do not exist at an industrial scale yet, and/or the costs remain prohibitive. For biomass materials, the IPCC estimates that the Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for about 22% of total net global greenhouse gas emissions—nearly 13 Gt CO_2e (IPCC 2019). Emissions from

AFOLU come primarily from food production: agriculture and associated land use change contribute to about 11 Gt CO_2e (IPCC 2019).

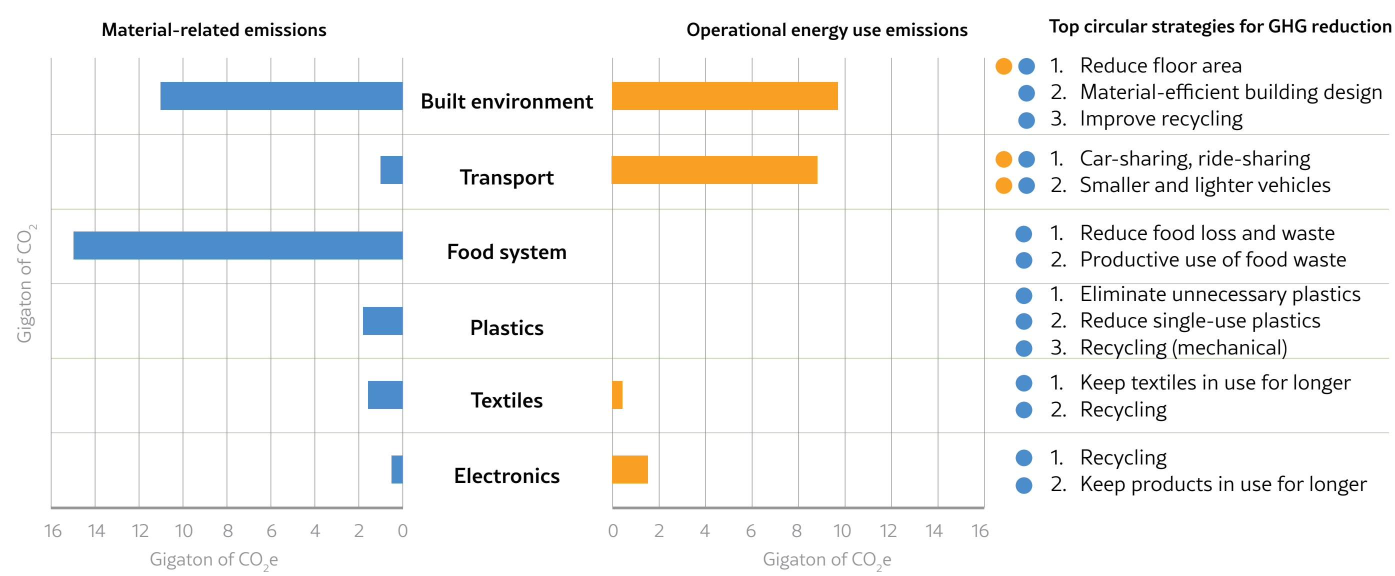
In addition to extraction and processing, materials-related greenhouse gas emissions also include waste management, mainly from open dumps, landfills and incineration. Data from 2016 shows that about 5% of global greenhouse gas emissions were generated from solid waste management (Kaza et al. 2018).

2.2 Projected reduction potential through circular economy strategies

There is broad agreement in the literature that by lowering demand for (virgin) raw materials and new products, circular economy strategies can lead to reduced emissions from industrial processes by avoiding production of emissions in the first place. For example, materials-efficient product design can lower demand for industrial material inputs; keeping products in use can reduce demand for new products; and recycling can decrease demand for virgin materials that are often more carbon-intensive to produce compared to recycled materials. It is important to notice that some circular economy strategies can also reduce greenhouse gas emissions from operational energy use such as heating/cooling in buildings and fuel in transport. Furthermore, by reducing the volume of waste and diverting it from landfills and incineration, circular economy strategies can reduce greenhouse gas emissions from waste management.

This section reviews the findings of the current literature on circular economy's potential to reduce greenhouse gas emissions across six sectors—built environment, transport, food systems, plastics, textiles and electronics, as projected in the literature. These six sectors correspond with the key product value chains identified by the European Commission for the circular economy (European Commission 2020). Collectively, they account for 85–90% of global greenhouse gas emissions.[10] Figure 3 summarises the materials-related emissions[11] and operational energy use emissions from each sector, as well as top circular economy strategies that are broadly agreed to have substantial greenhouse gas emission reduction potential.

Figure 3 | **Materials-related and operational energy use emissions by sector, alongside the circular economy strategies with highest projected greenhouse gas reduction potential**



Note: Blue dots indicate that a strategy decreases materials-related emissions. Orange dots indicate that a strategy decreases operational energy use emissions.

Sources: Built environment: Global Alliance for Buildings and Construction et al. 2019. Transport: IPCC 2022; Hertwich et al. 2019, with extrapolation by authors. Food system: IPCC 2019. Plastics: OECD 2022. Textiles: McKinsey and Global Fashion Agenda 2020. Electronics: Belkhir and Elmeligi 2018, with extrapolation by authors.

2.2.1 Built environment

Buildings currently account for about 30–40% of global greenhouse gas emissions—including nearly 10 Gt CO_2e energy-related emissions, primarily from energy used for heating, cooling, lighting etc.; and 11 Gt CO_2e embodied carbon in construction materials (Global Alliance for Buildings and Construction et al. 2019), dominated by concrete and steel (Hertwich et al. 2019).

The International Resource Panel (IRP) estimates that material efficiency strategies could reduce greenhouse gas emissions in the material cycle of residential buildings by 80–100% in G7 countries and China, and 50–70% in India by 2050 (IRP 2020). Material Economics and Ellen MacArthur Foundation estimate that circular economy strategies could reduce greenhouse gas emissions from the four key industrial materials (cement, steel, plastics and aluminum) used in buildings by 34–38% in 2050, in the EU or globally (Material Economics 2018; Ellen MacArthur Foundation 2019a). The Circularity Gap Report has forecasted greenhouse gas reduction potential as high as ~13 Gt[12] through circular solutions in housing (Circle Economy 2021).

The studies converge on the following strategies showing the highest potential to reduce emissions for material use in buildings: 1) reduce floor area per person (in higher income population); 2) material efficient design—for example, the amount of concrete and steel used in the building structure can be reduced without loss of functionality through optimised design (IRP 2020); 3) improved recycling rates and technologies for construction materials. Quantitative differences between the studies mainly arise from how various strategies are defined and modelled—this will be discussed further in Section 2.3.1.

Besides reduction of materials-related emissions, less floor area per person can also substantially reduce emissions from building energy use such as heating and cooling (Ivanova et al. 2020). IRP estimates such synergies can reduce a further 130 Mt of emissions in G7 countries in 2050, bringing the sum of emission reduction opportunity (materials plus energy) through material efficiency strategies to 35% for homes (IRP 2020).

2.2.2 Transport

Operational energy use in transport amounted to 15% of global greenhouse gas emissions, or 8.8 Gt CO_2e, in 2019 (IPCC 2022). The embodied emissions in materials used to make vehicles are about an order of magnitude lower compared to the operational energy use emissions (based on data from Hertwich et al. 2019), therefore estimated to be about 1 Gt CO_2e in 2019.

