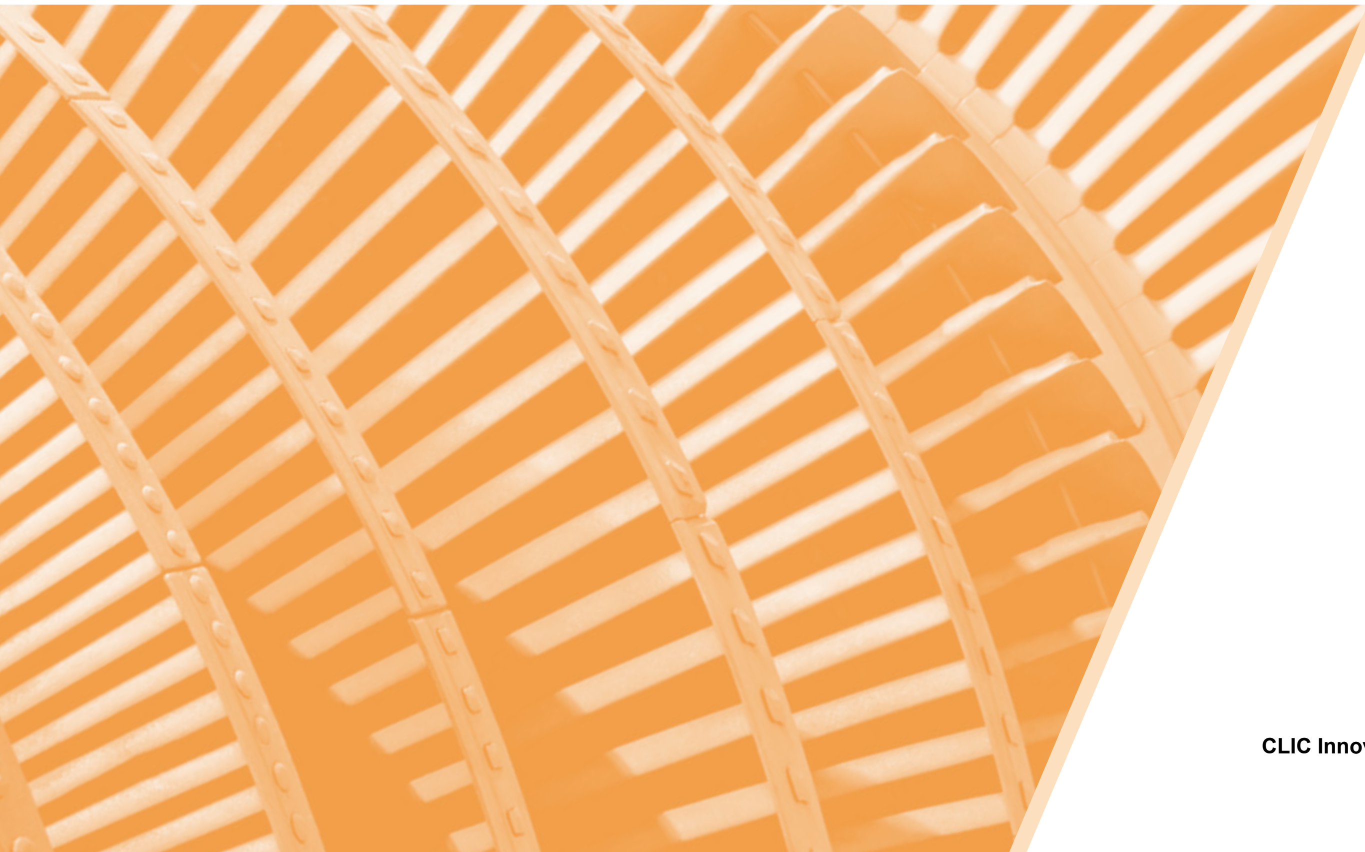
STRATEGIC RESEARCH
AND INNOVATION AGENDA

Circular Economy

CLIC INNOVATION LTD

Contents



Summary

Global material usage has grown rapidly during the 20th century and in the beginning of the 21st century. The continuation of overconsumption can no longer guarantee our future success. Instead, the plastic challenge, climate crisis and the associated decline in biodiversity are challenging the foundations of our society and the traditional political agendas, as well as business logic. We need to give everyone access to sustainable solutions that respect the limits of the earth's carrying capacity. While solving major global challenges, these solutions also provide opportunities to the economy and pave the way for sustainable growth and wellbeing in the society.

