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Circular Economy: The Concept and its Limitations

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ABSTRACT

Circular economy (CE) is currently a popular concept promoted by the EU, by several national governments and by many businesses around the world. However, the scientific and research content of the CE concept is superficial and unorganized. CE seems to be a collection of vague and separate ideas from several fields and semi-scientific concepts. The objective of this article is to contribute to the scientific research on CE. First, we will define the concept of CE from the perspective of WCED sustainable development and sustainability science. Second, we will conduct a critical analysis of the concept from the perspective of environmental sustainability. The analysis identifies six challenges, for example those of thermodynamics and system boundaries, that need to be resolved for CE to be able to contribute to global net sustainability. These six challenges also serve as research themes and objectives for scholars interested in making progress in sustainable development through the usage of circular economy. CE is important for its power to attract both the business community and policy-making community to sustainability work, but it needs scientific research to secure that the actual environmental impacts of CE work toward sustainability.

1. Introduction

Circular economy (CE) is a concept currently promoted by the EU, by several national governments including China, Japan, UK, France, Canada, The Netherlands, Sweden and Finland as well as by several businesses around the world. The European Commission recently estimated that circular economy-type economic transitions can create 600 billion euros annual economic gains for the EU manufacturing sector alone (COM, 2014; EMAF, 2013; see also CIRAIG, 2015 and COM, 2015). Finland's Independence Celebration Fund (FICF, SITRA) and Mckinsey (2014) jointly estimate 2.5 billion euros annual gains for the national economy of Finland through circular economy. The global economy would benefit 1000 billion US dollars annually (FICF and Mckinsey, 2014; see e.g. EMAF, 2013). China, as the first country in the world, adopted a law for the circular economy in 2008 (CIRAIG, 2015). Circular economy is recommended as an approach to economic growth that is in line with sustainable environmental and economic development (see EMAF et al., 2015; EMAF, 2013; EMAF, 2012; CIRAIG, 2015; COM, 2015; COM, 2014).

The current and traditional linear extract-produce-use-dump material and energy flow model of the modern economic system is unsustainable (Frosch and Gallopoulos, 1989). Circular economy provides the economic system with an alternative flow model, one that is cyclical (see EMAF et al., 2015; EMAF, 2013; EMAF, 2012; CIRAIG, 2015). The idea of materials cycles has been around since the dawn of industrialization. The idea has also been practiced accompanied by the argument that it reduces negative environmental impacts and stimulates new business opportunities already during the birth of the industrialization (Desrochers, 2004; Desrochers, 2002). But the linear throughput flow model has dominated the overall development causing serious environmental harm. Unlike traditional recycling the practical policy and business orientated circular economy (hereafter CE) approach emphasizes product, component and material reuse, remanufacturing, refurbishment, repair, cascading and upgrading as well as solar, wind, biomass and waste-derived energy utilization throughout the product value chain and cradle-to-cradle life cycle (EMAF, 2013; Rashid et al., 2013; Mihelcic et al., 2003; Braungart et al., 2007).

However, the concept of CE and its practice have almost exclusively been developed and led by practitioners, i.e., policy-makers, businesses, business consultants, business associations, business foundations etc. (see e.g. EMAF, 2013; COM, 2014; CIRAIG, 2015). The scientific research content of CE remains largely unexplored. Ecological economics may be the most fruitful source from which the new practical, policy and business orientated concept of CE could find scientific and theoretical support and guidance. Ecological economics has a long tradition in recycling and other CE-type concepts on the macroeconomic level although not presented under the CE term. Also on the microeconomic level, CE-type papers have been published in ecological economics, e.g.

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addressing eco-efficiency (Huppes and Ishikawa, 2009) or industrial ecology (Kenneth Korhonen and Snäkin, 2005). Nicholas Georgescu-Roegen (1971), Boulding (1966), Herman Daly (1996) and Robert Ayres (1999; see also Moriguchi, 2007) among others have debated the macroeconomic potential in cyclical material flows or the so called "fourth law" coined by Georgescu-Roegen (hereafter GR).

This paper has two research objectives. They are motivated by the fact that the scientific research content of the currently popularized business community originated circular economy concept remains superficial and lacks critical analysis. First, we will construct the concept of CE from the perspective of WCED sustainable development and sustainability science including the three dimensions of economic, environmental and social sustainability. Second, we will analyze the CE concept from the perspective of environmental sustainability. In the analysis, we will identify six challenges that need to be resolved for CE to be able to contribute to global net sustainability. These six challenges also serve as research themes and objectives for scholars interested in making progress in sustainable development through circular economy. Although the definition we will present for CE includes the economic, environmental and social dimensions of sustainability, we will leave the further analysis of economic and social dimensions for future work. In other words, it is beyond the scope of this paper to more thoroughly analyze economic and social sustainability in light of CE. The basic idea of the paper is to provide the reader with an initial attempt for conducting critical research analysis of CE.

The next section will consider the existing CE concept definition. After this, we attempt to produce a more scientific definition for CE from the perspective of sustainability science. The fourth section identifies six limitations of CE when analyzed against environmental sustainability that we perceive as fruitful research objectives for CE scholars. Conclusions are made in the fifth section.

2. Background: On the Current Concept of Circular Economy

2.1. The Main Challenge

In this section the new business community popularized concept of circular economy is considered from the perspective of the concept of and scientific research on sustainable development. In particular, sustainability science (Kates et al., 2001; Rockström et al., 2009; Broman et al., 2017; Broman and Robért, 2017; Robért et al., 2013) and the WCED (1987) three-dimensional concept of sustainable development are used as the main philosophy of the approach adopted in our discussion. Sustainable development (WCED, 1987) was originally defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. There exists a common consensus on this broad qualitative definition. It is beyond the scope of this paper to contest or discuss various diverging perspectives on this basic definition of sustainable development or sustainability science. The planetary boundaries of Rockström et al. (2009) are also widely accepted as the direction of environmentally sustainable global development (see, e.g. Robért et al., 2013).