Circular economy literature on transport focuses so far largely on passenger cars. IRP found that material efficiency strategies could reduce materials-related emissions of passenger cars in 2050 by 57%–70% in G7 countries, and by 40–60% in China and India (IRP 2020). Similarly, Material Economics and Ellen MacArthur Foundation found that a circular scenario could reduce greenhouse gas emissions from the industrial materials used in passenger cars by 70% in 2050 (Material Economics 2018; Ellen MacArthur Foundation 2019a). The Circularity Gap Report has forecasted greenhouse gas reduction potential as high as ~6.7 Gt[13] through circular solutions in mobility (Circle Economy 2021). There is consensus in these studies that changing patterns of vehicle use (e.g., ride-sharing and car-sharing[14]) and shifting towards smaller, lightweight vehicles both have high potential to reduce materials-related emissions in transport. Material Economics, Ellen MacArthur Foundation and Circle Economy also expect vehicle lifetime extension to play a significant role.

In transport, the most significant opportunity for reducing emissions through circular economy strategies can come from less fuel use[15] enabled by e.g. lighter/smaller vehicles or shifts in use pattern. For instance, it is estimated that, as a redesign strategy, using mainly aluminum would reduce the vehicle's total mass by 26%, therefore reducing total material input and improving fuel efficiency, which avoids 8% of life cycle greenhouse gas emissions (Modaresi et al. 2014). Further emission savings can be achieved through closed-loop recycling of aluminum (Modaresi et al. 2014). Moreover, since personal vehicles are being used on average only 5% of the time and to a third of their capacity (Hertwich et al. 2019), car-sharing and ride-sharing have the potential to reduce the total number of vehicles needed and the person-kilometres travelled, therefore cutting emissions from both material use and fuel use. The actual impact will depend on associated consumption behaviour change, such as the degree of rebound effects (Coulombel et.al. 2019; Tsuji et.al. 2020). IRP estimates that material efficiency strategies can reduce 25 Mt emissions from material use and 280 Mt from operational energy use in G7 countries in 2050, bringing the total life cycle emission reduction opportunity (materials plus energy) through material efficiency strategies to 40% for cars (IRP 2020).

2.2.3 Food system

Total global food system greenhouse gas emissions, including agriculture and associated land use change, plus emissions beyond the farm gate such as from the food processing industry, amount to as high as 11–19 Gt CO_2e (IPCC 2019). The World

Resources Institute estimates that slowing and shifting growth in food demand, including more sustainable diets and reduced food loss and waste, could reduce emissions from agriculture by 5 Gt CO_2e/year globally by 2050 (Searchinger et al. 2019). Ellen MacArthur Foundation expects that a circular food system—characterised by regenerative agriculture, food loss and waste reduction, and composting—could reduce annual greenhouse gas emissions from the global food system by 49% in 2050 (Ellen MacArthur Foundation 2019a). The Circularity Gap Report expects about 4.4 Gt[16] greenhouse gas emissions reduction from sustainable food production, healthy diets and clean cooking methods (Circle Economy 2021).

The contribution of regenerative agriculture to greenhouse gas reduction, e.g. by increased vegetation and soil carbon capture, is a topic of debate, partly originating from different definitions of regenerative agriculture (Ranganathan et al. 2020; EIT Food 2020; Morseletto 2020). It is expected by some to be a significant opportunity—for example, Ellen MacArthur Foundation projects that if 80% of the world's cropland adopts practices such as no till, intercropping and cover crops, it could lead to an annual carbon benefit of 2.5 Gt CO_2e; while managed grazing on half of the world's suitable pastureland could lead to a net annual carbon benefit of 1.4 Gt CO_2e in 2050 (Ellen MacArthur Foundation 2019a). On the other hand, the climate impact of farming depends on many factors, including geography, soil type, agriculture product type, practice and timeframe, therefore requiring context-specific approaches. Furthermore, there are concerns if forests are cleared to create new farmland to compensate for potentially lower yields from regenerative agriculture practices, net emissions may increase (Benton and Harwatt 2022). To ensure that enough food can be produced in ways that regenerate nature without further land use change, it is critical to shift what we eat—and therefore what we produce, and to minimise food loss and waste.

Food loss and waste reduction has widely recognised climate benefits, by reducing greenhouse gas emissions across the entire food value chain. Food loss and waste is currently responsible for about 8–10% of annual greenhouse gas emissions (IPCC 2019). The World Bank estimates that a reduction in food loss and waste by 50% at all stages of the supply chain would reduce global greenhouse gas emissions by 3%, with most of the decline associated with reduced output in the farming and transport sectors (World Bank 2020). More cold transport and storage will be needed to reduce food loss and waste, but the benefits are expected to outweigh the drawbacks (FAO 2019), especially if low-carbon cooling solutions are used.

Furthermore, nutrient cycling, through practices such as composting and applying manure, can improve the productivity of soils by improving water retention, reintroducing soil microbes and adding nutrients, thereby reducing demand for chemical fertilisers and irrigation on degraded soils. This reduces emissions from fertiliser production and emissions associated with the energy use for irrigation (Ellen MacArthur Foundation 2019a; Toor et al. 2021). The greenhouse gas benefits of nutrient cycling are especially high in degraded contexts, as soils can be transformed from carbon emitting to carbon sequestering. Turning food waste into productive uses (such as insect feed, textile or plastic feedstock, fertiliser and energy sources) can reduce greenhouse gas emissions from landfills. Some cities have started pioneering urban circular food ecosystems, turning food waste from one business into feedstock for another (PACE 2021d).

2.2.4 Plastics

Plastics generated 1.8 Gt CO_2e of greenhouse gas emissions in 2019 (about 3% of global emissions)—90% of these emissions come from the production phase (OECD 2018).

An integrated circular system change in plastics is projected to result in 25% lower plastic-related greenhouse gas emissions in 2040 (The Pew Charitable Trusts and Systemiq 2020). Circular economy strategies that eliminate unnecessary plastics and increase plastics reuse can reduce emissions related to plastics production and disposal. The greenhouse gas reduction potential of plastics recycling strongly depends on the technology. Compared to landfill, it is estimated that mechanical recycling can save up to 50% in lifecycle greenhouse gas emissions (The Pew Charitable Trusts and Systemiq 2020), and even greater reductions compared to incineration. Lifecycle greenhouse gas emissions of chemical recycling are currently similar to landfill, and lower than incineration. The climate impact of bio-based input materials for plastics can be highly variable, dependent on the type of plastic, feedstock, region, production process and land use (Piemonte and Gironi 2011; Walker and Rothman 2020).

2.2.5 Textiles

The global apparel industry currently emits between 1.0 and 3.3 Gt CO_2e per year across its value chain (Ellen MacArthur Foundation 2017; Quantis 2018; McKinsey and Global Fashion Agenda 2020; World Resources Institute and Apparel Impact Institute 2021). The large estimate variation originates from the scope, assumptions and methodology of each study and the specific cases used to calculate emissions for each material. It is estimated that 75% of these emissions are from the production stages: from fibre to yarn to fabric and to garment (UNEP 2020).