In recent years, the concept of circular economy has become an important component of both innovation and economic policies in many countries and international conventions. In addition to the EU Circular Economy Package and the New Circular Economy Action Plan, circular economy plays a significant role both in the UN Sustainable Development Goals and in the agenda of the von der Leyen commission.

The transition to circular economy requires systemic changes, novel solutions and drastic improvements in policies, regulation and consumer behaviour. In addition to novel technologies that enable a more efficient use of raw materials and create new alternative materials, there is a need for new business models and novel type of behaviour among actors. Digitalisation offers opportunities to get timely and specific information on materials, their quality and value chains. In order to reach these goals, seamless cooperation between the research community, industry and policymakers is pivotal.

In 2019, the shareholders of CLIC Innovation identified four critical circular economy areas where research, development and innovation (R&D&I) activities are most needed. This strategic research and innovation agenda (SRIA) for Circular Economy presents these four focus areas, which are:

1. Recycling of plastics and alternative materials
2. Nutrient cycles
3. Valuables in inorganic streams
4. Carbon recycling

In addition to the four key areas, four crosscutting topics were identified for further development:

1. Opportunities provided by digitalization and data management
2. Added value from combined material streams
3. Water and energy efficiency
4. Restricting factors

CLIC Innovation operates at the intersection between industry and academia to advance research, development, demonstration and innovation cooperation. To progress most efficiently in the selected focus areas for circular economy, we identified the following needs:

- The transition should take place in a systemic fashion, and therefore the process should be participatory, holistic and consider potential trade-offs.
- The development of novel technologies, materials and products should be supported.
- Wide utilisation of existing research and piloting facilities should be assisted by proper shared-utilisation models.
- Stronger and closer interaction between regulatory bodies and companies should take place.
- To enable these developments and to contribute to the long-term promotion and research of the circular economy, more public and EU funding is needed.

Foreword

CLIC Innovation is an open innovation cluster with the mission to facilitate creation of breakthrough solutions in three areas: bioeconomy, circular economy and energy. As a public-private-partnership, CLIC Innovation uniquely brings together the necessary industrial and academic competences to achieve its targets. CLIC Innovation aims at speeding up the production and commercialisation of new knowledge by initiating and managing solution-oriented collaborative projects covering the entire field from basic research to demonstrations.

Building strategic research and innovation agendas (SRIAs) is the primary tool used at CLIC Innovation to set common targets and to define focus areas for a significant number of actors. It is the document you are reading, and an output of intensive cooperation between the network of CLIC Innovation's owners and partners, comprising a broad group of stakeholders representing business and research. The development of this SRIA is an open and continuous process that goes far beyond CLIC Innovation. We actively invite other stakeholders to join and participate in the activities that originate from this SRIA. We commit to regularly re-evaluate the SRIA to ensure that it is up to date and relevant.

The current SRIA for circular economy set out and discusses four focus areas and four crosscutting topics:

- Focus areas: plastics, nutrient cycling, inorganic streams and carbon recycling
- Crosscutting topics: digitalization and data management, combined material streams, water and energy efficiency and restricting factors

The transition towards a circular economy is not only inevitable, but also offers growing global business opportunities. However, competition keeps getting harder in international business. The winning solutions and businesses are not created using the old ways of doing things – they require many kinds of cooperation models between parties from both private and public sectors.

