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Circular economy and the matter of integrated resources

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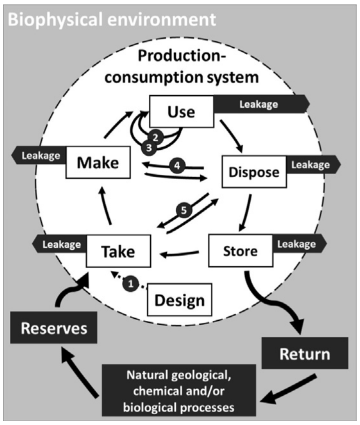
HIGHLIGHTS

- Circular economy has gained momentum in government and industry.
- ‘Butterfly diagram’ with separate biological and technical resource flows shapes action.
- But organic and inorganic elements are integrated in natural and engineered resource flows
- A new diagram for sustainable circular economy embedded in natural processes is proposed.
- This supports effective circular economy technologies, business models and policies.

GRAPHICAL ABSTRACT



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ABSTRACT

A circular economy offers solutions for global sustainability challenges through the transition from the linear take-make-use-dispose economy to a better organisation of resources. However, realising a circular economy has ran into various biophysical constraints. Circular economy implementation is shaped by the Ellen MacArthur Foundation's butterfly diagram that depicts ‘biological’ and ‘technical’ flows as separate cycles, subsequently interpreted as organic materials circulating in open loop systems via the environment and inorganic materials circulating in closed loop systems within society. Conversely, in our view, resource flows often contain tightly bound combinations of organic and inorganic materials either due to their natural composition or due to their technical design. Building on this observation, a new diagram is proposed that broadens the scope of the circular economy to cover extractive sectors and the return of materials from anthropogenic use to natural reserves, thereby reshaping the conceptual space within which solutions such as effective zero-waste-residue technologies, business models, and policies can be developed for the optimal management of integrated resources from a whole-system perspective. The diagram offers a realistic outlook on the biophysical limitations of circularity and endeavours to inspire discussion that supports the transition towards a sustainable circular economy.

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1. Circular economy

Between 1970 and 2010 global resource use has grown from 23.7 to 70.1 billion tonnes, driven by population and economic growth and changing consumption patterns (UNEP, 2016). The trend of accelerating natural resource exploitation, and simultaneously waste generation, is forecasted to continue (UNEP and ISWA, 2015; UN, 2018). Current global resource use, waste disposal and emissions led to critical levels of climate change and environmental degradation (IPCC, 2014; IRP, 2019; IPBES, 2019). For example, the extractive industries are responsible for half of global carbon emissions, resource extraction and processing resulted in 90% loss of biodiversity and water stress with more dangerous levels of impact on climate and natural life support systems than previously thought (IRP, 2019). Environmental decline driven by unsustainable resource management adversely impacts basic human rights such as the rights to life, food, water, self-determination and a safe, healthy and ecologically balanced environment while putting the stability of economies at risk (Rockström et al., 2009; UNEP, 2015; Raworth, 2017).

The circular economy has been proposed as a solution to minimise raw material input and waste generation. Circular economy is an umbrella-term for a wealth of ideas, contributing to its pluralist definition (Kirchherr et al., 2017), introduced here with the words of the leading Ellen MacArthur Foundation (2017): "*Looking beyond the current 'take, make and dispose' extractive industrial model, the circular economy is restorative and regenerative by design. Relying on system-wide innovation, it aims to redefine products and services to design waste out, while minimising negative impacts*". The preservation of technical, functional value (Iacovidou et al., 2017) of materials and products could be considered as an engine for the creation of economic, social and environmental net-benefits (Velenturf and Jopson, 2019).

Circular economy, however, is still an emerging subject area and while the potential of greater resource circularity to contribute to sustainable development has been widely recognised, the relations between the concepts of sustainability and circular economy, practical implementation and quantitative evidence of beneficial effects of circular economy practices on the triple bottom line in the economic, environmental and particularly the social domains are underexplored (D'Amato et al., 2017; Geissdoerfer et al., 2017; Koumparou, 2017; Velenturf and Purnell, 2017; Haas, 2019; Millar et al., 2019). The implementation of a circular economy encounters the biophysical limitations of circularity such as high energy requirements of resource recovery and resource quality losses (Brown and Buranakarn, 2003; Castro et al., 2007), continued demand for virgin resource extraction (UN, 2018), and resources containing organic and inorganic elements by nature or design. This article discusses these biophysical constraints (Sections 2–3) and endeavours to redefine the theoretical boundaries of a circular economy, the relation to the environment, and how resources can circulate within society and the environment (Section 4). The new perspective reshapes the conceptual space within which solutions for the transition towards a circular economy are developed and implemented, to enable effective technologies, business models and policies (Section 5).

