POTENTIALS AND LIMITATIONS OF THE CIRCULAR ECONOMY WITH REGARD TO THREE EXEMPLARY MATERIAL FLOWS (TYRES, ROTOR BLADES FOR WIND TURBINES, LCD SCREENS)

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1. Introduction

In the following article[1], the opportunities – but also the limitations – of the circular economy for three material flows are analysed and described in detail. As exemplary material flows, tyres, rotor blades from wind turbines as well as LCD screens have been selected. The article is based on a study conducted by the Fraunhofer Institute for Environmental, Safety, and Energy Technology (UMSICHT) on behalf of the Regional Association NRW of the German Chemical Industry Association (VCI)[2].

2. Methodology

This analysis is based on comprehensive literature research. The institute's own know-how has been incorporated into the analysis. Subsequently, guiding questions were elaborated on the basis of the information compiled. These questions were discussed in interviews with experts in order to include third party expertise in the project. In particular, the interviews were used to close knowledge gaps found in the literature and to substantiate the findings of the analysis. A well-founded description of the limitations and potentials of the circular economy was ensured in this manner.

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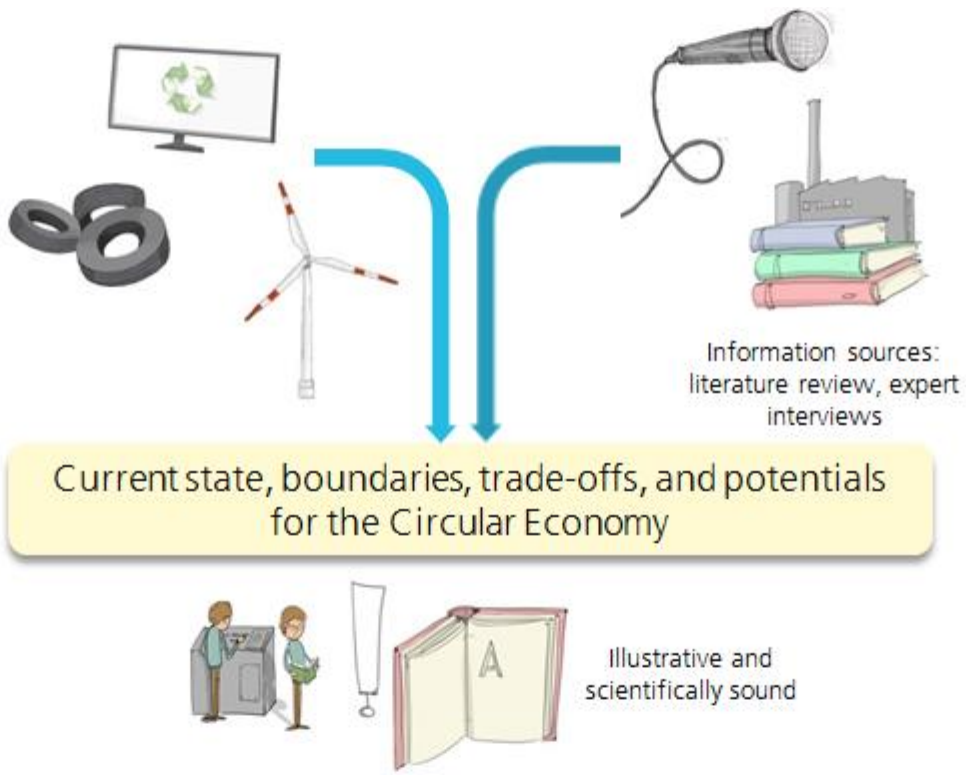
1 This article cites the names of companies or products, processes or services so that authors, the publications of sources and references quoted and analysed in this article can be clearly identified. In particular, it should be noted that the mentioning of names does not constitute any judgment, ranking, emphasis or recommendation concerning the range of offers from certain companies.