The owners of CLIC Innovation Ltd seek to reduce the global overuse of natural resources with novel technological and service solutions. The owners are prepared to invest significantly in a Public-Private Partnership for circular economy both by co-financing applied research and by investing in demonstration and development projects.

Addressing global challenges

During the 20th century, the total global material extraction grew by a factor of about eight. Global resource use has more than tripled from 27 billion tons in 1970 to 92 billion tons in 2017,

and the future trend is predicted to be similar (UNEP, 2011; UNEP, 2019). This has led to a re-evaluation of the current economic strategy. The extended period of overconsumption can no longer guarantee our future success. Instead, the plastic challenge as well as the climate crisis and the associated decline in biodiversity are challenging the foundations of our society and the traditional political agendas, as well as business logic.

The circular economy is a concept to significantly reduce the extraction of virgin raw materials by technological, management and system innovations and practices. In recent years, the circular economy has become an important component of both innovation and economic policies in many countries. For the European economy, the net benefit of the circular economy has been estimated to be around 1800 billion euros by 2030 (Sitra, 2016). The different political approaches share many common measures to promote technological innovation, economic growth, ecological sustainability and resource efficiency. However, there is great variation in the political aims and measures taken by individual countries. The underlying motivations range from a desire to secure access to raw materials to comprehensive regeneration of the innovation system and a transformation of the economy.

The transition to circular economy is guided by the UN Sustainable Development Goals, the EU Circular Economy Package 2015 and the supplementary mini package published in 2018. Moreover, the circular economy will be a crucial element in the agenda of von der Leyen's Commission. The European circular economy transformation will be fostered with the aid of a New Circular Economy Action Plan for a cleaner and more competitive Europe (COM 202098 final) (European Commission, 2020a).

The effective EU Circular Economy Package contains 54 actions that are currently either being delivered or under implementation. The circular economy is considered to be a backbone of the EU industrial strategy for all industrial sectors (European Commission, 2020b). Moreover, the new Action Plan presents a set of interrelated initiatives such as a sustainable product policy framework, key product value chains, creation of less waste and more value, making circularity work for people, regions and cities, leading the global efforts and monitoring the change. Additionally, the plan contains crosscutting actions with climate neutrality, economics, research, innovation and digitalisation. Further, the circular economy has been one of the focus areas of the biggest EU Research and Innovation programme Horizon 2020, and it is expected that in the next framework programme it will also have a significant role.

Global long-term development requires a controlled transition from the current, unsustainable, fossil-based consumer society to a sustainable, circular economy. This entails a conversion from an economy that is largely based on fossil raw materials to a more resource-efficient economy that extensively utilises renewable and non-renewable resources in a circular way, aiming to minimise the extraction of virgin raw materials.

Figure 1. UN Sustainable Development Goals

Strategic research and innovation agenda

This Research and Innovation Agenda summarises the views of CLIC's owners and partners on the necessary research and development efforts to advance the circular economy. The development of sustainable use of the natural resources is driven by scientific and technological advancements, for example in process technologies, industrial biotechnology, synthetic biology and information technologies, and by new business and consumption models. New technologies for intelligent material circulation, extraction of materials from versatile sources, and implementation of nitrogen and carbon circulation speed up the transition towards a circular economy.

The agenda has been built around four thematic key areas: plastic recycling and replacement, nutrient cycling, inorganic streams as a source of valuable materials, and carbon recycling (Figure 2). In addition to the four key areas, four crosscutting topics have been identified. The crosscutting topics cover factors that may restrict recycling, opportunities provided by digitalisation and data management, benefits from combining material streams, and objectives to reach water and energy efficiency in the circular economy processes.