2. Biological and technical flows

Current views on circular economy are shaped by the Ellen MacArthur Foundation's butterfly diagram, which separates 'biological' and 'technical' materials flows (EMF, 2017). 'Technical' materials are finite materials, used in a closed loop system through sharing, maintaining, reusing, remanufacturing, and recycling of products. Conversely, biological materials are renewable and organised in an open loop system of resources cascading through subsequent steps of extraction, production of bio-based materials, energy recovery, and returning nutrients to the biosphere to feed the next cycle of primary produce.

This diagram has grasped the imagination of people in business and political circles alike, helping to put circular economy firmly on the agenda (UN Global Compact and Accenture, 2014; EU, 2015). It has influenced strategies and structures for funding and investment, e.g. the EU Circular Economy Package (2015) building on EMF (2015). The direct depiction of its biological wing for the bioeconomy by Carrez and van Leeuwen (2016) informed the position of the Bio-Based Industries Consortium (2015) in response to the EU Circular Economy package. The diagram suggests the belief of a perfect natural environment where waste does not exist (biological wing) and that people are separate from nature and live in a wasteful technosphere (technical wing); rather than fully embracing the notion of ecosystem stewardship in which people are an integral part of the environment (Velenturf and Purnell, 2017).

Aside from the question whether people are part of nature or not (Schouten, 2007), there are various issues with the diagram. A fully closed loop economy is unlikely due to unavoidable losses of material quality in consecutive cycles and the energy requirements of resource recovery processes (Brown and Buranakarn, 2003; Castro et al., 2007). Circulating more materials within the economy will cost more energy input and a balance must be struck or else, at a whole system-level, net-negative impacts on the environment will accrue. Moreover, significant natural reserves are forecasted to be exploited for the growing global economy (UN, 2018; EU, 2015), including those required for sustainable developments such as renewable energy which are considered a core building block of a circular economy (Vidal et al., 2013; EMF, 2017; EU, 2018). For example, the manufacturing of electric vehicles and wind turbines requires a step-change in the supply of rare-earth metals such as neodymium (Dawson et al., 2014; EU, 2018; Fishman and Graedel, 2019). Brushing aside these forecasts of accelerating natural resource exploitation even within a circular economy, the extractive sectors and initial processing of materials are largely excluded from the butterfly diagram (Velenturf et al., 2019). These sectors are the largest waste producers and energy-consumers in the production-consumption system (Haas et al., 2015; Circle Economy, 2019) and circular economy thinking could offer significant benefits here to minimise oft-neglected environmental and social externalities. Rare-earth mining, for example, causes poorly quantified environmental and social impacts (McLellan et al., 2014). Finally, materials tend to be heterogeneous when extracted from the environment and/or transformed during production, consumption, and disposal i.e. materials and products are usually made of more than one type of resource; this article will delve further into this observation.

3. Organic and inorganic elements are integrated in resources

Large proportions of material flows contain composites and mixtures of organic (such as agricultural produce) and inorganic (such as metals) elements[1] that are technically difficult and costly to separate. Composites and mixtures occur in the environment naturally, for example in the form of most sedimentary rocks (conglomerate and aggregate), mineral and metal ores, soils and living organisms. Materials can also be designed, consciously or subconsciously, to become integrated during extraction, production, consumption and disposal. Examples are acid/metal mine drainage, precious metal wastes (e.g. road dust and furnace linings), steel slag, car components, paint, sewage water and bioenergy residues (e.g. ashes and digestate).