2 Hiebel, M.; Bertling, J.; Nühlen, J.; Pflaum, H.; Somborn-Schulz, A.; Franke, M.; Reh, K.; Kroop, S.: Studie zur Circular Economy im Hinblick auf die chemische Industrie; Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT (Hrsg.), Study on behalf of Verband der Chemischen Industrie e.V., Landesverband NRW; Oberhausen, February 2017

Figure 1:
Methodology



Taking into account the development of the circular economy concept, Fraunhofer UMSICHT developed and used the following definition for this analysis:

Table: Definition of Circular Economy for the purposes of the analysis described

Definition of Circular Economy by Fraunhofer UMSICHT
»In a circular economy, the materials utilized in products should remain in a materials circle that extends beyond the life cycle of goods. Wastes, emissions, dissipative losses and, consequently, also the extraction of raw materials from the environment should be reduced as far as possible. Important elements for implementing a circular economy include the reuse of goods, the recycling of materials, and product designs that facilitate their circular management while retaining both their quality and performance. At the same time, the accumulation of substances which may impede the circular management of products and materials should be avoided. By means of this procedure, the useful life of products should be extended as long as possible and at their end-of-life stage product materials should be fed back into the material circle as quickly as possible. The lowest possible energy demand for maintaining the circularity of products and goods is an important requirement which essentially co-determines the quality of a circular economy. The energy demand should ideally be provided from renewable resources. Used products and materials unsuitable for re-circulation as a material should be channelled into utilisation of energy from waste. Materials, where dissipative losses cannot be avoided, should be degradable. The concept of circular economy for individual products and goods may be equally applied to regions, sectors, companies or households.«

3. Limitations and potentials of the circular economy for three exemplary waste streams

To provide an illustrative picture of the potentials and limitations of the circular economy, three material flows were examined in detail: tyres, rotor blades for wind turbines, and LCD screens.

3.1 Tyres

Tyres are complex composite products whose mechanical recycling is rendered more difficult by the diversity and adhesive property of the components and, in particular, the irreversible cross-linking of the matrix material rubber. Therefore, today's material recovery of used tyres is characterised by cascade use where numerous secondary products are produced (e.g. elastified asphalt, fall protection mats, infill granules for artificial lawn, etc.). Concerning gross value creation and employment figures, the secondary market for products based on used tyres is currently ca. 17 % of the primary market.

In order to improve the degree of circularity, primarily the following two approaches would lead to the desired goals:

1. Clear increase of the »recycled content« by using secondary raw materials or casings (or other tyre components) in the production of new tyres.
2. Intensification of research and development for new concepts in retreading and devulcanisation of rubber (including development of new tyre materials with reversible cross-linking) and for removing contaminants (e.g. polycyclic aromatic hydrocarbons/PAHs, heavy metals) from tyres.

In contrast, raising the end-of-life (EoL) recycling rates would not be target-oriented, particularly for a material like rubber, whose production process is neither simply reversible nor repeatable. That would lead to »inventions« of new secondary uses. But it can be assumed that much of what is feasible and economically viable for used tyres (and especially for rubber granulate) from today's perspective is already put into practice. Otherwise, the shares of energy recovery would shrink much faster than they are doing at the moment.

3.2 Rotor blades for wind turbines

Rotor blades for wind turbines consist of various shares of resins, balsa wood, glass or carbon fibres, rigid foam, iron and non-ferrous metals and paints. Rotor blades are important elements of the *Energiewende* (energy transition in Germany). While they must be low-weight, they need to fulfil high material requirements, thus enabling a wide rotor diameter. At the end of their useful life, rotor blades should go into recovery of the highest possible quality. Today some scrap wind turbines are completely dismantled and then re-erected and put into further operation at other sites. In the future, this path will become more difficult due to a market saturation effect. Further limitations are the growing size of wind turbines and, consequently, rising logistics costs and the falling number of suitable sites. From the circular economy perspective, continuing the operation of wind turbines for periods longer than 20 years – in compliance with all safety regulations – is an immaginable approach , so long as there are no satisfactory material recovery options and further operation does not stand in the way of expansion targets under the German Renewable Energy Sources Act.

At present, rotor blades from scrap wind turbines are mostly placed in storage due to the lack of suitable high-quality recovery options. The use of comminuted rotor blades in cement kilns is a possibility for utilising the energy content of rotor blades and for incorporating the basic constituents of the glass fibres into the cement. However, problems of occupational health and safety in comminution should be properly addressed.

High-quality recycling of rotor blades – the reuse of identical glass fibres with the same fibre lengths in new rotor blades – is technically not feasible at the present time. Moreover, there are no applications for reuse. Potential application options would be the use of glass fibre powder as a substitute for primary material (»glass fibre to glass«) or the use of »glass fibre as filler« in building chemistry and in the plastics industry.