In Fig. 1, the main challenge of sustainable development is depicted from the perspective of physical flows of materials and energy. The key issue in global sustainable development is the linear (one way) throughput flow of materials and energy between nature and human economy. The throughput flow is "running down" the system in which it operates, from which it sources and to which it releases its wastes and emissions. Brown (2006) shows that the global ecosystem is becoming smaller. The global natural ecosystem is shrinking in size and volume. The shrinking is clear if measured simply in quantitative terms, but very apparent also in the sense of the qualitative potential of the earth's ecosystems to provide life-sustaining functions. Measured by the land area that can support human habitation, the earth is shrinking, and at an accelerating pace. Deserts are expanding, the sea level is rising, the population is growing, per capita consumption is increasing,

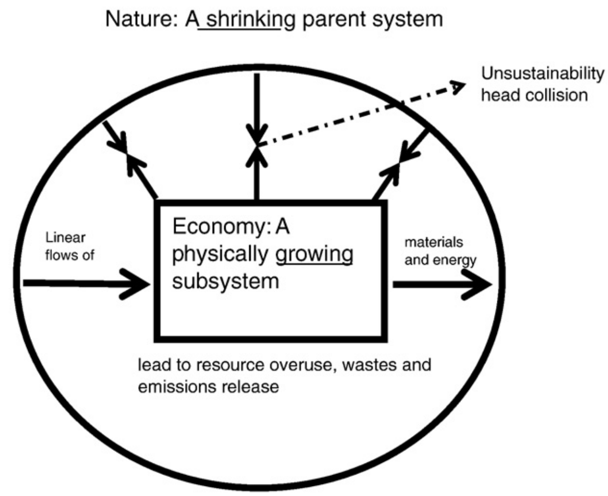

Fig. 1. Linear materials and energy flow in the shrinking world. Linear (one way) throughput flow of matter and energy resulting in the current unsustainable development of the global economy. The economic subsystem operating within the parent ecosystem uses physical flows of materials and energy in a linear fashion. Resources and energy are extracted from the parent system, produced and consumed within the human economic subsystem and wastes and emissions are dumped back to nature in harmful concentrations. The life supporting parent ecosystem that used to be fixed/constant in its size is now shrinking in terms of physical scale. Deserts are expanding and sea level is rising reducing the life-supporting physical scale of nature. As the human economic subsystem is growing, development is encountering a head-collision. Overwhelming scientific evidence shows that the linear flow is unsustainable in terms of all the three dimensions of sustainable development; economic, ecological and social.

the volume of livestock and cattle is growing and biodiversity is depleting at ever faster rates. The shrinking is best illustrated by advancing deserts and rising sea levels that work inwards in Fig. 1 toward the economic system, which in, turn is expanding outwards. This process is leading to a head-collision.

A simple and logical answer to the problem of the linear flow model is its reverse; a cyclical flow of materials and energy. Although, by definition, energy cannot be recycled, only cascaded for extended use on lower temperature and pressure levels, one can speak about materials and energy cycling for the purpose of simplification.

2.2. The Currently Proposed Circular Economy Solution

The answer to the question of unsustainable global linear flow economy would seem to come from the physical flow concept in which the flows are reverse; the concept of circular economy. In this paper, the CE concept is considered in scientific terms. The CE vision is here constructed from the viewpoint of the WCED definition of sustainable development and from the perspective of planetary boundaries on environmental sustainability (Rockström et al., 2009; Robért et al., 2013).

The current practitioner and business world formulated CE concept is given in Fig. 2. The CE message is that the inner circles of Fig. 2, product reuse, remanufacturing and refurbishment, demand less resources and energy and are more economic as well than conventional recycling of materials as low-grade raw materials. The time the value in the resources spends/lives within the inner circles should be maximized. Materials should first be recovered for reuse, refurbishment and repair, then for remanufacturing and only later for raw material utilization, which has been the main focus in traditional recycling. According to CE, combustion for energy should be the second to last option while landfill disposal is the last option. In this way, the product value chain and life cycle retain the highest possible value and quality as long as possible and is also as energy efficient as it can be.

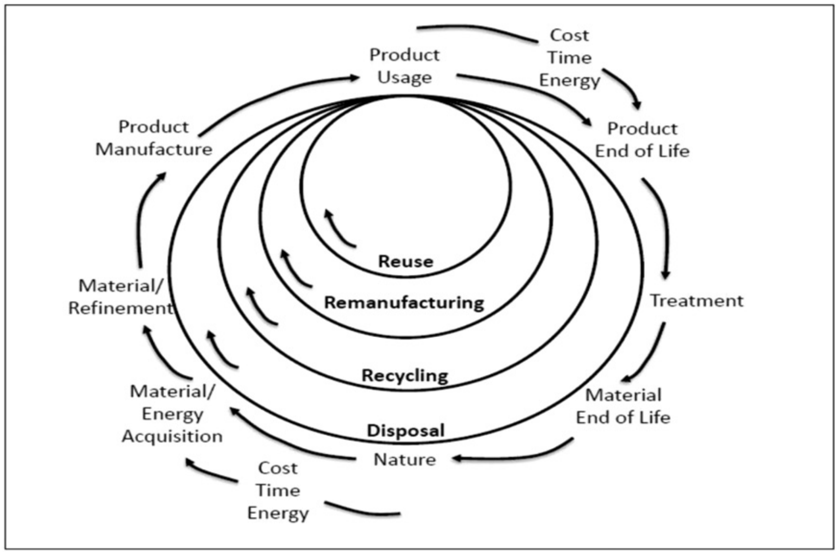

Fig. 2. The current concept of circular economy (for the graph, see Mihelcic et al., 2003). The CE message is that the inner circles demand less resources and energy and are more economic as well. The time the value in the resources spends within the inner circles should be maximized.

Once a raw material is extracted, refined and produced with the usual costs, it makes economic and business sense to use the value produced as long as possible, i.e., keep the product function/service and use-value in economic circulation as long as possible. This often results in environmental gains as well when compared with traditional linear extract-produce-use-dump material and energy flow model of the modern global economic system. The currently popularized CE concept extends conventional waste and by-product utilization and recycling by emphasizing the utilization of the value embedded in materials in as high value applications as possible (see e.g. Asif et al., 2016; Rashid et al., 2013; Mihelcic et al., 2003). It adds to traditional recycling, which usually recycles materials as raw materials, i.e., in applications where much of the economic value of the product has already been lost.