The butterfly diagram is based on cradle-to-cradle thinking by Braungart and McDonough (2009). They distinguished biological and

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[1] "Organic" means minimally-processed materials of biological origin that can be recirculated within the environment via naturally-occurring geo-biological processes within reasonable timescales, whereas "inorganic" means technical materials normally derived from mineral or petro-chemical sources and processed such that their recirculation within the environment is slow and potentially damaging to ecosystem services. By this definition, for example, polymers and hydrocarbon solvents (considered chemically as organic materials) would be considered inorganic.

technical nutrients, initially defined as materials required by the biosphere and the technosphere (system of industrial processes) respectively. Biologically available nutrients can be organic or inorganic and are described as materials or products "*designed to return to the biological cycle by being consumed by micro-organisms in the soil and by other animals*" (p. 105, Braungart and McDonough, 2009). Technical nutrients are designed to stay within the technosphere only, but there is "*a confusion of flows*" in which materials that can be harmful to the environment (e.g. metal and mineral-based products) enter organic matter and water flows. Despite this, Braungart and McDonough argue to strive to keep flows separate, as indicated in the butterfly diagram. In this diagram, the biosphere wing is depicted as the source of organic resources, omitting the role of the biophysical environment in (re-)circulating other materials that are essential for society (e.g. water, aggregates, minerals, and metals). As indicated above, the bioeconomy community continued to build on this image and adopted the biosphere wing as being the 'bioeconomy' part of the circular economy (e.g. Carrez and van Leeuwen, 2016; Karagouni, 2018). Based on the prevalence of naturally occurring and designed material composites and mixtures, the consideration of separate flows of organic and inorganic is inappropriate, as noted by others (e.g. Carus and Dammer, 2018). The initial starting point of Braungart and McDonough, distinguishing flows of materials within our industrial system and to and from the wider environment, may be a more fruitful one to visualise the circular economy anew.

4. A new perspective on circular economy

4.1. Introducing a new diagram

Continuing the line of thought on visualising types of circular economy that was initiated by others such as Stahel and Reday (1981), Braungart and McDonough (2009), EMF (2017) and Carus and Dammer (2018), here a new diagram for a circular economy is proposed based on integrated materials (consisting of mixed organic and inorganic materials) flowing through the biophysical environment and the production-consumption system, thereby revisiting the relationship with the environment and the theoretical boundaries of a circular economy. Note the following aspects of the new perspective (Fig. 1):

- The production-consumption system that is made and controlled by people is embedded in the wider biophysical environment that, although not controlled by human activity, may be influenced thereby. Both production-consumption systems and biophysical environments form context specific conditions that may vary between different parts of the world and actions to implement circular economy may have to be tailored to local conditions (Jensen et al., 2011; Velenturf and Jensen, 2016; Taddeo et al., 2017) yet optimised from a whole-system perspective (Millward-Hopkins et al., 2018).