However, research in circular design needs to continue into suitable recycling processes and alternative materials for substituting the glass fibre reinforced plastics of rotor blades. Here, potential conflicting targets regarding energy yield in wind turbines operation and recyclability should be taken into consideration. It should be ensured that wider rotor diameters remain feasible.

3.3 LCD screens

Flat screens are complex products with a large number of valuable materials but partly also with a relevant content of hazardous substances. In the initial treatment of the devices, whose design is strongly determined by the need to remove pollutants, numerous fractions suitable for high-quality recycling are obtained (e.g. iron and aluminium metals or circuit boards). Concerning the plastics fraction, recycling only makes sense for a part-flow since flame retardents constitute a burden.

At present, strategically important metals (especially indium) in LCD screens are not recovered because recovery structure systems and economic incentives are lacking. Indium is not only used in LCD screens but also in alloys and solders, photovoltaic modules and light-emitting and laser diodes [Christman-2014], [EC-2016]. For this reason, indium is relevant as a raw material for European industry even though no production sites for LCD computer screens are located in the EU.

There are also relevant obstacles in the preparation for reuse, e.g. damage during collection of LCD screens or lack of spare parts. Measures such as a recycling-friendly product design and improved product labelling could reduce existing obstacles and drive forward the circular economy for LCD computer screens.

3.4 Overview and transferability of the three material flows

In the following table, the three material flows were brought in relation to each other.

Table 1: Products/material flows examined

Characteristic	Vehicle tyre	Rotor blades for wind turbines	LCD screens
Structure, composition	Complex material composite	Rather straight-forward material composite	Complex product of many different components and materials
Circulation period/ lifespan	Up to 8 years, depending on remaining tread depth	Usually after 20 years, depending on the turbines-specific situation, or 15-25 years, determined by material fatigue or measures to increase efficiency (repowering)	Ca. 6.6 years (first and secondary use) [Buchert-2012]; determined by fashions and trends
Collection points and logistics	In Germany: nation-wide fee-paying points for return to workshops and recycling yards	Not regulated, strong fluctuations regarding time and locations; at wind turbines, generally nationwide in Germany; current focus in Northern Germany	Collection by public law disposal entities and distributors (regulated in the ElektroG (German act on Electrical and Electronic Equipment)) [ElektroG-2015]
Generated volumes in Germany per annum	568 000 t/a (2015)	On average 3 000 t/a between 2012 and 2016	Ca. 17 000 t/a, 3 million items (2013), estimate according to [Sellin-2016] and [Elektrocycling-2015]
Current state of circularity	Cascade use and secondary applications are established	No existing recycling methods to separate glass fibre composite materials; energy/material recovery in cement plants	Recycling for widely used and precious metals and for selected plastics; recycling of critical metals is not economically viable (e.g. for indium)
Potential conflicting targets (trade-offs)	Driving safety, fuel consumption, noise emissions	Further operation: exports abroad of scrap wind turbines; possible performance losses due to different rotor blade materials	Manufacturers need secrecy in global competition regarding construction and composition; product safety
Transferability to other material flows	Elastomer products like sealings, vibration	Classic glass fibre-reinforced plastic (GFRP) applications like boats,	Other electrical and electronic devices or components

Characteristic	Vehicle tyre	Rotor blades for wind turbines	LCD screens
	dampers, silicon products for kitchens, elastic and foamed polyurethane components	carports, campers, toys, other carbon fibre-reinforced materials like GFRP in aircraft and vehicle construction	

3.5 Potential trade-offs/ Conflicting targets

All life cycle phases need to be taken into account when optimising the overall system because the optimum for one individual phase is not necessarily the total optimum for a product. For many optimisations, the trade-offs (conflicting targets) need to be considered – i.e. mutual dependencies frequently bring counteracting effects for a given target system. For example, where one product property is optimised this can have adverse effects on another product property.