Interventions on both materials and energy have been proposed in a roadmap to net zero emissions in the apparel industry (World Resources Institute and Apparel Impact Institute 2021). Keeping textiles in use for longer (including shifting away from fast fashion), and increasing recycling rates, are in general expected to reduce greenhouse gas emissions if new production and/or virgin material input is displaced. If on average the number of times a garment is worn were doubled, then greenhouse gas emissions would be 44% lower (Ellen MacArthur Foundation 2017). Climate benefits of re-use will likely outweigh additional transport needs such as in used clothing export, provided that the exported clothing gets re-used for a sufficiently long period. For textile recycling, caution should be paid in the case of energy-intensive recycling technologies with high-carbon energy sources (Sandin and Peters 2018). Shifting from high carbon footprint textile inputs to recycled materials can reduce greenhouse gas emissions (Global Fashion Agenda and The Boston Consulting Group 2017; Shen et al. 2012; van de Vreede and Sevenster 2010). However, the climate impact of shifting from synthetic to plant-based fibres is more complex since it may lead to land conversion—where forests are cleared, emissions will increase (Forster et al. 2013; Peltzer 2014). On the other hand, where wood-based fibres are grown on degraded cropland, it may help reduce greenhouse gas emissions by increasing soil carbon (Piemonte and Gironi 2011).

2.2.6 Electronics

Although electronics[17] are not yet considered a predominant contributor to global greenhouse gas emissions, the sector's carbon footprint is increasing rapidly. It is estimated that ICT alone already accounted for 3–3.6% of global emissions in 2020 (Belkhir and Elmeligi 2018). The breakdown between materials-related emissions and operational energy use emissions strongly depends on the product category.

Substituting virgin materials with recycled materials will reduce greenhouse gas emissions from electronics, as the production of recycled materials is on average much less carbon intensive (OECD 2018). For instance, aluminum recycling saves 95% of the energy footprint of producing virgin aluminum (Material Economics 2018). Recycling of rare earth elements uses 58-88% less energy compared to baseline primary production (Sprecher et al. 2014). Certain electronic products, such as refrigerators and air conditioners, use potent greenhouse gases such as fluorinated gases, with much higher global warming potential than CO_2. Proper collection and recycling of these products will therefore be crucial for greenhouse gas emission reduction (GIZ 2017). Keeping electronics products and their components in use (either for longer or more intensively through sharing) can reduce, or at least slow down the increase in, emissions from new production, especially since electronics manufacturing is currently concentrated in countries with carbon-intensive coal-fired power in their energy mix. In most cases, greenhouse gas savings from displaced new production can outweigh emissions from reverse logistics and potential energy efficiency improvements of new products (Parajuly et al. 2019).

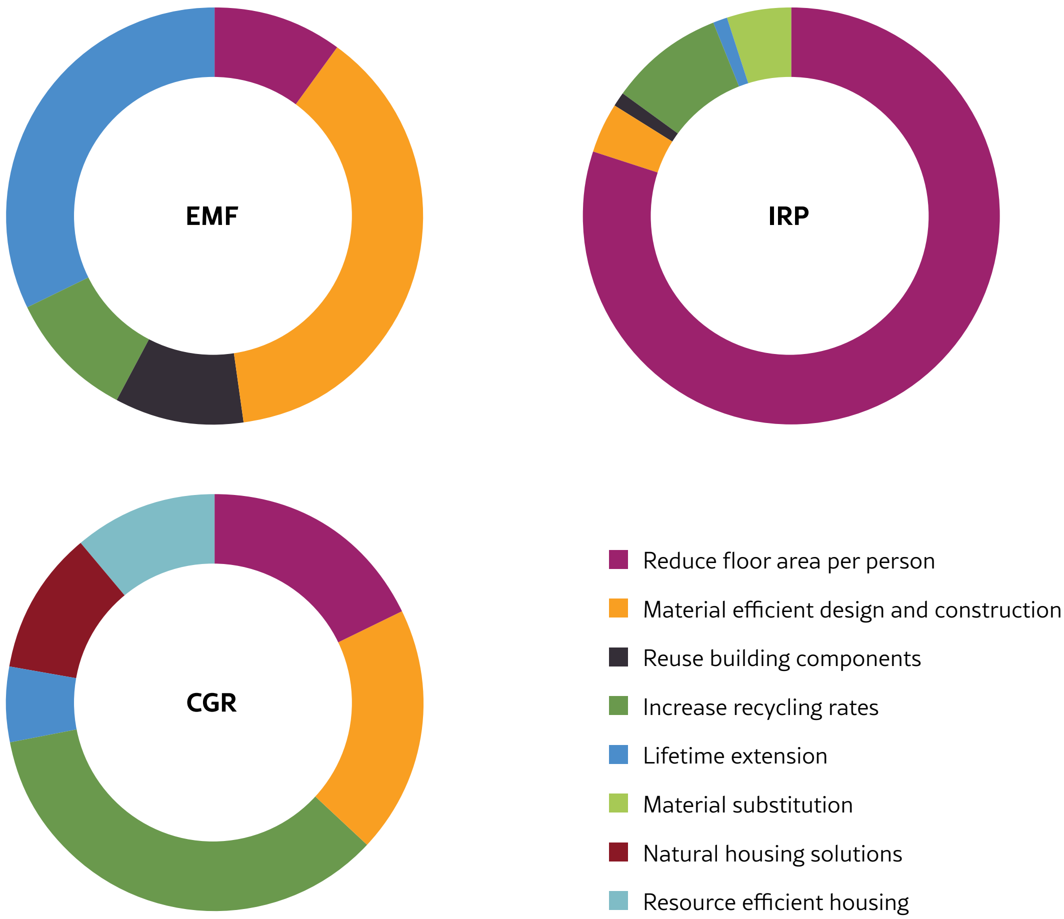
2.3 Discussions

2.3.1 Magnitude of the benefits

Although the existing literature largely agrees that circular economy strategies can play a significant role in reducing greenhouse gas emissions, they diverge considerably on the magnitude of the potential benefits. The quantitative differences originate from a variety of factors, including the scope of what is considered a circular economy strategy, the scope of greenhouse gas savings included, as well as the assumptions and data used by different research groups.

Take the built environment as an example. Figure 4 compares the sets of strategies considered by three widely quoted reports on this subject, and their relative greenhouse gas emission reduction potential according to each report. Some of the differences in scope, such as material substitution and natural housing solutions,[18] have substantial impacts on greenhouse gas emissions and may explain the large variations on the magnitude of the benefits across the reports. This example illustrates that, although the knowledge community is converging on the basic principles and definition of the circular economy, there are still important differences in interpretation of the scope of circular economy strategies.

Figure 4 | **Comparison of circular strategies for the built environment and their relative significance in greenhouse gas emissions reduction potential, as modelled in different studies**



Sources:
EMF: Ellen MacArthur Foundation. 2019a. IRP: International Resource Panel. 2020. CGR: Circle Economy 2021.

For a specific circular economy strategy the estimated benefits in emission reduction can still differ significantly, since some literature considers only direct savings in materials and their embodied carbon, while others count also synergic energy savings in the use phase. An example here is car-sharing, which can reduce the total number of vehicles needed and therefore save emissions from their production. It can also reduce the total number of kilometres travelled, which saves emissions from fuel use. When operational energy savings are included, the magnitude of the benefits can be a lot higher.