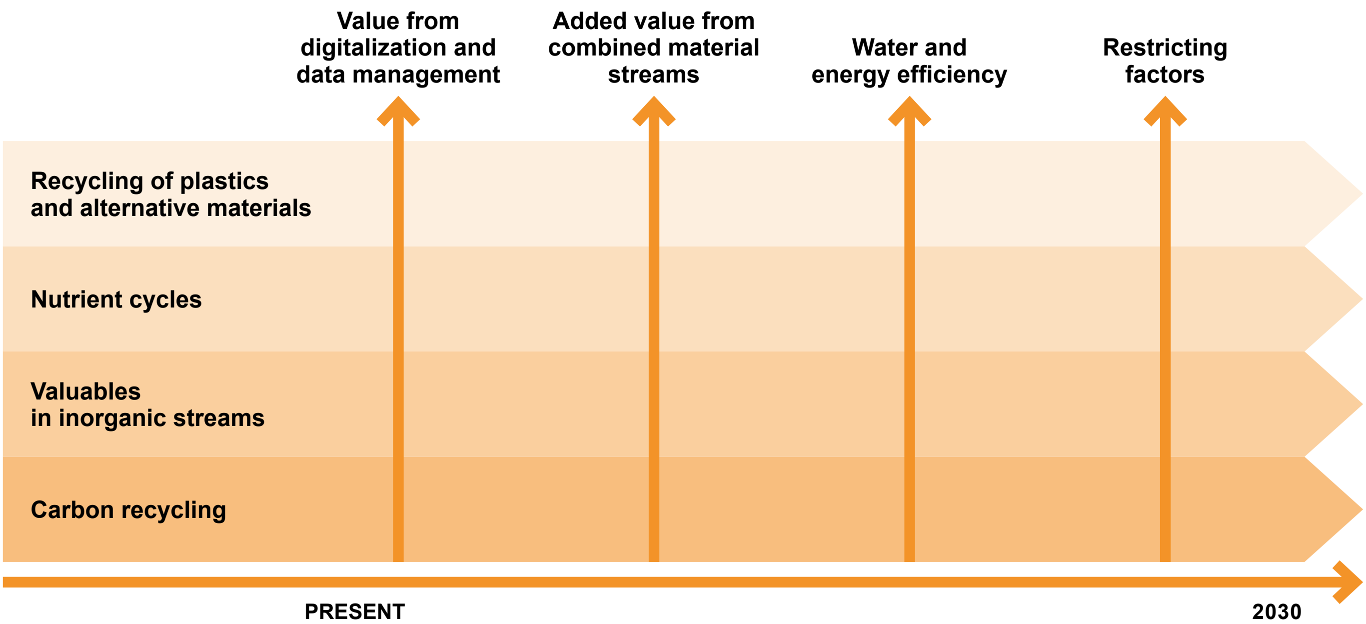


Figure 2. Circular economy, key topics

The rapid development of digital and data management tools has brought immense opportunities to the circular economy. Advanced technologies, such as smart sensors, artificial intelligence and block chain, offer tools to make a shift from centralised to decentralised systems where all the essential assets and operations are connected. This shift enables decisions concerning the utilisation of natural resources to be made on real-time data from systems where materials are produced and used. However, this development brings about new questions related to e.g. the availability, accessibility and ownership of data in addition to the environmental impacts of digitalisation. The growing production and use of electronic devices in addition to the digital infrastructure increases the need for resources and energy.

Water is a crucial element in all living and a necessity for industrial processes. Water scarcity and access to clean water are growing concerns that have to be taken into account in all circular economy activities. Improved water-efficiency and smart water management are vitally important. Like water, energy is vitally important both for life and for industrial operations. Hence, clean energy production and energy efficiency play an essential role in a viable circular economy.

Factors that may restrict recycling of the selected key material streams as well as the benefits that could be reached if streams where combined in some way are shed light on in the following focus area descriptions.