3. Circular Economy for Sustainable Development: Toward a New Scientific Definition

CE concept is loosely based on a fragmented collection of ideas derived from some scientific fields including emerging fields and semi-scientific concepts. These sources cover, for example, industrial ecology (Frosch and Gallopoulos, 1989; Graedel, 1996; Lifset and Graedel, 2001), industrial ecosystems (Jelinski et al., 1992) and industrial symbioses (Chertow and Ehrenfeld, 2012), cleaner production (Stevenson and Evans, 2004) including reviews on manufacturing systems' circular materials flows and developments to that end (Lieder and Rashid, 2016), product-service systems (Tukker, 2015), eco-efficiency (Huppes and Ishikawa, 2009; Welford, 1998a; Haas et al., 2015.), cradle-to-cradle design (Braungart et al., 2007; Braungart and McDonough, 2002; McDonough and Braungart, 2003), biomimicry (Benyus, 1997; Benyus, 2003), resilience of social-ecological systems (Folke, 2006; Crépin et al., 2012), the performance economy (Stahel, 2010; Stahel, 2006; EMAF, 2013), natural capitalism (Hawken et al., 2008), the concept of zero emissions (Pauli, 2010) and others.

While some of these approaches have made important sustainability science contributions, the connection to the current popular concept of CE is unclear and difficult to comprehend. The scientific research on this link is practically non-existent. Ecological economics is an established scientific field and has a long tradition in recycling and its related issues (Georgescu-Roegen, 1971; Daly, 1996; Ring, 1997; Ayres, 1999). Ecological economics seems to be the proper place to start the scientific groundwork on CE.

Perhaps the most influential background concepts of CE have been the business actors created cradle-to-cradle concept of "eco-effectiveness" (Braungart et al., 2007; Braungart and McDonough, 2002; EMAF, 2013; CIRAIG, 2015) and the industrial ecology concept (Graedel, 1996; Frosch and Gallopoulos, 1989) including the industrial ecosystem vision of "inter-system ecology" (Korhonen, 2001). In these highly idealized visions, e.g. those of eco-effectiveness, economic systems and natural systems are positively recoupled into a one system, which relies 100% on renewable energy and recycles all the materials. This ideal of a single cyclic system, while desirable, is not realistic. In the world, approximately 75% of the energy production is based on non-renewable sources extracted from the lithosphere that are combusted. The combustion releases emissions to biosphere in forms and concentrations that nature cannot tolerate or assimilate. This is the most obvious example of the linear throughout economy and the best example of the limits of the current CE visions.

This paper adopts a critical scientific approach to the new business concept of CE. By critically considering the concept of CE from the perspective of sustainable development and its three dimensions, economic, environmental and social, we suggest the following new definition for CE (Fig. 3):

> Circular economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading[1]-type energy flows. Successful circular economy contributes to all the three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates.

CE should utilize nature's cycles for preserving materials, energy and nutrients for economic use. The material flows released from economy

[1] It would be easier to refer to "energy cycles" or "recycling of energy". However, in physics, energy cannot be recycled. Therefore, the utilization of lower pressure and temperature levels of energy in cascades is the scientifically accurate expression. A good example very relevant for the global climate change mitigation efforts is co-production of heat and power (CHP) in which the waste/residual heat from electricity generation is used for district heat and industrial process steam generation or for horticulture etc. Only three countries in the world, Denmark, The Netherlands and Finland have organized their national energy supply systems to a large extent into CHP. Fuel efficiencies in CHP can achieve 90% while in conventional condensing power the efficiencies are around 40%.

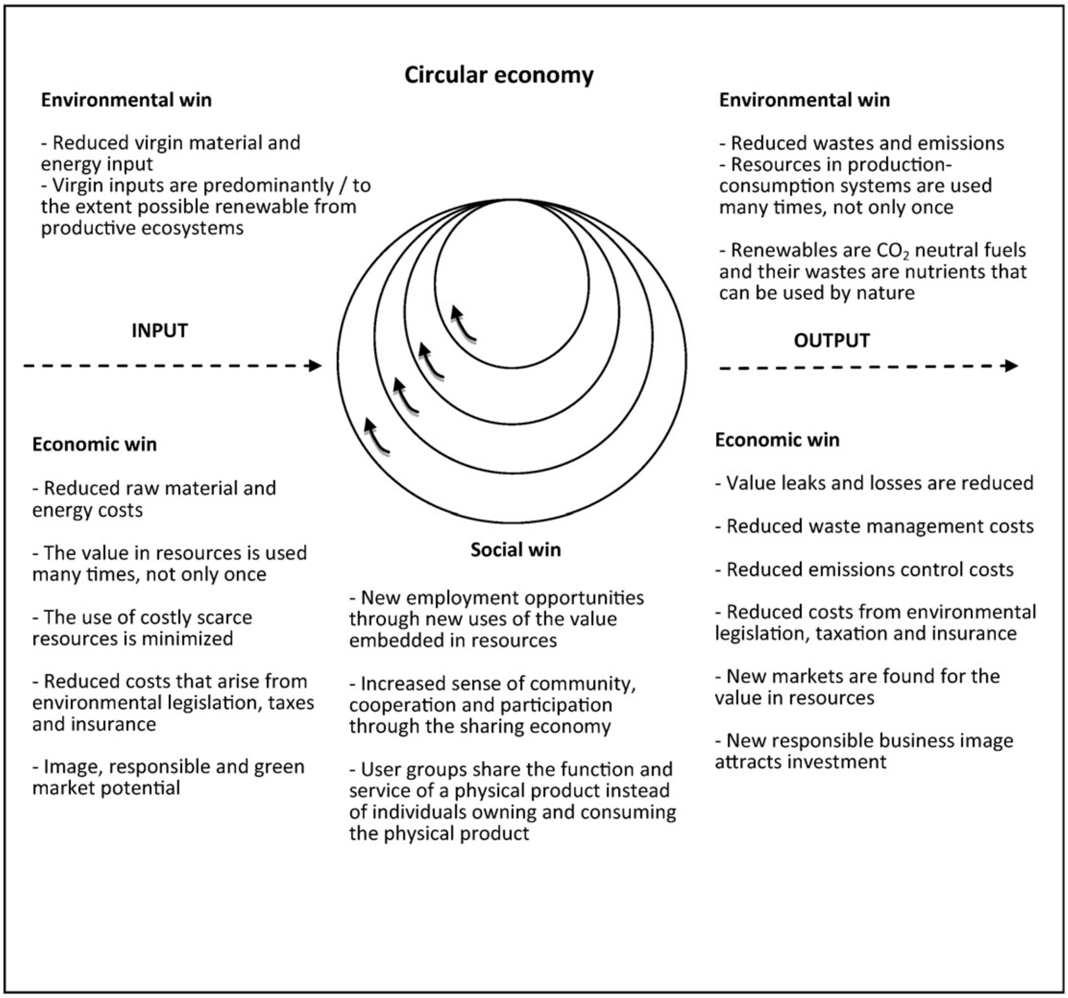

Fig. 3. Circular economy for sustainable development. The win-win-win potential of circular economy. This paper suggests that successful circular economy contributes to all the three dimensions of sustainable development, economic, environmental and social. Circular economy should adapt to the natural ecosystem cycles and utilize these in economic cycles by respecting their reproduction rates.