Another major source of quantitative differences comes from the assumptions. There are very few empirical studies on the greenhouse gas emission impacts of circular economy strategies. Most literature is based on speculative modelling. Assumptions on the effectiveness of the strategies (e.g., whether assuming a 2x increase or a 1.5x increase in building lifetime), or on the scale of uptake (e.g., whether assuming 10% or 50% of the world population adopts healthier diets) will clearly affect results. These assumptions are not always clearly explained in the literature, nor are the lower and upper limits of the estimated results clearly marked.

Finally, data source and quality also lead to differences in the magnitude of the benefit. Due to the lack of empirical data at a larger scale, most literature uses secondary data extrapolated from limited case studies, which vary in quality and in magnitude due to different contexts.

2.3.2 Time horizon of the benefits

For climate change mitigation, not only is the magnitude of the greenhouse gas reduction important, the timing of the reduction also matters. There is still very limited information from current literature on the time horizon of the climate benefits from different circular economy strategies. Important factors for the time horizon would include:

Transition speed. Models used in the current literature typically assume that circular economy strategies are implemented at a large scale. However, there is still very limited understanding on the practical timeline of scaled transition, considering costs, incumbent technology lock-in, dispersion of innovation, geopolitical situation, etc.

Product life cycle. For example, buildings typically have very long lifespans. Therefore, circular economy strategies such as building lifetime extension and new design/construction methods for building component reuse are long-term strategies. Their emission reduction benefits will only be realised decades from now. On the other hand, strategies with longer-term benefits should not be considered less important. Precisely because of their long lifespan, linear building design and construction methods of today will have a long-term lock-in effect, hampering reuse and recycling potentials decades into the future.

2.3.3 Relation with decarbonisation

Circular economy strategies mainly reduce greenhouse gas emissions in the production phase of (virgin) raw materials and new products through demand management. It is therefore important to understand how this relates to decarbonisation strategies that reduce emissions in the production phase through fuel/feedstock switch, process change or carbon capture.

While some argue that deeper decarbonisation in production processes will make the potential greenhouse gas emission reduction benefits of circular economy strategies less important, the circular economy is in general considered as a complementary lever to decarbonisation[19] and energy efficiency to achieve net zero emissions (Energy Transitions Commission 2018). Where decarbonisation technologies are either still premature or too expensive, circular economy strategies can allow greenhouse gas emission reduction to start sooner and potentially at a lower cost. Furthermore, by reducing demand for virgin materials and new products, the circular economy also helps make a fuel/feedstock switch in decarbonisation easier to achieve.

Applying circular economy strategies for the decarbonisation technologies themselves is necessary for their scaling. Since decarbonisation technologies (such as solar or wind power) can be more mineral intensive than their conventional counterparts (IEA 2021), care is needed to make sure that their scaling does not shift our dependency on one finite resource (fossil fuel) to another (e.g., rare earth elements), and cause unintended environmental or social consequences along the way. Therefore, decarbonisation and circularity need to go hand-in-hand. Section 3 dives deeper into this aspect.

2.3.4 Win-wins and trade-offs

Next to synergetic win-win opportunities outlined in 2.2.1 and 2.2.2, there are also potential trade-offs **between materials-related and operational energy-related greenhouse gas emission reduction** in some cases. A representative example is whether it is better for the climate to extend the use phase of products with lower energy/fuel efficiency, or to replace them with new ones. There is no simple, uniform answer here. Generally speaking, for products that generate most of their lifetime emissions in the manufacturing phase, use life extension may be more favourable; while for products that generate most of their lifetime emissions in the use phase, product replacement may be more favourable (Glöser-Chahoud et al. 2021; Tasaki et al. 2013). But this trade-off also depends on the energy mixes in the locations where the product is produced and used. In areas with a low-carbon energy mix, extending the use life of a less energy-efficient product may have a higher net gain.

Sometimes there are trade-offs **between different circular economy strategies**: certain practices to improve one circular economy strategy may negatively affect another. For example, gluing components together in electronics design increases product durability, but can make repair and recycling more difficult, costly and environmentally burdensome (Thompson et al. 2020; Norgren et al. 2020).

Furthermore, although this paper focuses on the climate impact, it should not be the only lens to evaluate circular economy (or any other) strategies. Other environmental impacts such as pollution and biodiversity, as well as socio-economic impacts such as decent work and social equity, should also be considered to reach a balanced assessment. As in any complex system change, the transition to a circular economy can lead to both win-win opportunities and potential trade-offs **between material/**

climate impacts and other environmental or socio-economic impacts (PACE 2021). The European Commission applies the "Do No Significant Harm" principle, which requires activities that benefit one environmental or social objective do not significantly harm other objectives in the process (European Commission 2021a). These win-wins and trade-offs depend on many factors. Therefore, a systemic and context-specific impact assessment should be used to inform the best decision.

2.3.5 Consumption and absolute reduction

Since a major mechanism for the circular economy to reduce greenhouse gas emissions is through demand management for (virgin) raw materials and new products, the extent of the benefit will depend on whether actual demand is indeed reduced. Important factors affecting actual demand change include displacement rate and rebound effect.

Displacement rate. Displacement refers to the extent to which product reuse replaces the production and consumption of new products. For example, whether the purchase of a secondhand garment or the renting of an item happens instead of the purchase of a new garment. It is proposed that brands launching such new business models should build in effective means to monitor and evaluate the actual outcomes (Cunningham 2020).

Rebound effect. The rebound effect refers to an increase in consumption which may occur as an unintended side-effect of the introduction of policy, market and/or technology interventions aimed at environmental efficiency improvements (Maxwell et al. 2011). It is speculated that resource productivity improvements from successful implementation of some circular economy strategies may lead to increased demand and higher consumption of other goods, such as more individualised transport, more floor space and food, which may offset the environmental benefits in resource use and greenhouse gas reduction (Best et al. 2018). The risk of rebound effect is expected to be lower for some circular economy strategies (such as repair) and higher for others (such as sharing) (Koide et al. 2022).

There is growing attention to the consumption side of resource use and the circular economy. Unlimited growth in consumption will offset any efficiency improvement on the production side. According to IRP, "an absolute reduction in the use of natural resources is indispensable to meet climate change, biodiversity and pollution ambitions" (Potočnik and Teixeira 2022; SYSTEMIQ and Center for Global Commons 2022). Therefore, it is important to not only address "efficiency", but also "sufficiency". Shifting consumption patterns are increasingly recognised as critical to addressing climate change (Institute for Global Environmental Strategies et al. 2019).

3 Circular economy strategies can support a sustainable clean energy transition

The transition to clean energy technologies such as solar, wind and electric vehicles is a prominent part of global climate action. Their scaling-up will bring new challenges in both the input (e.g., critical mineral supply) and output (i.e., waste streams from decommissioned equipment) ends of the industry.

On the input side, current clean energy technologies are often mineral-intensive. The International Energy Agency (IEA) estimates that global clean energy transitions will have far-reaching consequences for mineral demand over the next 20 years. Total mineral demand from clean energy technologies is projected to double by 2040 under the current policy scenario, and even quadruple under a sustainable development scenario, turning the energy sector into a leading consumer of minerals (IEA 2021). The demand increase will be particularly drastic for some critical minerals, potentially by a factor of 20 or more for lithium, cobalt and nickel (Xu et al. 2020). Today's mineral supply chains are not ready to support such accelerated energy transitions (IEA 2021). The pandemic and geopolitical crises in the last few years have further exacerbated the vulnerability of mineral supply chains.