Focus areas for research and innovation

RECYCLING OF PLASTICS AND ALTERNATIVE MATERIALS

Summary

The immense growth in the use of plastics in products and packaging has created a global waste problem that requires systemic circular economy solutions. Solving the plastic challenge requires better collection and recycling of plastics, but also changes in business models, regulation and consumer behaviour. Alternative materials may provide help and so can digital services that offer timely information about the materials, value chains and waste streams. Our circular economy approach to plastics covers the 6Rs: Reduce, Redesign, Remove, Re-use, Recycle and Recovery.

Recommendations for future actions

- Creating a comprehensive collection and sorting system for plastic waste
- Developing recycling technologies for complex multi-material streams
- Creating new cost-efficient ways to identify components in plastic waste streams and to purify and separate valuables and hazardous compounds as well as to upgrade the quality of the recycled plastics
- Utilising digitalisation better to offer timely information about the existing material streams, their quality and value chains
- Developing alternative material solutions from renewable feedstocks

Current status

Plastics are a necessity for modern society. Today, however, plastics also constitute a massive challenge on a global scale. Currently, around 8 million tonnes of plastics end up in the ocean every year (Fabres et al., 2016).

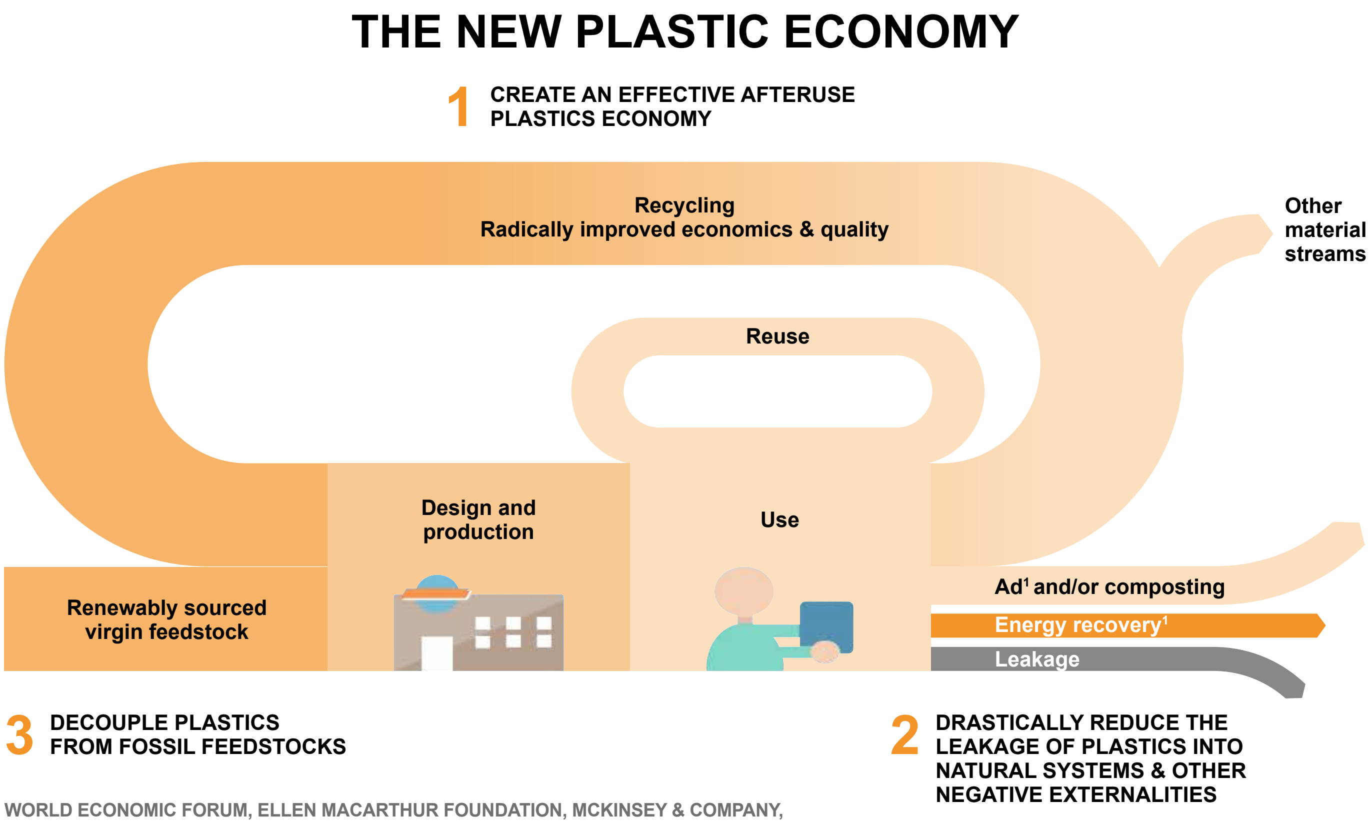
In Europe, around 29 million tons of post-consumer plastic waste was generated in 2018 (Crippa et al., 2019). Most of this plastic waste comes from packaging materials. Only an estimated 42 percent of the plastic packages were recycled in 2017 in the EU (Eurostat, 2019). In order to significantly improve plastics recycling, a Europe-wide strategy on plastics was adopted in January 2018, aiming at all plastic packaging on the EU market to be recyclable by 2030 (European Commission, 2018a). The amendments to the EU Waste Framework Directive 2008/98/EC tighten the recycling targets for plastic packaging. Further, the Directive on the reduction of the impact of certain plastic products on the environment i.e. SUP directive (Directive (EU) 2019/904) was accepted in June 2019. In addition, the mitigation of plastic pollution is included in the targets of The European Green Deal and the related Investment Plan (European Commission, 2020c, 2020d) as well as in the targets of the New Circular Economy Action Plan (European Commission, 2020a).