Concrete examples of trade-offs (see table 1) for tyres include potentially higher fuel consumption, reduced adhesion properties or increased noise emissions through the use of more recycling-friendly materials. For rotor blades, the substitution of GFRP with sheet metals or wood could cause performance losses with lower yields from wind farms in the use phase (which is decisive for the *Energiewende*/energy transition). These theoretically possible alternative materials would be recyclable in well-established recovery processes, but, according to the current state of knowledge, they would not achieve the same rotor blade lengths and identical material properties. Where LCD screens are concerned, for example, the manufacturers' need for confidentiality in global competition regarding structure and composition contrasts with the need for information that would be required for the development and, in particular, the large-scale implementation of innovative recycling methods. This holds true especially for the development of recycling processes for critical metals which EoL devices only contain in low concentrations. Another conflicting target can exist in the field of product safety. For example, flame-retardant plastics must be used in certain components. Depending on the type of substances used for flame protection, the recyclability of screens can be hampered. The use of other materials needs to be examined carefully as to performance, environmental soundness and costs.

Therefore, all life cycle phases should be considered in all circular economy decisions, in order to identify undesirable trade-offs and to avoid them wherever possible.

4 EU Circular Economy Package and the circular economy

The article describes challenges and developments that can ensure the circular economy from the EU Circular Economy Package. These affect production and product design, consumption, waste management, secondary raw materials, plastics and plastic wastes, critical raw materials, construction and demolition wastes, biomass and bio-based products, innovation and investment. For example, one consequence of the Circular Economy Package might be that consumers are provided with product-related environmental information that they can take into account in both purchasing decisions and during the useful life of products (e.g. repairability, recycled content). Consequently, the goal is to establish durable products which are suitable for circularity and open to innovations in the market.

4.1 The necessity of and arguments for a circular economy

In this article, the circular economy concept is assessed taking into account various perspectives. If a circular economy is desirable as a long-term goal, the path towards its implementation needs to consist of competitive intermediate steps so that this very goal is not threatened. Various arguments can speak for a circular economy, e.g. value creation through recycling, ever scarcer resources, less competition for land and fewer emissions, supply security, and lower structural risks in raw material supplies.

4.2 A systemic glance at and potential conflicting targets of a circular economy

A systematic glance at the circular economy reveals fundamentally conflicting targets. As a result, 7 points can be summarised as central challenges for implementing a circular economy:

Central challenges for the transformation towards a circular economy
1. The development of recyclable, i.e. recoverable products is vital in realising a circular economy. To become effective it requires that such products are competitive vis-à-vis non-recoverable products. In this regard, competitiveness demands that, in particular, the efficiency and performance of products needs to be considered in terms of both manufacturing and use.
2. The circular share of produced goods, i.e. in the form of repaired or refurbished products, reused components and recycled materials and raw materials needs to be increased. At the same time, safety requirements as well as comprehensive environmental standards must be secured.
3. Generally, existing mechanisms of product and waste management should be recognised. Sorting, separation and treatment technologies, including systems for logistics and materials identification along the life cycle, need to be further developed. For this purpose, close coordination with the development of recoverable products plays an important role as do the interrelationships among stakeholders concerned in the waste value chain.
4. The partly immense temporal difference between the demand for raw materials and the availability of secondary raw materials, including related problems regarding volumes, quality and acceptance, require new methods for forecasts and a long-term raw materials strategy.
5. Material losses due to either dissipation or due to those applications that intentionally show-up in the environment[3] need to be reduced. Materials, where losses cannot be avoided or are intended, should be sufficiently rapidly degradable.
6. Raw material demands which cannot be met by a circular economy or which are required to meet the energy consumption needs of a circular economy should be obtained increasingly from renewable sources in a sustainable manner, taking into account the competition of land-use for food production.
7. A circular economy and its concrete implementation must not counteract other important societal goals like coping with climate change, energy transition or reducing poverty.