On the output side, decommissioned clean energy equipment will soon become a fast-growing new waste stream. For instance, if the current situation continues of limited recycling infrastructure, generally non-existent or unclear policies, and challenging recycling economics, end-of-life solar panels are expected to generate 78 million tons of waste cumulatively by 2050 (IEA PVPS/IRENA 2016). This new waste stream will become comparable to the world's total e-waste volume today and, if not properly managed, may pose the risk of joining e-waste in causing further environmental and social hazards for developing countries (Barrie and MacEwen 2021). Similarly, wind turbine blades are projected to generate 43 million tons of waste cumulatively by 2050 (Liu and Barlow 2017).

Circular economy strategies are expected to be able to support a more sustainable scaling of the clean energy transition by helping relieve the material supply pressure, increasing supply chain resilience, preventing new waste challenges, accelerating the adoption of clean energy technologies, as well as maximising the climate benefits of deployed equipment in the following ways:

Materials-efficient product design and manufacturing. For example, over the past decade, 40-50% reductions in the use of silver and silicon in solar cells have been achieved, which has contributed to a substantial rise in solar PV deployment (IEA 2021). Reducing high-impact materials in EV batteries, for instance through the development of low-cobalt or cobalt-free cathodes, could have similar effects while reducing the socio-ecological costs and carbon footprint. There are a number of promising cathode prototypes that provide alternatives to cobalt-intensive designs, although more research is necessary to ensure these designs can be safe and cost-effective (Cui et al. 2021; Gourley et al. 2020; Li et al. 2020).

Product lifetime extension. Clean energy technologies often enjoy a high innovation speed and rapidly increasing energy efficiency. However, since the equipment is often material- and energy-intensive to manufacture, it can be better for the climate to keep the equipment in use for longer, instead of early replacement with newer technologies, as one recent life cycle assessment of solar panels has suggested (Rajagopalan et al. 2021). Lifetime extension strategies, such as upgrade, repair, cascade reuse applications, refurbish and remanufacture can therefore help to maximise the climate benefit of deployed clean energy equipment. Furthermore, some of these strategies (such as cascade reuse applications) can provide access to clean energy at lower costs, thus helping to accelerate the transition.

Recycling. Recycling has already been recognised by the clean energy sector as an important strategy, particularly for critical minerals. For instance, it is estimated that by 2040, recycled copper, lithium, nickel and cobalt from decommissioned batteries could reduce the demand for primary supply of these minerals by around 10% (IEA 2021).

4 Circular economy strategies can enhance climate change adaptation

Regardless of future climate action, 1.1°C of global warming has already taken place (GISTEMP Team 2022), and further temperature increases are "locked-in" due to the long atmospheric lifetime of existing emissions (UNEP 2019). This means that adapting to the effects of climate change will be essential for a thriving, inclusive future. Literature on the relationship between circular economy strategies and climate change adaptation is still limited, but the following linkages are considered to be relevant:

Slow down nature degradation through reducing demand for virgin materials. Ninety percent of terrestrial biodiversity loss and water stress are caused by material resource extraction and processing (IRP 2019). Reducing the demand for virgin materials will decrease pressure on natural ecosystems, which might otherwise be damaged by extractive processes such as mining or industrial forestry and agriculture. This enables those natural areas to contribute to both climate mitigation (through carbon sequestration) and adaptation (through ecosystem services such as mangroves protecting against flooding or forests regulating temperatures), as well as safeguarding biodiversity, local heritage and land-based livelihoods.

Improve soil health through regenerative agriculture. Regenerative agricultural practices can prevent and revert the loss of healthy soil. For example, researchers found that organic amendments can improve overall soil carbon (Poulton et al. 2018). Increased carbon plays an important role in soil health, water holding capacity and nutrient cycling, which can increase resilience against both intense rainfall and drought.

Increase flood resilience through better waste management. Increased risk of severe flooding is one of the most widespread and damaging effects of climate change for human settlements. When urban drainage infrastructure is blocked by trash, water collects more quickly and drains more slowly. Plastic debris in rivers in particular causes a faster and denser blockage in waterways (compared to organic matter), creating additional flood risks for urban environments (Honingh et al. 2020). Through various circular economy strategies, waste can be reduced, collected, recycled or properly disposed of.

Relieve freshwater stress through circular water solutions. According to the IPCC Sixth Assessment Report (IPCC 2022), climate change will increase both wet and dry extremes and the general variability of the water cycle, bringing more intense rainfall and associated flooding as well as more intense drought in many regions. This affects the quality and amount of freshwater resources in regions already suffering from water stress. Circular water approaches can improve water efficiency, re-optimise, re-use and replenish aquifers, therefore ensuring the resilience of agricultural and industrial systems to climate change impacts. Examples of circular solutions for water, many of which are already applied in water scarce regions in the Global South, include a range of approaches ranging from micro-level solutions such as rainwater harvesting, dry toilets and eco-sanitation to alternative ways to manage wastewater and effluent from agriculture. Other more macro-level approaches such as green water infrastructures and landscape and wetland restoration are needed to rebuild ecosystems and make settlements more resilient against flooding and climate change (Schröder 2018).

Enhance local resilience through more circular value chains. Going beyond the physical/infrastructure side of adaptation, developing a circular economy could also play an important role in building community level and national level resilience to climate shocks and stresses. At a community level, the scale-up of the sharing economy could improve access to essential goods and services when needed. At the national scale, by increasing capacity for reuse, repair, refurbishment, switching to regenerative agriculture practices and use of local materials for production, countries can become more resilient to global supply chain shocks induced by increasingly volatile climate events.

5 From knowledge landscape to calls-to-action

Based on a review of prominent circular economy literature and extensive expert consultation, we find that there is broad, qualitative consensus in the current knowledge landscape that circular economy strategies can deliver clear, significant benefits for climate change management:

- Built environment, transport, food system and clean energy are the most relevant sectors for circular economy strategies to deliver climate change mitigation benefits.
- Circular economy strategies can complement decarbonisation measures to further reduce greenhouse gas emissions from material production, help lower emissions from operational energy use in the built environment and transport, and cut emissions from waste management.
- The largest potential greenhouse gas emissions reductions through circularity come from consumption-side measures (such as reducing floor area per capita, car-sharing/ride-sharing, and keeping products in use for longer) and "upstream" production-side measures (such as materials-efficient design of buildings and vehicles). For the food system, reducing food loss and waste has widely-recognised substantial climate benefits.
- Circular economy strategies can support a sustainable clean energy transition, by helping relieve the material supply pressure, increasing supply chain resilience, preventing new waste challenges, accelerating the adoption of clean energy technologies, and maximising their climate benefits.

There are also areas with debates, important attention points, or knowledge gaps:

- More quantitative consensus is needed on the magnitude and timeline of the climate benefits of circular economy strategies.
- To achieve net benefits for climate change mitigation, it is important to understand and balance potential trade-offs between materials-related and operational energy-related greenhouse gas emissions.
- Outcomes on the consumption side, including displacement rate and rebound effects, need to be better evaluated and managed for an absolute reduction in resource use and total emissions.
- Literature on the role of the circular economy in climate change adaptation is still very limited.
- Climate change is not the only lens to evaluate circular economy strategies. Other environmental and socio-economic impact categories (such as biodiversity, pollution, decent work and social equity) need to be considered to reach a balanced assessment.