to nature should be in a form in which nature can utilize them in its own functions. It is true that there are many individual examples of achieving this in practice demonstrated, e.g. in above noted cradle-to-cradle studies (see e.g. Braungart et al., 2007) or in applications of industrial ecology in inter-system ecology (Korhonen, 2001) etc. Not only bioenergy, pulp, paper, timber, food and biomaterials can be part of nature-economy-nature-economy etc. cycles, but also other wastes produced by society can serve as part of these joint renewable cycles. This kind of activity is strongly argued for in recent cradle-to-cradle business visions, where so called “biological nutrients” within industries that utilize biomass are released back to biosphere where they contribute to biomass growth and to biodiversity maintenance, i.e., supporting nature's work and supporting the source basis of economies in nature.

Waste fluxes produced by society can be used in nature's own cycles for benefit of nature and of the human economy. Carbon dioxide (CO_2) emissions produced by the national forest industry of Finland, for example, are absorbed to the annual growth of the renewable forest resource, because the annual cuttings are lower than the annual growth (Kauppi et al., 2014). The forests serve as a carbon sink. Naturally, climate change is a global problem and for the global ecosystem, the overall burden matters. Incineration ash generated by renewable biomass combustion for energy can be utilized for fertilizer in forests. When forest growth is increased as a result, more CO_2 neutral fuels are created (Korhonen and Snäkin, 2015). However, the cadmium concentrations in the ash can create environmental problems.

In anaerobic digestion (AD) of biowastes from the agricultural and food industry (agrofood) life cycle/value chain for renewable energy, nutrient rich wastes are produced as a by-product. These can be released to fields where they increase the nutrient value of the cultivated ecosystems (Korhonen and Niutanen, 2004). The resulting growth of biomass may help society to substitute for non-renewable and emissions intensive fossil fuels in production and consumption systems. It must also be noted, that lot of nutrient rich biomass is currently combusted for energy (FICF and Mckinsey, 2014), which substitutes for fossil fuels. But a higher value solution would be to utilize the nutrient value in the resources better, e.g. in nutrient cycles for food production. This would mean that the value is used before combustion, where important part of the nutrient value is lost. There are many opportunities to enhance CE through using the existing cyclical and reproductive cycles of nature.

In the idealized situation of Fig. 3, CE-type arrangements of the physical flows of materials and energy would reduce virgin inputs to the system and waste and emissions outputs from the system (see e.g. Korhonen et al., 2004; Korhonen, 2004). Resource and energy costs would be reduced and also waste and emissions costs, e.g. those arising due to environmental legislation, taxes or waste and landfill management, would decrease. New business, market and employment opportunities are created, because the value embedded in materials is used many times (kept in the economic circulation as long as possible) instead of only once as is usually the case in the modern global economic system. An obvious possibility in this vision for business is also the improved image that helps green marketing of products and services.

CE extends current business or corporate environmental management systems in that, inter-sectoral, inter-organizational and inter-life cycle material cycles and energy cascades are encouraged for capturing the highest economic value possible in resources (see, e.g. Korhonen et al., 2004). Hence, CE could be a form of inter-organizational and network environmental and sustainability management (Seuring and Gold, 2013; Seuring, 2004). Much work is needed before inter-organizational and network environmental and sustainability management systems of companies are sufficient for the vision of CE (as in Fig. 3). Inter-organizational systems tend to be self-organized (Chertow and Ehrenfeld, 2012). This makes their planning, design and management difficult.

In the current business reports on CE (e.g. EMAF, 2013; FICF and Mckinsey, 2014), a new consumption culture is also emphasized as an important part of CE, and again without a clear link to scientific research. We would interpret new consumption systems as user groups and communities sharing the use of the function, service and value of physical products (see e.g. Welford, 1998a; Tukker, 2015) as opposed to individuals that only own and consume ("run down") the physical products. New business concepts may include leasing and renting the service provided by the product, take back strategies, reverse logistics and concepts that enhance sharing the function of the product between many users. The "sharing economy" may bring significant efficiency improvements in how people live or, for example, organize their travel accommodation (renting apartments vs. hotel rooms) and how people travel (owning a vehicle vs. sharing its use). The idea is to involve as much as it is possible of the existing material capacity in economic systems into efficient use. This is interesting. It is common knowledge in Finland, for example, that the average use rate of cars is less than 10%. How would a credible business leader of any company justify the purchase of machinery the use rate of which will be less than 10%?

In the sharing economy, office spaces are shared or empty office spaces are converted to housing, cars are not necessarily owned rather used by many individuals who utilize the digital economy for coordinating the shared use. Vacation apartments can be used by many families by benefiting from digital economy thus preventing the building of new spaces that would be empty for most of the year. Empty apartments due to travel can be rented as "hotel rooms" reducing the need for materials and energy use for construction of new buildings. Laundry services can be shared and those home equipment and devices such as trills can be shared by neighbors instead of each apartment owning its own trill that is used some 15 min a year. Therefore, the new consumption culture is a critical part of the circular economy in its effort to reduce the nature-society-nature linear throughput flow of materials and energy.

In sum, in our definition of CE for sustainable development, the environmental objective of CE is to reduce the production-consumption system virgin material and energy inputs and waste and emissions outputs (physical throughput) by application of material cycles and renewables-based energy cascades. The economic objective of CE is to reduce the economic production-consumption system's raw material and energy costs, waste management and emissions control costs, risks from (environmental) legislation/taxation and public image as well as to innovate new product designs and market opportunities for businesses. The social objective is the sharing economy, increased employment, participative democratic decision-making and more efficient use of the existing physical material capacity through a cooperative and community user (user groups using the value, service and function) as opposed to a consumer (individuals consuming physical products) culture.

Table 1
Six limits and challenges for the circular economy concept.

Thermodynamic limits
- Cyclical systems consume resources and create wastes and emissions
System boundary limits
- Spatial: problems are shifted along the product life cycle
- Temporal: short term non-renewables use can build long-term renewable infrastructure
Limits posed by physical scale of the economy
- Rebound effect, Jevon's paradox, boomerang effect
Limits posed by path-dependency and lock-in
- First technologies retain their market position despite of in-efficiency
Limits of governance and management
- Intra-organizational and intra-sectoral management of inter-organizational and inter-sectoral physical flows of materials and energy
Limits of social and cultural definitions
- The concept of waste has a strong influence on its handling, management and utilization
- The concept is culturally and socially constructed
- The concept of waste is always constructed in a certain cultural, social and temporal context and this context is dynamic and changing

4. Limits of the CE Concept

The scientific and research basis of the CE approach seems to be only in its infancy. To authors' knowledge the definition given above in section three (3) is the first attempt to present a scientific research-based definition of CE.