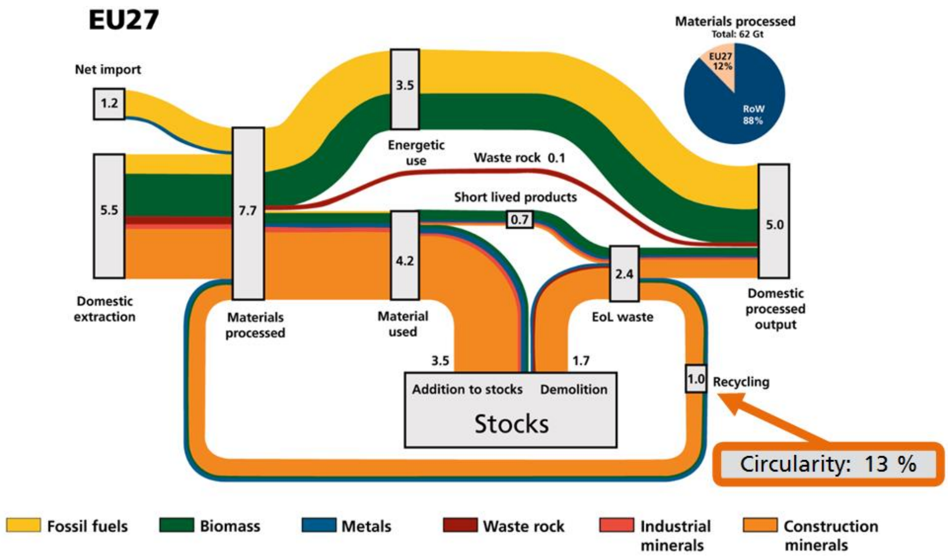
4.3 Status of the transformation towards a circular economy

The current situation with respect to the transformation towards a circular economy is a sobering one. With reference to the total volume of materials used (62 billion tonnes), the recycling share is ca. 6.5% globally and 13% in the EU-27 (cf. figure 2) [Haas-2015]. This is also the yardstick for circularity of the global economy and the EU, respectively. According to this model, circularity in

[3] These are, for example, materials which are supposed to remain in the environment e.g. flower pots or floor grids.

Germany was ca. 17% in 2014; when including unrecovered domestic extraction, it was only 7.6% (data from [DESTATIS-2016]).

Figure 2:
Material flows and circularity in the EU in the year 2005 – all data in billion tonnes, based on [Haas-2015]



The conclusion from the above is that only a small share of the total of processed materials is currently part of closed loops. At present, neither the world nor the EU or Germany are anywhere near a point where a realised circular economy would be in sight – when taking all materials used as the reference parameter. Today, about 45% (3.5 billion tonnes) of these materials go directly into energetic use, i.e. they are not circular. Therefore, the progressing phase-out of fossil energy sources from the energy system combined with the rising use of renewables (e.g. following the model of the German *Energiewende*/energy transition) would clearly help increase circularity – even without material recycling. Recycling is an additional component in the transformation towards a circular economy if it can be done in a manner which is sound in economic, ecological and competitive terms. But recycling alone is not enough to set things right because, firstly, now as in the past the material consumption of fossil energy sources remains very high and, secondly, global material stocks in long-life products and buildings are rising fast and steadily (and such materials can be recovered only with time delays). Access to stocks of materials (anthropogenic stocks) is only possible if, firstly, at any moment in time enough information is available about the material mix used in construction and the volumes of materials used in the given case and, secondly, if there is a combination of suitability for further use, modularisation, strengthening of components, recycling-friendly design, and an economically viable recycling technology.

4.4 Obstacles in the implementation of a circular economy

Figure 3 shows the technological, economic and ecological challenges and limitations for moving from a »linear economy« to a circular economy. Technical challenges include e.g. the product design or dissipative material losses. Ecological challenges are, for example, the specific energy and raw material requirements of recycling as well as critical emissions. Economic challenges comprise, inter alia, the prices of secondary raw materials as compared with primary raw materials and the approach to dealing with by-products, which are obtained both intentionally and unintentionally in a production process, in addition to the main product.

Figure 3:
Limitations and challenges for a circular economy; own chart

4.5 Transformation process towards a circular economy

The circular economy demands innovative processes and innovations which provide, at the same time, a basis for new business models. This calls for driving forces and drivers; they can come from the market economy and/or the political-strategic sector (see figure 4).