In areas where clear potential benefits are agreed upon by the knowledge community, actions from government, business and civil society leaders are needed to turn the potential into real progress towards the climate goal. In areas with critical debates and knowledge gaps, actions from the research community are needed to advance the knowledge base to better inform practitioners. Building on this knowledge landscape, the following nine distinct yet related areas are identified for collective action:

1. **Shift consumption patterns**

There is clear consensus from the knowledge landscape that the highest greenhouse gas reduction potential of a circular approach will come from shifts in consumption patterns (in higher income populations), such as reducing floor space per capita, car-sharing or ride-sharing, and keeping clothes in use for longer.

Achieving consumption pattern shifts at scale will need a palette of levers, such as consumer information and education, service-based business models and policy nudges (Institute for Global Environmental Strategies et al. 2021). One powerful lever is (sub)urban planning, which can reduce needs for physical products while delivering the same function or wellbeing benefits through better system design. For example, design our cities better to become more adaptable to ever-shifting societal needs[20] and minimise the number of unused buildings, and roll out green public and active transport infrastructure to significantly reduce the need for private ownership of cars. We need to move beyond product-centric circularity towards better understanding of city-level circular approaches. Some municipalities and national governments have started to co-develop policy roadmaps to design for city-level circularity (Ellen MacArthur Foundation 2019b). Some examples can be found from the Circle Lab for Cities programme (ICLEI 2022).

Outcomes on the consumption side, whether as the result of efforts to shift consumption patterns or as consequences of other circular economy strategies, need to be better evaluated and managed for an absolute reduction in resource use and total emissions. Important examples here are displacement rate and rebound effects, where quantitative analysis is still quite limited and often not yet accounted for in impact assessment and policy decisions.

2. **Stimulate product circularity from the design phase**

Regardless of whether the magnitude or the time horizon of the climate benefit is considered, more attention needs to be given to stimulate product circularity from the design phase. As discussed in Section 2.2, materials-efficient design for the built environment and for transport is among the circular economy strategies with the highest greenhouse gas reduction potential. Since material efficient design reduces emissions at the very beginning of the product life cycle rather than at the end, it can be attractive from a time horizon point of view as well. Besides material efficient design, product design is also a key enabler for other circular economy strategies such as lifetime extension and recycling later in the product life cycle.

Since current market mechanisms are often insufficient to incentivise product design according to circularity principles, policy instruments can provide the much-needed stimulation. The European Commission has proposed Ecodesign for Sustainable Products Regulation[21] (European Commission 2022), which would further reinforce product design for durability, repairability and recyclability. For the built environment, policies and tools such as building codes and standards, construction material passports and assessments of buildings' circularity can be used to further stimulate materials-efficient design and the adoption of design and construction techniques that allow for full deconstruction and re-use of building components (reversible design) (Debacker and Manshoven 2016).

3. **Incorporate circularity across clean energy value chains**

Circular economy for clean energy value chains is a young yet increasingly active field. While encouraging progress has been made, a lot more still needs to be done. According to a recent literature review of the circular economy for lithium-ion batteries and solar panels (Heath et al. 2022), current efforts are overwhelmingly focused on recycling only. While significant efforts are indeed still needed to set up recycling in these value chains (including technology improvement, regulatory framework and market studies), the attention to other circular pathways such as reuse should increase, to fully capture the environmental and social benefits of circularity.

Businesses, governments, NGOs and researchers need to come together to define a common vision and collective actions to embed circular economy strategies in clean energy value chains, such as solar and wind power and electric vehicles. The material side of the clean energy transition needs to be properly managed from the beginning, to support their sustainable scale-up, and to avoid having to repair any unintended environmental and social negative consequences retrospectively.

4. **Integrate circular economy strategies into national climate policies and plans**

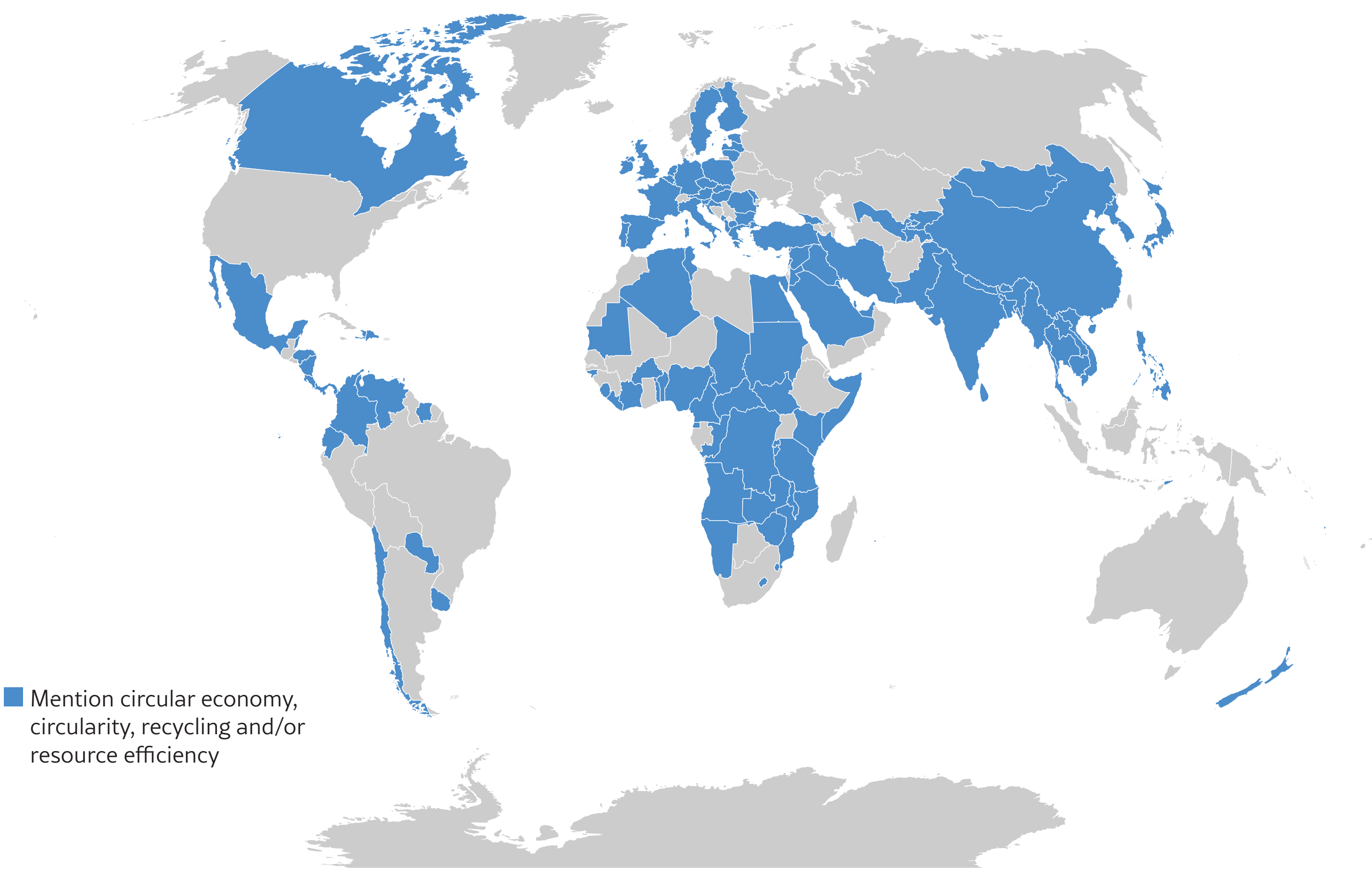
Circular economy strategies can enhance and complement existing sectoral climate targets and policies. There has been increasing momentum to call on policy makers to include circular economy approaches in national climate plans (UNDP-UNEP 2020; GIZ 2021; IPCC 2021; GACERE 2021). Germany, for instance, has integrated circular economy along with other strategies in their national greenhouse gas neutrality scenario analysis (UBA 2020). Using NDCs as a proxy to indicate the approaches considered by countries—with the notion that national climate policies are a lot broader than NDCs alone – the number of COP parties mentioning circular economy or equivalent strategies in their NDCs has substantially increased between 2015 and 2022 (see Figure 5). Nevertheless, most of these focus only on waste management. While waste management has an important role in greenhouse gas emissions reduction, more systemic and upstream circular economy strategies are needed to deliver higher greenhouse gas reduction potentials. Furthermore, some of the largest emitters have not yet considered circularity at all in their NDCs.[22]