Many key questions are still open. These will arise, e.g. from the nature of self-organized complex social-ecological systems (see e.g., Chertow and Ehrenfeld, 2012; Folke, 2006) to which CE systems belong. Material flows exceed man-made boundaries and the complexity will increase when new uses are found for the existing flows, the basic idea of CE. Furthermore, the utilization of bio-based materials and biofuels will have an important role in CE. But the assessments of the actual environmental impacts of biofuels (see e.g., Holma et al., 2013; Mattila et al., 2010), biomaterials (Weiss et al., 2012) or various types of eco-efficiency initiatives (Huppes and Ishikawa, 2009) still face many unresolved methodological and other limitations, e.g. those concerning the common method of environmental life cycle assessment (LCA) in these types of cases.

This section identifies six challenges for the CE concept in terms of environmental sustainability. Although the above definition we presented for the CE concept includes also the economic and social dimensions of sustainability, we will leave the further analysis of economic and social dimensions for future work. In other words, it is beyond the scope of this paper to more thoroughly analyze economic and social sustainability in light of CE. The basic idea of the paper is to provide the reader with an initial attempt for conducting critical research analysis of CE.

The six limits are explained below and gathered in Table 1. We suggest these six limitations and challenges could serve as overall research themes for more in-depth research on CE in the future. It is our intention that scholars interested in the new popularized and business community originated concept of CE could extend scientific research in the areas of these six challenges.

4.1. Thermodynamic Limits

The work of Georgescu-Roegen (GR) on thermodynamics and economics science, Daly's views on it and developments from it have been perhaps the most important body of knowledge on which the scientific field of ecological economics was originally established. This was the link between a) the physical flows of matter and energy and b) the abstract monetary flows or the exchange value that both influence economics science and decision-making.

However, one of the arguments of GR, the so called "fourth law" (Georgescu-Roegen, 1971; see Daly, 1996) has later been rejected by the ecological economics community. With the fourth law, GR argued an explanation for the impossibility of complete recycling, impossibility even in theory. Georgescu-Roegen pointed that due to the second law of thermodynamics, entropy, recycling will always require energy and will always be incomplete generating wastes and side-products (increasing entropy, decreasing exergy) of its own. This, of course, is true. Dissipated materials are lost in the ecosystem and it is impossible to recover them. The search, gathering and recovery would require vast amounts of energy. Therefore, complete recycling is impossible in GR.

Because of entropy, like all material and energy using processes, circular economy promoted recycling, reuse, remanufacturing and refurbishment processes too will ultimately lead to unsustainable levels of resource depletion, pollution and waste generation if the growth of the *physical scale* of the total economic system is not checked. Others have later contested the fourth law and elaborated especially on the fact that earth is an open system receiving the flow of infinite solar energy that could, in theory, be harnessed and utilized for materials collection, recovery, shorting and other recycling and CE-type processes (see e.g. Ayres, 1999; Graig, 2001; Converse, 1997; 1996). Green plants utilize less than 1% (less than 1%) of the incoming solar energy (Ayres, 1999) and still biosphere is very advanced in nutrient cycling. In human economic terms, one can say that the incoming solar energy is not only a renewable resource, rather an infinite resource (of course in some very distant future sun too will collapse).

Hence, in theory, actually it is possible to recycle everything by using the incoming renewable (infinite) energy from the sun. This would require lot of work, e.g. for tracking, finding, recovering and processing the dissipated materials and nutrients. But in theory, this is possible. GR was wrong in his fourth law as ecological economics authors now agree (e.g. Ayres, 1999; Craig, 2001; Converse, 1997; Converse, 1996). But despite of limits posed by entropy and also despite of speculations on theoretical possibilities to recycle everything, it is very clear that in the current global linear throughput production-consumption market economy system of physical flows we operate in, radical improvements can be achieved through the simple arrangement of the physical flows toward a more cyclical model.

Therefore, cyclical material flows and renewable flow-based energy cascades offer an important opportunity toward a more sustainable material and energy flow model of the global economy. And this is so even in terms of entropy. But the second law of thermodynamics means that every circular economy-type process or project should be carefully analyzed for its (global) net environmental sustainability contribution. A cyclic flow does not secure a sustainable outcome. For example, in the utilization of forest residues from cuttings as a source for renewable energy and for substituting fossil fuel combustion, nutrient rich parts of the trees, twists, needles, bark and branches are removed from the forest ecosystem where they would support ecosystem health, biodiversity and forest growth (Korhonen et al., 2001). This activity requires energy and machines that run on energy. The machine manufacturing process further requires energy and materials and produces wastes and byproducts. The sustainability contribution of circular economy projects is a question that needs a case-by-case analysis.

It can be understood that usually circular economy promoted product reuse, remanufacturing and refurbishment should be the first desirable options in light of thermodynamics. Recycling for raw-material value only and combustion for energy are less desirable and should be avoided. It is important that cycles are increased, maintained and utilized before recycling for raw-material value or for combustion for energy. The landfill disposal is the last option. But all of these processes are subject to laws of physics.

4.2. Spatial and Temporal System Boundary Limitations

The current global economic system is largely a linear throughput flow economy in terms of the physical flows of materials and energy. Approximately 75% of the global energy production is based on nonrenewable and emissions intensive fossil fuels the combustion of which does not adapt to biosphere's reproductive cycles; dead resources are extracted from nature, from litosphere, processed, used and dumped back to living nature, to biosphere in a harmful form. Therefore, although sustainable development is a global goal, CE-type projects that have been implemented and that will be implemented in the near future will always be local or regional at most. No global body for governance exists. But perhaps gradually and step-by-step from the roots up the world of the future could be transformed toward something similar to the CE vision provided the vision is clear enough and in line with sustainability.