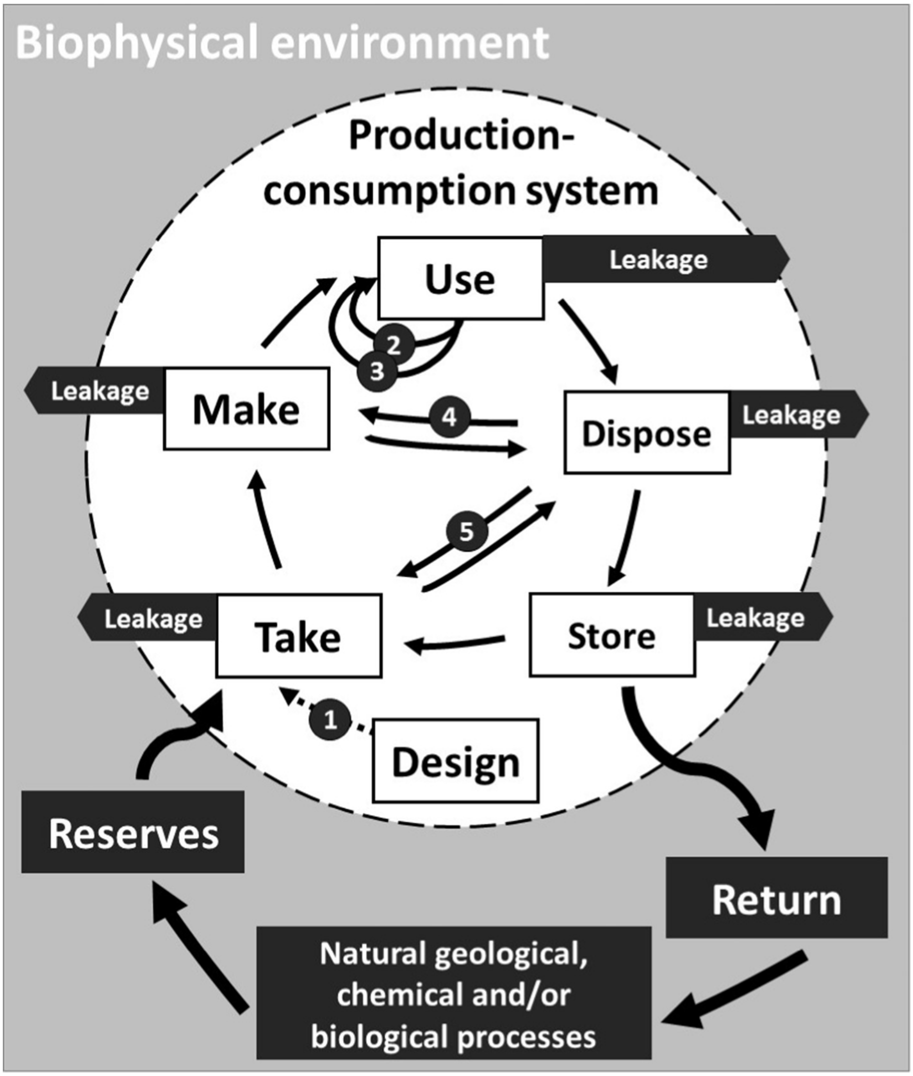

Fig. 1. Integrated resource flow diagram for the circular economy (legend: Thick arrows are natural materials, thin arrows are industrial materials, dotted arrow is immaterial; [1] prevention by designing out all avoidable wastes, [2] shared consumption, [3] reuse and repair, [4] remanufacturing, [5] recycling).

- People take natural materials (thick arrows in Fig. 1) from reserves in the uncontrolled environment and turn them into industrial materials (narrow arrows), which are used within the production-consumption system. The terminology initiated by the cradle-to-cradle philosophy of biological and technical materials is to be replaced by natural and industrial materials:
    - o Industrial materials are transformed in the production-consumption system and would ideally be engineered in ways such that if their useful life is over they can be reintegrated via natural processes and without negative environmental consequences into the uncontrolled biophysical environment.
    - o Natural materials reside in the wider biophysical environment that is not directly controlled by people, they may be of natural or engineered origin and take part in naturally occurring geological, chemical and biological processes without causing environmental harm.
    - o Natural and industrial materials can include organic or inorganic materials or, more likely, a mix thereof (as discussed in Section 3).

- Ideally, production-consumption systems would be designed with a sustainable circular economy in mind, thereby prioritising the crucial design stage of products. Arguably, it is the design that determines 80% of environmental impacts and benefits of products in their entire lifecycle (Aldersgate Group, 2017). It is at this stage that avoidable wastes can be designed out of the economy (Iacovidou et al., 2018). Design is [1] in Fig. 1, followed by promoting shared consumption [2], reuse and repair [3], remanufacturing [4] and recycling [5]. This will increase resource productivity per functional unit and could support the generation of net-positive environmental and social impacts through resource use.
- Products and/or materials that cannot be recycled at end-of-use within the production-consumption system, for example due to a lack of suitable waste management infrastructure (Purnell, 2017), should be redesigned to eradicate all avoidable waste (Walport and Boyd, 2017); for the time that such materials and products do persist, energy recovery or storage in a controlled environment have to be considered.
- Products and materials that are already, and in the future may have to be, stored in a controlled environment can be subjected to resource recovery solutions that are engineered to mimic and accelerate processes found in natural systems to recover materials and leave no other materials than those that can be used by industry and/or safely returned to the uncontrolled biophysical environment (examples of such resource recovery systems are described in Section 5).
- Uncontrolled leakage of industrial materials into the environment in the form of pollution (from litter to run-off of liquids and other emissions) should be managed holistically and stopped when possible. Designing environmentally damaging leakage out of the system is challenging and costly but technically practicable in new build infrastructure (EU, 2015b), especially when combined with a better design of the production-consumption system and the materials, products and processes therein.
- Industrial materials that are no longer required for production should be safely returned to the biophysical environment that is not directly controlled by human activity (grey area in Fig. 1), surrendering materials to natural geological, chemical and biological processes and reintegrating them into natural capital reserves that can feed future production-consumption cycles.