Due to the circular economy's systemic and cross-sectoral nature, it is important to not only raise awareness, but also build capacity on how to integrate it with other climate strategies and adapt to country context in practice. GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) has proposed a generic process for countries to incorporate circular economy strategies into their domestic climate policies (GIZ 2021). UNDP, UNEP and UNFCCC have developed a guidance toolkit for policy makers to integrate circular economy and other sustainable production/consumption measures into their NDCs.

5. **Incentivise cross-border greenhouse gas emissions reduction**

Existing policy mechanisms for greenhouse gas reduction usually consider only emissions within national or regional borders. This siloed focus can have the unintended consequence of countries offshoring emissions by shifting carbon-intensive operations elsewhere. Furthermore, it provides little incentive to integrate circular economy into climate actions, since circular economy strategies reduce emissions in the value chain, which often extends beyond borders. In some cases, it even causes resistance to incorporating circular economy strategies which can reduce

Figure 5 | **COP parties with circular or equivalent strategies mentioned in NDCs based on 2022 data**



Source: This map was made using the keyword search functionality on WRI's Climate Watch. Keywords used: circular, recycling, resource efficient, and resource efficiency. Each mention of 'circular' was checked manually and only those that referenced a circular economy were included. Each mention was also scanned to determine whether systemic, upstream circular economy strategies are included. The NDCs that have not yet been added to Climate Watch were searched manually using the same methodology as above.

emissions at a global level, but may increase emissions locally. Therefore, to fully capture the circular economy's climate mitigation benefits, new accounting and policy mechanisms are needed to break siloes and incentivise measures that can cut emissions beyond country borders.

While several such mechanisms are under development, their use in practice is still very limited. **Consumption-based accounting (CBA)**—which counts the life cycle emissions of all the products consumed within a country (Tukker et al. 2020) – could be adopted alongside production-based accounting to inform cross-border emissions reduction measures in national climate policies. Reducing greenhouse gas emissions using CBA could incentivise importing countries to choose imports with lower carbon footprints to reduce their overall emissions, and exporting countries to reduce their materials-related emissions to make their export products more attractive (Afionis et al. 2017). More profoundly, it can encourage high-consumption countries to consider demand management strategies (such as through circular economy strategies) to reduce their carbon footprint. However, CBA's use is currently mostly limited to academia (e.g., SDSN et al. 2021),[23] because production-based accounting is simpler and provides more certainty. Similar to CBA but at a company level, **scope-3 emissions** include all the indirect, upstream and downstream emissions resulting from a company's practices, such as the emissions of the goods and services a company buys, or the emissions generated by their products (GHG Protocol 2013). While scope-3 emissions reporting is still voluntary, there is a small but growing movement towards greater adoption amongst companies. Besides accounting mechanisms, policy instruments such as **carbon tax** have also been proposed. The EU, for instance, has proposed a phased implementation of carbon border tax between 2023 and 2026, where importers will eventually buy carbon certificates corresponding to the carbon price that would have been paid for their production, had the goods been produced inside the EU (European Commission 2021b).

Each of the above accounting and policy mechanisms has its pros and cons, but a common challenge for all of them to work in practice is data availability. The fluctuating carbon content for essentially every traded good will need to be determined, which is not feasible with current data collection capacities and may be particularly challenging for industries with highly complex or fragmented supply chains (Patchell 2018; Russell 2019; Bacchus 2021). Nonetheless, starting to use consumption- and value chain-based carbon accounting is a crucial step towards greater international cooperation on reducing materials-related greenhouse gas emissions globally.

6. **Connect circular economy metrics with climate change impact**

Measuring circularity is a vibrant field that has seen significant development over the past few years, resulting in a large number of metrics and targets. Existing targets are often defined using individual company or country contexts, instead of being derived from desired global outcomes and impacts. While circularity can be and should be measured by a multitude of metrics, selecting the best ones and defining SMART[24] targets are crucial for guiding the transition to deliver optimal benefits for climate change, as well as other environmental and socio-economic impact categories.

This need has already drawn attention from various stakeholders and initiatives, including the European Commission, EUROSTAT, WBCSD and Circular Economy Indicator Coalition. Building upon progresses in modelling and other impact analyses, metrics developers and users will increasingly be able to work out a science-based approach to identify circularity metrics that are most relevant for climate change management and set targets accordingly. Such an approach could potentially be adapted to connect circularity metrics with other planetary boundaries.

7. **Increase transparency and comparability in modelling methodologies**

Although there is qualitative agreement on the benefits of circular economy for greenhouse gas emission reduction, the magnitude and timeframe of the benefits is debated due to differences in the scope of what is considered circular economy, the scope of greenhouse gas savings included, the assumptions and data used by different research groups.

Agreeing on the scope of the circular economy is an essential first step to reaching consensus on its environmental and socio-economic impacts. Progress is being made through e.g., the EU Taxonomy and ISO Technical Committee 323. Increased exchanges and collaborations within the research community are needed to work towards more comparable methodologies for modelling the greenhouse gas emission impact of circular economy strategies, including greater transparency on the assumptions and data used. Furthermore, since countries currently differ on the definition, collection and reporting of resource flow data (especially waste flows), greater harmonisation is needed to improve data availability, quality and comparability for aggregation.

8. **Apply systemic and context-specific impact assessment to inform decision-making**

Any complex, systemic change has many interlinkages, leading to both trade-offs and synergies. So does the circular economy. These trade-offs and synergies depend on many factors and are often context specific, where single-focused or "one size fits all" approaches are not suitable. Therefore, to achieve net climate benefits and avoid problem shifting, it is important to assess the potential outcome of a certain strategy by applying systemic and context-specific impact analysis (e.g., Life Cycle Assessment) to inform decision-making for policies and for businesses.