Each CE project should be considered for its contribution to *global net sustainability*. This means what is left as improvement or positive outcome after an individual project or action as compared to a situation before the project. The project, action or initiative should be assessed for its contribution to sustainable development of the system "society within biosphere" and in the long-term (Robèrt et al., 2002; Ny et al., 2006). This is a very difficult challenge. Initial attempts of analyzing individual sustainability efforts, projects and applications of sustainability tools such as those of material flow studies in light of their global net sustainability contributions have been undertaken in qualitative terms with the so-called sustainability principles, The Natural Step Principles of the Framework for Strategic Sustainable Development (FSSD, Robért et al., 2013). This work was recently bridged to the quantitative definition of global sustainability in planetary boundaries by Rockström et al. (2009) in Robért et al. (2013).

It is possible to show what are the main issues and problems in the CE approach in terms of global net sustainability. One of these is spatial system boundaries. The physical flows of materials and energy cross organizational, administrative and geographical boundaries. The phenomena of problem displacement and problem shifting (Korhonen, 2004) should be minimized, i.e., reducing environmental impact in one part of the system by shifting the problem to another part of the system. There are many examples of efficiency, environmental and social gains in local and regional economies that have resulted, either directly or indirectly, through supply chains, value chains, product life cycles and their networks, into difficult problems in other locations.

Most industries today produce products with international and inter-regional markets and life cycles. The biggest environmental and social problems tend to affect the poor developing countries worst (Welford, 1998b). It has been shown that very high eco-efficiencies have been achieved in local biomass-based industries while the exports of this industry have created difficult problems at the end-management phases of the product life cycle (Korhonen and Snäkin, 2005) or the imports of this industry have violated the biodiversity of the ecosystems in the source country (Mayer et al., 2005). In a local recycling network that was very successful in waste and by-product utilization, the biggest environmental impacts occurred outside the local industrial park in its supply chain (Mattila et al., 2010).

It can be very difficult to assess the overall global net sustainability contribution of land-use and use of space by circular economy activities. Consider a situation in which mining of lithosphere is reduced and use of biosphere is increased. Land demand for mines is reduced but land required for, e.g. renewable energy production, is increased. With increased material cycles and recycling more roads may be needed for transportation of recycled materials and less road infrastructure for transportation of virgin raw-materials. The sustainability effects of these issues pose a complex question.

The system boundary question also relates to the temporal dimension of the CE projects initiated. The physical flows of materials and energy mobilized by the human economy create both short-term and long-term environmental impacts and this should be taken into account when designing reuse, remanufacturing and recycling projects. Many of those impacts are currently unknown, some will be observed and found in the near future, some later or never (Robért et al., 2013; Robèrt et al., 2002). Furthermore, just like interdependencies of species in nature, the interdependencies of materials and energy flows mobilized by human economy and interdependencies of their ecological impacts are complex, changing and dynamic.

One issue related to the temporal boundary question that might arise when planning for CE systems is product durability. CE presents product durability as a desired property of products, because this keeps the function and economic value provided longer within economic circulation (EMAF, 2013). When the value and service is utilized many times, need for resource extraction for new products should be reduced. However, due to the fact that many of the impacts human mobilized material flows generate in nature are currently unknown, extending product life-time might create economic and organizational structures that risk unsustainability in the long-term. This is if those products turn out to create negative impacts, impacts currently unknown. In such a situation, short life-times and continuous innovation and market penetration of new products might have an environmental advantage. Here is a conflict between product reuse and traditional recycling, which does not try and prolong the product life, rather utilizes its waste materials for the low quality raw material value only.

Many business or corporate environmental management projects tend to focus on the environmental impacts reduction of an individual short-term action (Robèrt et al., 2002). But in terms of sustainable development, which is an inter-generational goal, the investments now should be considered for their contribution to the larger and long-term goal of global net sustainability in the future. Many decisions in societal decision-making lock-in the development paths of the future for decades to come (Norton et al., 1998). Despite these would be CE-type and eco-efficient when compared to other current alternatives, their performance might rank very low when assessed against future innovations, which are unknown in light of their innovation potential. Energy infrastructures are examples of investments that dominate the market for 30–40 years after the initial decision and the paybacks on investment occur slowly.

4.3. Limits Posed by Physical Economic Growth: Rebound Effect, Jevon's Paradox and the Boomerang Effect

In the CE visions of Figs. 2 and 3, the efficiency of use of the existing physical material capacity of the global economy is increased. This is done through reuse, remanufacturing, and refurbishment of products as well as through the conventional recycling of the raw-material value of the product. But the main CE innovation in light of materials flows is reuse, remanufacturing and refurbishment of already existing products as shown in Figs. 2 and 3. The new consumption culture of the sharing economy is important for the vision and a good example of product reuse.

All economic efficiency increases are subject to rebound effects (Berkhout et al., 2000), to the “Jevon's paradox” (Mayumi et al., 1998; Jevons, 1990)[2] and to the “boomerang effect” (Mayer et al., 2005). When production efficiency increases, production costs decrease and eventually the prices of end-products decrease. This boosts up consumption. The overall economic growth may more than offset the initial environmental gains created by better efficiency. For eco-efficiency, i.e. environmental impacts per unit of economic production (Brattebo, 2005; Huppes and Ishikawa, 2009), the rebound effect and the Jevon's paradox can be harmful. The rebound effect and the Jevon's paradox have also been identified belonging to the main reasons why eco-efficiency is not in line with the resilience theory and its adaptive renewal cycle (for further discussion see Korhonen and Snäkin, 2015; Korhonen and Seager, 2008).

Even in the idealized eco-effectiveness and cradle-to-cradle concepts (Braungart et al., 2007) that are among the background concepts of CE, the rebound effect and the Jevon's paradox problems matter. In eco-effectiveness, eco-efficiency is seen as irrelevant, because all emissions are in a form that nature tolerates and recycles as biological nutrients and as “healthy emissions” (Braungart et al., 2007; Braungart and McDonough, 2002). Society and biosphere are positively recoupled into a single cycle of materials flows as nature processes industrial wastes and emissions and in this way continues to provide for society. However, because 100% complete nature-economy-nature-economy etc. cycles will not be achieved any time soon, perhaps never, the growth of the physical scale of the economic subsystem within the parent ecosystem will remain the key question of sustainability. The rebound effect concerns also the ideal of eco-effectiveness. Entropy will harm sustainability if the physical scale of the economy is not checked. The physical scale is, of course, measured by the physical material and energy footprint, not by money or GDP. Furthermore, in case of product remanufacturing, which is among the key characteristics in the currently popular CE concept (see Asif et al., 2016; Lieder and Rashid, 2016; Rashid et al., 2013), it should be noted that all manufacturing including remanufacturing is subject to thermodynamics and the effects of economic growth.