Figure 4:
Drivers for a transformation towards a circular economy; own chart

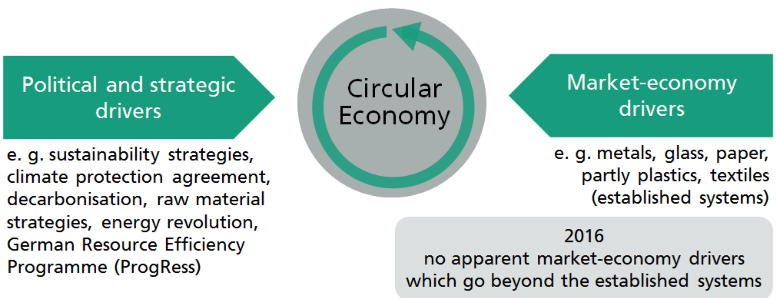


Figure 5 sums up the transformation process towards a circular economy. This process is within the framework of digitalisation and intelligent business models. In order to implement a circular economy, it is essential to improve the exchange among and the synergies between actors (idea of an innovation platform). Furthermore, pilot and demonstration plants – funded by public or public-private partnerships – are important for material flows which cannot be (economically) recycled today in order to build competencies and knowledge. Research programmes for material and product development and criteria for measuring circularity are relevant to measure successes and to ensure the information transfer between production and recovery. This also includes labelling across entire life cycles. Product design can contribute to the circular economy by way of a modularisation of product components (exchange, repairability, refurbishment). Finally, it is important to establish a digital inventory which covers time horizons and geographical areas and includes data on the content of long-life products so that new business models can be realised by means of a digitalisation of the circular economy.

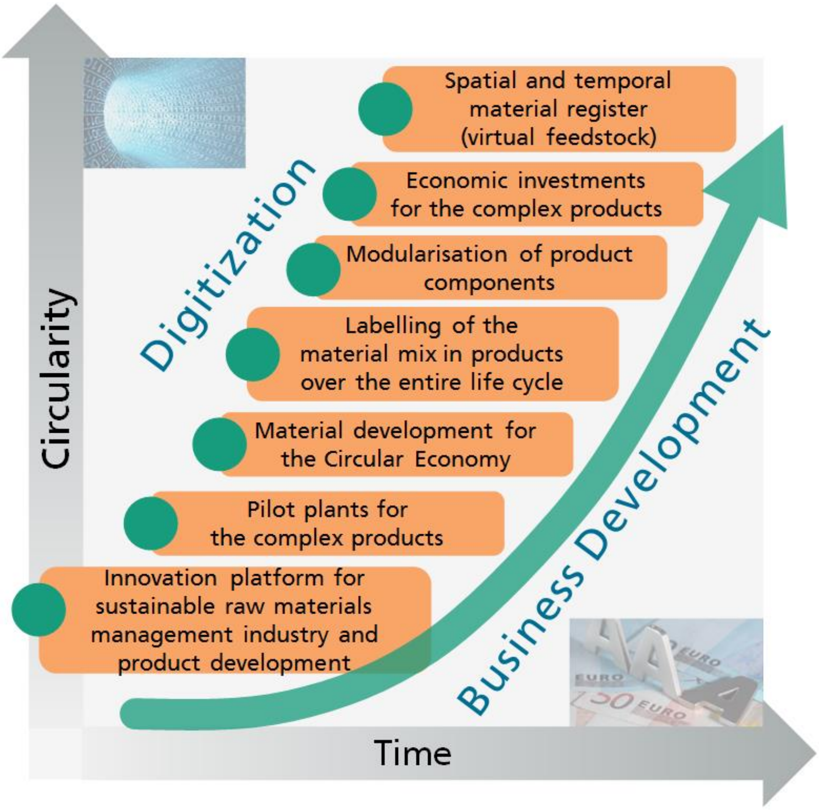


Figure 5: Measures to increase the circularity of industrial countries; own chart

Conclusions and recommendations

The analysis of potentials and limitations of circular economy in the study conducted revealed that an increased circularity can be achieved by different measures:

- In order to increase the application of secondary raw materials, harmonized quality standards should be developed to ensure a high degree of substitution and circularity.
- Pilot and demonstration plants – funded by public or public-private partnerships – are important for types of materials that cannot be (economically) recycled today in order to build competencies and knowledge and to bridge the gap between research and application in the industrial environment.
- Research programmes supporting the development of recyclable materials and products as well as the development of criteria for measuring the circularity of materials, products and entire branches are required.
- Recycling quotas should consider the criticality of recovered raw materials in order to support the recovery of critical elements.
- Products and secondary raw materials should be labelled life-cycle wide in order to provide information on material composition, amounts and quality.
- A digital inventory covering time horizons and geographical areas and including data on the content of long-life products could help to realize new business models by means of a digitalisation of the circular economy.

5 Literature

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