4.2. The new perspective in action: an example from the steel industry

This section demonstrates how a material could flow through the lifecycle stages included in Fig. 1 with an example from the steel industry. Iron ore, a natural material, is extracted from natural reserves and turned into iron, an industrial material, and crosses the boundary from the biophysical environment and enters the production-consumption system (in Fig. 1 flowing from natural reserves to take). Low grade iron ores and mining wastes could be subjected to bio-mining technologies to recover metals such as cobalt, copper and zinc (Falagan et al., 2017); such operations should be planned in balance with the ecological, geological, educational and cultural values of former mining sites (Sinnett, 2019). Early results show that stimulating indigenous iron-reducing microbial communities combined with leaching technologies has potential to recover zinc and copper while reducing pollution (Roberts et al., 2017). This would create a reciprocal step between take and dispose, and could eventually result in safely surrendering remaining materials, such as soils, to natural biogeochemical processes (as indicated in Fig. 1).

Iron is transformed into various types of steel and steel products such as towers for wind turbines (from take to make), and in this step wastes and by-products are produced. For example, dust collected in air pollution control systems, i.e. preventing leakage of environmentally damaging substances into the air, could be treated with electro-kinetic processes to recover materials such as zinc and lead (Peppicelli et al., 2018) and possibly make recycling of iron back into steel making processes possible (Sapsford et al., 2017) – enabling flows from dispose back to take and make. Blast furnace slag (iron slag) is a by-product used as aggregate material in for example road surfaces and concrete building materials, moving from make to use in Fig. 1, resulting in carbon and cost savings across industries (Deutz et al., 2017; Millward-Hopkins et al., 2018). Basic oxygen furnace slag (steel slag), on the other hand, is considered a waste that legally has to be stored ca. six months for weathering ahead of further processing (Deutz et al., 2017) and, moving from dispose to store in the diagram, is kept in bulk volumes in industrial landfills where it can impact on the surrounding aqueous environment for 50–80 years and possibly longer due to leakage (Riley and Mayes, 2015). However, steel slag can be a source of materials that are critical for low-carbon technologies and infrastructure (Marshall et al., 2018a). For example, rather than allowing a substance like vanadium to dissipate into the environment (Hobson et al., 2017), it could be recovered with the use of organic matter e.g. from municipal solid waste, bioleaching, and ion exchange resins (Gomes et al., 2017, 2018) and subsequently used for the production of light-weight steel used in wind turbine towers and electric vehicles or in the next generation of energy storage technologies (Deutz et al., 2017) – enabling a partial flow from store to take and make, and returning the remainder to the environment in the form of remediated soils. A country like the UK with ambitious plans for clean low-carbon growth could potentially source the majority of the critical material vanadium that it requires from steel slag stored in legacy industrial landfills (Marshall et al., 2018a, 2018b; BEIS Clean Growth Strategy, EU, 2018), with the added environmental benefits of limiting pollution and enabling atmospheric carbon sequestration – limiting and reversing leakage respectively (Mayes et al., 2018).

Demand for steel in the renewable energy sector is forecasted to grow exponentially. Globally, solar and wind power are expected to grow from ca. 400 TWh in 2012 to 25,000 TWh in 2050, accompanied with a demand of 3200 million tonnes of steel (Vidal et al., 2013). Given the anticipated net-growth of the renewable energy sector, it is unlikely that circular economy approaches such as reuse, remanufacturing and recycling can initially curb demand for input of materials from outside the sector for the foreseeable future (Dominish et al., 2019), although steel from other sectors such as oil & gas platforms could possibly be recycled for the manufacturing of renewables infrastructure. Renewable energy infrastructure, nevertheless, should be ‘designed for circularity’. For example, a wind turbine tower should be designed for durability, balanced with design that enables repair, reuse, remanufacturing and recycling (Purnell et al., 2018).

5. Benefits of the integrated materials perspective

The integrated perspective on materials (Fig. 1) creates a new conceptual space for the development and implementation of effective technologies, business models, and policy for a sustainable circular economy.

The multicomponent nature of current waste materials (organic/inorganic) requires new resource recovery systems, ideally targeting several components to avoid value dissipation. Also, they should be associated with low and efficient energy inputs. This is a direct requirement for achieving an affordable price in the process of recovering materials, sometimes occurring in low concentrations (e.g. Cu in bioenergy residues), from complex tightly bound matrices which currently require high energy input. Technologies that can recover organic and inorganic fractions simultaneously through systems that aim for zero waste residue and that require low external energy input are under development, such as:

- Microbial electrochemical systems, which can be made from 'waste' materials themselves, to recover organic compounds, metals, chemicals and clean water (Sadhukhan et al., 2016; Christgen et al., 2015).
- Biorefineries that incorporate microbially-mediated metal recovery approaches to produce new catalysts from liquid wastes, for the production of liquid and gaseous fuels in addition to generating electricity from bio-hydrogen via fuel cell catalysts (Macaskie et al., 2017; Murray et al., 2017).
- As discussed in Section 4.2, vanadium recovery from steel slag and red mud leachates using ion exchange resins (Gomes et al., 2016, 2017), and metal recovery from steel slag using bioleaching (Gomes et al., 2018).
- In-situ resource recovery from mining and other industrial wastes through increased microbial activity and the use of engineered nanoparticles for the targeted mobilisation of metals (such as copper, arsenic, iron, and lead), thereby simultaneously cleaning soils and water flows (Sapsford et al., 2017; Crane and Sapsford, 2018).
- Bioenergy generation from anaerobic digestion and thermal transformation yield by-products (digestate and biomass ash), which present essential components for the plant-soil system functioning (e.g. N, P, organic matter). These residues can be used to prepare blends for application to land as fertiliser and/or soil improver (Riding et al., 2015; Semple et al., 2017).

New resource recovery systems must be accompanied by innovative business models that enable the creation, supply and capturing of values from circular supply chains. Circular business models (CBMs) are a rapidly developing subject area with several research gaps including CBMs for companies active in primary sectors and early stages of materials (re)processing, and tools and approaches for the increasing inclusion of multi-dimensional values across environmental, social, technical and economic domains into business models (Bocken et al., 2014; Bocken and Van Bogaert, 2016; Iacovidou et al., 2017; Agrimax, 2017). One recurring issue in the up-scaling of new resource recovery technologies is the commercial viability (Pant et al., 2011; Bajracharya et al., 2016; Gomes et al., 2019). This is often because the assessment of commercialisation-potential hinges on the sales of one or few of the recovered materials (e.g. a metal), rather than considering the full range of recovered materials (e.g. including cleaned aggregate/soil) as well as the additional social and environmental values that are created (e.g. including reduced pollution, carbon capture and amenity value of remediated land). New approaches are required to identify and incorporate such values into CBMs. This has to be supported by an understanding of how environmental, social, economic and technical values are created, transformed, preserved and lost throughout supply chains such as analysed by the Complex Value Optimisation for Resource Recovery approach (Iacovidou et al., 2017). This approach might be suitable to formulate and update CBMs (Agrimax, 2017), as well as for the development of policies (Marshall et al., 2018a, 2018b).

Implementing a circular economy drives change in diverse areas of government, such as environment, industrial strategy, economic growth, infrastructure, communities, international trade and defence. A major challenge in realising circular practices is the limited coordination and policy integration between government departments and their policies and regulations (Velenturf et al., 2018) resulting in, for example, missed opportunities in terms of low-carbon growth through greater resource efficiency (Green Alliance, 2018). Additionally, it is common governance practice to steer by material type and/or sector, with organic resources being covered by a separate bioeconomy strategy and each energy intensive sector having its own decarbonisation and resource efficiency plan by one department, resource strategy and food waste and plastics being singled out as priority issues by another department, etc. (BEIS, 2017; BEIS, 2018; DEFRA, 2018). Supply chains in a circular economy connect different sectors and an additional intersectoral strategy and business support programme, recognising that resources can be mixed and flow between sectors, would have great potential to accelerate the transition towards greater circularity (Marshall et al., 2018a, 2018b; Purnell et al., 2019).

6. Conclusion

The proposed diagram (Fig. 1) broadens the scope of the circular economy and reshapes the conceptual space within which solutions can be developed for the optimal management of integrated resources from a whole-system perspective. Circular economy has established itself as an academic subject and generated an optimistic wave of action in government, industry and across society. Concerns are raised, however, that the outcomes of these actions may not bring the aspired economic, social and environmental net-gains. To maintain the positive momentum, in the immediate future it is important to critically engage with the ability of circular economy approaches to contribute to sustainable development from a position of practical idealism where theory and implementation meet. The perspective presented herein offers a realistic outlook on the biophysical limitations of circularity and endeavours to inspire discussion that supports the transition towards a sustainable circular economy.

Author contributions statement

Article concept, complete draft and finalising (AV), contributions to technological and material science details and general edits (SA, HG, BC, ALB, PP).

Declaration of Competing Interest

The authors have no conflicts of interests to declare.

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