Mayer et al. (2005) argued that in the global economic system, when a rich country increases its nature protection areas and its eco-efficiency (or even its absolute environmental sustainability) through national environmental policy and natural resource demand simultaneously increases due to economic growth, the harmful production can be transferred to poor bordering countries. The “boomerang effect” happens when the reduced biodiversity of the poor country reduces the migration of certain scarce species toward the rich country from the poor country's ecosystems, because the rich country is dependent on these migrations for its biodiversity. Nature protection in the rich country will not achieve its goals, because the protection areas' biodiversity will decrease due to low levels of species migration from the poor country's ecosystems, the biodiversity of which is deteriorating.

Due to the laws of thermodynamics, all economic activities, also circular economy activities consume energy, increase entropy and decrease exergy. This means that all CE-type initiatives, projects and activities generate environmental impacts and consume resources. When the physical economy grows, these impacts increase. If economic growth must be allowed, the growth of the physical scale of the economy (Daly, 1996) measured in physical material and energy flows should be limited. So far the practitioner and business world-led circular economy concept has not addressed these issues. In Daly (1996), eco-efficiency is different than sustainability. Even efficiently organized systems will collapse if their overall burden on their supporting systems exceeds a sustainability limit or as Daly says that also optimally loaded boats sink even though they would sink optimally.

Physical scale of the economy is different than the size of the economy measured in abstract exchange value. Using common knowledge and commonly available statistics, it is easy to estimate that the physical scale of the global economy measured by its physical material and energy flow footprint or by its overall natural resource use will continue to grow for the next 50 years even though the circular economy would operate perfectly in the western industrialized countries now. Of course, CE is only in its infancy in the western industrialized countries. The population growth, living standards increase and urbanization in developing countries and transition economies will more than offset the envisioned CE innovations' gains in developed countries in terms of global net sustainability contributions of CE.

Therefore, perhaps the most important question for CE in terms of long-term sustainable development of the global society is how can the saved resources and money generated by the CE ideal be directed to sustainable consumption practices. If the current consumption culture will not change, CE will remain as a technical tool that does not change the course of the current unsustainable economic paradigm. It is important to note that CE presents a new vision for the consumption culture with the “sharing economy”. But it is beyond the scope of this paper to further consider the promise of the sharing economy in

[2] Not the William Stanley Jevons. Rather, a scholar with a similar name.

terms of changing the current global consumer culture. Through product reuse and the sharing economy CE offers fruitful ideals, but their implementation in practice remains an open question.

4.4. Path Dependencies and Lock-in

When an economic innovation is launched at the market, immediately a process that determines its influence power starts. Usually the first accepted idea achieves the best markets and receives most awareness. Returns to scale and learning effects make the first innovation stronger in the market than innovations penetrating the market later. This phenomenon is known as path dependency and lock-in (Norton et al., 1998), the "survival of the first" instead of the fittest. In CE terms, this means that new innovations, models and systems designed for product reuse, remanufacturing and refurbishment have to compete in the market with the more conventional recycling for low quality raw-materials utilization systems and combustion for energy solutions. There will be competition between existing and new CE models. Also conventional linear flow models take part in the competition for materials usage.

When the existing infrastructures and their associate clusters, networks, stakeholder discourses and the financial investments directed, e.g. to slow payback time technological solutions such as energy production, dominate, CE-type innovations will have many difficulties to break through in the market. This is even if they were economically, ecologically and socially superior than the prevailing technologies. In other words, also the recycling market just like all other markets, has established structures, cultures and operational routines. CE-type high value product reuse, remanufacturing and refurbishment, and not least the sharing economy, will have to compete with these cultures, routines and management models. The economics and business logic of path dependency may prevent many of the suggested CE innovations from penetrating markets.

The practitioner and business CE reports seem to suggest that the simple economic and business logic of superior technologies and business models will convince the linear economic production and consumption systems and structures to change into a circular and reproductive materials and energy flow system. However, the long tradition in economics science in research on path dependency and technological lock-in (see e.g. Ehrenfeld, 2000; Norton et al., 1998; Dimaggio and Powell, 1983) show that technological superiority or even management superiority do not guarantee long-term business and market success. This is because the technologies and business models that have achieved their leading position first will not adopt other new technologies or models. Businesses tend to hold their ground and rather continue the old way of doing things than venture into unknown futures.

CE physical materials flow innovations of product reuse, remanufacturing and refurbishment pose a difficult question for the issue of path dependency. Consider that many firms may rely their business model on the existence of waste materials that are usable as raw materials or as sources for energy. The waste derived resources may serve to substitute for virgin materials or for fossil fuels. In CE, the availability of such waste flows may be reduced, when the product life or the life of its value is extended with high value solutions of reuse, remanufacturing and refurbishment. The firms in question will have to increase their virgin material use and fossil fuel combustion. CE, hence, can create an undesirable path dependency from the perspective of sustainability, in this case, increased overall virgin resource use. What part of the product/service supply chain, value chain or life cycle is affected and how?

In addition to product quality, the path dependency issue also relates to organizational culture, business strategy and management models and their inherent reluctance to adopt new modes of behavior. All these issues remain unexplored in the new popular CE concept and its suggested applications.

4.5. Intra-organizational VS. Inter-organizational Strategies and Management

The physical flows of materials and energy extracted from nature travel through many different interdependent parts within the economic production-consumption system before they end up as wastes and emissions in ecosystems. The flows do not respect man-made/defined administrative, geographic, sectoral or organizational borders and boundaries. New business models including product design for multiple life cycles, leasing and renting the product while maintaining its ownership and reverse logistics in the supply chain have been proposed for CE (Rashid et al., 2013; FICF and Mckinsey, 2014). All of these require inter-organizational sustainability management. Inter-organizational cooperation is required between the supplier firm and the customer firm (business to business marketing) and between the producer and consumer, e.g. in leasing or renting the product while retaining ownership.

Some practical initiatives exist in the literature where a systems approach has been adopted to govern and manage the physical flows. For example, a network of business companies including the local/regional public authority such as the municipality organization can engage in CE-type collaborative materials and energy utilization. Terms used for such inter-organizational arrangements include industrial ecosystems, industrial symbioses and industrial recycling networks (Chertow and Ehrenfeld, 2012; Chertow, 2000; Korhonen, 2004; Korhonen et al., 2004). However, the conclusion from these studies is that the system boundary definition will remain incomplete in terms of sustainability and that also many other key questions remain open in these networks.