An example is the food system. A fundamental reason for the current debates around the climate impacts of regenerative agriculture is that the impact strongly depends on different geographic, cultural, climatic and economic contexts. Therefore, it may not be possible, or even desirable, to reach consensus on a common set of regenerative agriculture practices that should be promoted everywhere. Instead, there is an urgent need to invest in context-specific research in regenerative agricultural practices, followed by effective policies to promote their implementation.

9. **Investigate the role of the circular economy in climate change adaptation**

Current studies have mostly focused on the role of circular economy strategies in climate change mitigation. Enhancing adaptation to climate change is equally urgent, and requires an even broader set of environmental, economic and social strategies. A systematic transformation towards a circular economy can be an important part of that strategy set, creating co-benefits for people and nature. Yet the knowledge base is only in its infancy. We call for greater efforts from the knowledge community to investigate how circular economy strategies can best support climate change adaptation, from both environmental and socio-economic perspectives.

Conclusions

The knowledge base on circular economy for climate change mitigation and adaptation is relatively young but growing fast. Recent years have seen increasing awareness that tackling energy-related emissions alone is not sufficient to combat climate change, as well as increasing awareness that circularity is not the end goal but a means to achieve greater environmental and socio-economic impacts. This combined awareness has sparked a rapidly growing number of studies on the intersection between circular economy and climate change, from academia, NGOs, multilateral organisations and other research/advocacy groups.

Important consensus is emerging from the current knowledge base on where circularity can deliver big wins for climate change mitigation. The consensus clearly points out that measures affecting both production and consumption are needed. Although recycling has been, and will continue to be, an important circular economy strategy, the key to substantially reducing greenhouse gas emissions through circularity is in demand management. We need to deliver the same function or wellbeing benefits with fewer products and materials. Embracing circularity from the product design phase, as well as shifting consumption patterns (such as through applying circular thinking in city design), are crucial pathways to achieve this.

Stronger collaborations are needed to continue advancing the knowledge base and to better support the integration of circular economy strategies into climate change management: including between research groups, to compare and harmonise methodologies in estimating the benefits; between researchers and practitioners, to build better understanding on the practical timeline of the transition and its benefits; and between circular economy and climate/energy communities, to find out how circularity may best work with other existing climate change mitigation and adaptation strategies, to become an integrated part of the solution.

ACRONYMS

EIT	European Institute of Innovation and Technology
GACERE	Global Alliance on Circular Economy and Resource EfficiencyBEV battery-electric vehicle
GISTEMP	NASA Goddard's Global Surface Temperature Analysis
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IEA	International Energy Agency
IEA PVPS	International Energy Agency Photovoltaic Power Systems Programme
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRP	International Resource Panel
ISO	International Organization for Standardization
NDC	Nationally Determined Contributions
OECD	Organisation for Economic Co-operation and Development
PACE	Platform for Accelerating the Circular Economy
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WBCSD	World Business Council for Sustainable Development

ENDNOTES

1. Greenhouse gas emissions include not only carbon dioxide, but also other gases such as methane, nitrous oxide and fluorinated gases.

2. "Practitioners" refers to governments, businesses, philanthropies, NGOs and multilateral organisations.

3. This includes reports from International Resource Panel, Ellen MacArthur Foundation, Material Economics, and Circle Economy. These reports are frequently used as sources by other publications in the practitioner world on this subject.

4. For example, the United Nations defines circular economy as "one of the current sustainable economic models, in which products and materials are designed in such a way that they can be reused, remanufactured recycled or recovered and thus maintained in the economy for as long as possible, along with the resources of which they are made, and the generation of waste, especially hazardous waste, is avoided or minimised, and GHG emissions are prevented or reduced, can contribute significantly to sustainable consumption and production" (UNEA 2019); the European Union's Taxonomy Regulation defines circular economy as "an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption and thereby reducing the environmental impact of their use" (European Commission 2020); the Ellen MacArthur Foundation has laid out three circular economy principles—design out waste and pollution; keep products and materials in use; and regenerate natural systems.

5. Material resources are defined as biomass (crops for food, energy and bio-based materials, as well as wood for energy and industrial uses), fossil fuels (in particular coal, gas and oil for energy and industrial uses), metals (such as iron, aluminium and copper used in construction and electronics manufacturing) and non-metallic minerals (used for construction, notably sand, gravel and limestone) (IRP 2019).

6. Energy recovery from materials is not consistently included in circular economy literature.

7. This includes the full supply chain of all inputs and disposal phase of all outputs arising in these stages, also called "cradle-to-gate".

8. This includes both direct emissions from the industrial process, and the reallocation of emissions from electricity and heat used by the industry.

9. Only counting direct emissions from cement production.

10. By adding up the emissions from Figure 2.

11. Also often referred to as "embodied carbon".

12. Authors of this paper have extrapolated the 13Gt from the report (Circle Economy, 2021) by adding up the estimated greenhouse gas emissions saving from several interventions for housing: natural housing solutions, resource efficient construction, reducing floor space, increasing housing durability, and circular construction materials; and then subtracting their overlaps approximately.

13. Authors of this paper have extrapolated the 6.7Gt from the report (Circle Economy 2021) by adding up the estimated greenhouse gas emissions saving from several interventions for mobility: reduced travel, improving vehicle utilisation, circular vehicles, vehicle durability, and vehicle design improvements, and subtracting their overlaps approximately.

14. Ride-sharing means joining someone for (part of) a trip; car-sharing means collective ownership of a car but used individually. Both are different from "ride hailing", which is a taxi-like service.

15. Here only internal combustion engine vehicles are considered.

16. Authors of this paper have extrapolated the 4.4Gt from the report (Circle Economy 2021) by adding up the estimated greenhouse gas emissions saving from several interventions for nutrition: sustainable food production, reduction of excess consumption, healthy diet and clean cooking stoves, and subtracting their overlaps approximately.

17. In this paper, "Electronics" includes all types of electronic and electrical equipment as defined by the EU Waste Electrical and Electronic Equipment (WEEE) Directive. This specifically includes devices and equipment from six product categories: temperature exchange equipment, screens and monitors, lamps, large equipment, small equipment, and small IT (European Parliament and European Council 2012).

18. By "material substitution", the IRP 2020 report referred to replacing brick or concrete with timber. "Natural housing solutions" referred to green roofs, passive houses, and producing own renewable energy in the CGR 2021 report.

19. Circular economy and decarbonisation are not always considered distinct concepts. For example, renewable energy is included in many circular economy frameworks.

20. For example, the booming of e-commerce may reduce the need for retail buildings, the rising of work-from-home reduces the need for office spaces, demographic change leads to shifts in demand for residential buildings.

21. Once the proposal is adopted, an ecodesign and energy labelling working plan will carry out from 2022–2024.

22. The G7 countries have recently agreed in the Berlin Roadmap to leverage circular economy to step up their NDCs (G7 2022).

23. UK and Scotland publicly publish their consumption emissions every year. Although there are no legal targets yet associated with the reduction of the consumption-based emissions.

24. SMART stands for Specific, Measurable, Achievable, Relevant, and Time-Bound.

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Since 2018, PACE has become the global collaboration platform for key public and private decision makers to share a vision, best practices, and scale the circular economy together. Nearly 100 leaders from governments, companies and civil society, across continents and sectors, have joined PACE's Leadership Group to help accelerate the transition to a circular economy globally.

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