The difficult questions of inter-organizational sustainability management that have not been discussed in the current CE initiatives include (see e.g. Seuring and Gold, 2013; Seuring, 2004; Korhonen et al., 2004): Who is the leader in the network, who bears the biggest responsibility, who gains the most from the network operation, who loses the most if the project is unsuccessful or faces the biggest risks, what is the overall budget of the network, who controls it and which actors contribute to it, what is the network decision-making platform, who organizes it etc.

Consider a single company that is implementing its environmental management system (EMS) such as the EU Eco-Management and Auditing Scheme (EMAS) or the ISO 14001 Environmental Management Standard. The aim of these single company-focused management systems is obviously the reduction of the generated waste materials flows. But if these particular waste flows are viewed in the larger local or regional business network context for a CE vision it may be justified to argue that the flows should be maximized. This is if the other actors within the network may use these waste flows as raw-materials or as sources for energy. The other companies can in this way substitute the waste flows for virgin materials. The overall net sustainability contribution of the network system in question may be bigger than that of the individual firm EMS. How can an individual firm convince its stakeholders, customers and authorities that its strategy of "waste maximization" is beneficial for the environment and sustainability?

4.6. Definition of Physical Flows

History, culture, community and society have decided and will decide what material flows are good and what are bad. The definition will always be changing and dynamic. The definition, naturally, decides what flows are addressed in governance, policy and strategic management. The CE-type material flow categories are largely missing from existing statistics used by environmental administrations globally. The conventional waste material utilization in recycling and in energy recovery is now commonly categorized in the statistics of national environmental administrations in the western industrialized countries. However, product reuse, remanufacturing and refurbishment are not defined categories in these statistics. Therefore, it is difficult to officially define and implement policies, legislation or other public policy instruments for circular economy activities.

Furthermore, the concept of waste is dynamic and changing (Pongracz, 2002). It is related to culture, society, community, history and level of societal development. It is difficult to define the exact moment when the material with economic value becomes waste with no or negative value. When waste is perceived as a resource for materials or for energy, the flow has an economic value. The distinction between waste and by-product is also problematic.

When the CE categories of product reuse, remanufacturing and refurbishment are added to the mix, the conventional definition of material flows becomes very problematic. Without a proper definition of certain types or phases of physical material flows in economic systems, it is very difficult to intentionally support their utilization. It will also be very difficult to assess the actual environmental impacts of CE-type-activities without a clear definition of what type of material and energy is good or bad in light of sustainability.

Before industrialization, during its early years and certainly before modern environmental policy, many flows now determined as harmful wastes in modern environmental policy and legislation, were resources with economic value (Desrochers, 2002, 2004). Modern environmental policy and legislation have burdened the defined waste flows with permits etc. that actually can make it difficult to utilize the valuable resource embedded in the waste stream. It is also clear that the definition of waste is culturally bound. In developing countries people literally eat societal and residential wastes. Therefore, in these cultures, waste equals nutrient value for humans. Naturally, problems concerning the definition of waste and limitations for its utilization exist also in many developed countries and the definitions vary, are changing and dynamic. The physical flows cross man-made, administrative and organizational boundaries and borders. Therefore, a consensus on what is usable and what is not is very important for the ideals of circular economy to contribute to global sustainability.

The definition of a material flow is temporal, spatial and cultural. Therefore, all CE proposals and suggestions should be placed into and considered within their temporal, spatial and cultural contexts. All definitions are cultural, social and community-based, they are social and cultural constructs. It will never be easy to assign certain flows to certain categories of material and energy flows. We do have some “absolute” information and knowledge in references of critical material and substance flows and their environmental thresholds or boundary values in ecosystems (Rockström et al., 2009; Robért et al., 2013), but the social and cultural definition of an individual flow will always be changing and dynamic according to prevailing cultural and social interpretations.

5. Conclusions and Discussion

The concept of circular economy (CE) is currently promoted by the EU, by several national governments and by several business organizations around the world. The concept has been created mainly by practitioners, the business community and policy-makers. This article has been the first attempt to start building a scientific basis for the CE concept and assess the CE concept with a critical analysis. For the concept definition of CE, we employed the original WCED definition of sustainable development as the basic reference point. For the critical analysis we used the widely accepted Planetary Boundaries concept and its interpretation in The Natural Step (and FSSD, Framework for Strategic Sustainable Development) for reference of environmental sustainability. Without systematic scientific groundwork, there is a risk that the CE concept will not achieve its ambitious goals.

CE seems to be a promising concept, because it has been able to attract the business community to sustainable development work. It makes common sense, that if you extract a resource from nature and work hard for it to become a product or a service that has an economic value, you use this value many times, not only once. This makes perfect business sense. It is also simple and logical to argue that once one uses the value embedded in resources many times, not only once as is the common practice in the linear material flow pattern of the global economy, one reduces the virgin input and the waste and emission output of the economic activity. Furthermore, many use the natural ecosystem physical material and energy flow model as the desired vision of the human economy. The global natural ecosystem is materially closed and runs entirely on renewable (or infinite) solar energy emitting only waste heat (infrared radiation to space) as the “waste output”, which does not matter as the input source is infinite. Despite of the differences between these two systems, e.g. in terms of space, time and e.g. energy supply, it is interesting that the CE model too seems to follow that of nature in light of the physical flows of materials and energy. It is interesting that many scholars have time and time again referred to the natural ecosystem material and energy flow model in the course of centuries and in terms of human economic sustainability.

In sum, this article makes the following contributions:

- The paper provides the first comprehensive attempt to make sense of the actual concept of the circular economy in terms of scientific research. We have shown the potential of CE in light of all the three dimensions of sustainable development, economic, environmental and social.
- Based on the above, the paper has demonstrated that there is quite little that is truly new in the CE concept in terms of sustainability science research. The two contributions of the CE concept are: 1) CE highlights the importance of high value and high quality material cycles in a new manner and 2) shows the possibilities of the sharing economy alongside sustainable production for a more sustainable production-consumption culture.
- However, this paper shows that there are several limits and challenges in the concept of CE in light of environmental sustainability. We identified six main challenges, for example those concerning thermodynamics, definition of CE system boundaries and challenges in the governance and management of the CE-type inter-organizational and inter-sectoral material and energy flows.

All of the identified challenges relate to the understanding of the actual environmental impacts of CE activities. These six limitations and challenges serve also as research themes and project proposals for scientists, policy-makers and for business actors that are interested in making progress in sustainable development through CE. Circular economy has a great inspirational strength and equipped with critical sustainability assessment it can be important for global net sustainability.

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