Globally, billions of people lack appropriate waste management. At the same time, people may be dependent on plastic products, for example, on plastic bottles to ensure access to clean drinking water. Disposable plastics are a burden to waste management systems and easily end up in the environment. The use of unnecessary packaging materials should be avoided, but this alone will not solve the plastics problem. In the short term, extending the collection of plastics to all plastic goods is necessary, and the efficiency of recycling needs to be improved. In the longer term, alternative material solutions that are based on renewable raw materials provide potential for building a sustainable material system as a whole.

Market opportunities

As waste management systems in many countries are either non-existing or inefficient, there are major global business opportunities for efficient, affordable and clean technologies and solutions for waste collection, sorting and recycling as well as for landfills and waste-to-energy plants. In the EU, as a consequence of the tightening regulation, market demand is growing especially for improved recycling solutions.

Building efficient collection, sorting and recycling systems may take time. Therefore, ensuring biodegradability for certain plastic products can be beneficial from the environmental point of view and, hence, biodegradable plastics show growing market demand. In addition, the interest towards bio-based materials as alternatives to fossil plastics is growing. Fossil-based plastics can be replaced by either bio-based plastics or by quite different bio-based materials solutions often easier to recycle or with superior material properties. Currently, the overall share of the bio-based plastics is still modest, around 2% of the total plastic production. The demand, however, appears to grow at a steady annual rate of 1.5–2% in Europe and 3–4% globally (Crippa et al., 2019).



WORLD ECONOMIC FORUM, ELLEN MACARTHUR FOUNDATION, MCKINSEY & COMPANY,
A NEW PLASTICS ECONOMY: RETHINKING THE FUTURE OF PLASTICS (2016)
ELLENMACARTHURFOUNDATION.ORG/PUBLICATIONS
1 Anaerobic digestion
2 The role of, and boundary conditions for, energy recovery in the New Plastics Economy needs to be further investigated.
Source: Project Mainstream analysis

Figure 3. The New Plastics Economy, Ellen McArthur Foundation 2016

Focus areas for research and innovation

To overcome the plastic challenge, efficient recycling and reuse processes, cascading use of materials and alternative material solutions to fossil-based plastics are needed. Research and innovation activities should be directed to the following areas:

- New technologies that increase the recyclability of the plastic waste and improve the efficiency of the recycling system
  - Advanced and cost-efficient on-line analytics for the sorting and separation of plastic waste streams
  - Novel imaging and/or spectroscopic solutions for mechanical separation, e.g. identification of black plastic, colour removal and multi-layered films
  - Technologies for purification, separation and control of hazardous substances in recyclates (e.g. contaminants, additives, bromine-based fire retardants)
  - Technologies for recycling of complex, multi-material waste streams
  - Technologies for chemical recycling
- Alternative material solutions to fossil plastics
  - Bio-based mono-material solutions, e.g. for food packages, from forest-based feedstocks
  - Performance and optimised properties of the bio-based materials
  - Compatibility of the bio-based alternatives to the current recycling system
  - Multi-material solutions, e.g. composites, for construction, transport and agricultural applications
- Industrial health and safety
- New business models for material efficiency and recycling
- Development of the whole recycling system and policy instruments in a cross-disciplinary and cross-sectoral cooperation
  - Databases on streams, volumes and value chains
  - Classification systems and standards for recycled plastics
  - Consumer behaviour and acceptance

NUTRIENT CYCLES

Summary

The finite nature of nutrients has led the EU to being dependent on imported phosphorus. At the same time, there are major nutrient losses leading to harmful environmental impacts. The solution is a transition to a nutrient cycling economy that supports a food system that is regenerative and restorative. An efficient nutrient-cycling economy utilises both agricultural, municipal and industrial wastes, wastewaters and side streams as sources for nutrients.

Recommendations for future actions

- Developing viable technologies for the recovery of nutrients from wastes, wastewaters and side streams, and for upgrading of the recovered nutrients to valuable fertiliser products
- Developing cost-efficient and scalable removal and control technologies for organic and microbial contaminants and physical impurities in recycled nutrients
- Developing solutions for integrated biogas production and nutrient recycling, i.e., for nutrient biorefineries

Current status

Nutrients are a critical resource for society. The world's mineral phosphorus sources are finite, and EU countries are remarkably dependent on imported phosphorus. The EU Circular Economy Package promotes the use of nutrient cycling by introducing a new regulation that aims to cut the EU´s phosphate import by a third, from six million tonnes to four million tonnes (European Commission, 2015; Euractiv, 2016). In addition, EU aims at optimising the use of fertilisers by sustainable agricultural practices.

To improve nutrient management and the quality of soil, novel agricultural practices are called for, and it is generally acknowledged that we need to transform our current food system towards one that is regenerative and restorative. The transition to an efficient nutrient cycling economy requires a combination of various measures including, e.g., developing fertilising instructions and restrictions to suit the needs of crops, promoting the demand for organic fertilisers, encouraging manure processing and use, increasing the use of recycled nutrients at crop farms, and improving the operating conditions for local biogas production.

Nutrients can be recycled from different sources including waste and side streams from industries. The major challenge lies in the cost. Advanced technologies are needed for scalable and resource- and cost-efficient separation and recovery of nutrients, phosphorous and nitrogen in particular. Further, recycled nutrients are not necessarily chemically suitable for direct reuse, and thus chemical modifications may be necessary. Also, management of antimicrobial resistance is needed (Zhu et al., 2019).

Market opportunities

Major economic value lies in the development of efficient nutrient cycles as well as in the reduction of nutrient loss and the resulting harmful environmental emissions. Nutrient cycling is an opportunity to strengthen the existing businesses as well as to create new business operations and start-up companies with new service business models. Economic benefits are generated through profits from new businesses, direct costs savings in existing businesses, improved trade balance, improved food and raw material security and reduced environmental health risks (Aho et al., 2015; Marttinen et al., 2017; European Commission, 2020a).

There is a global market potential for recycled nutrients and fertilisers. The market is still quite limited but can be developed. In addition to fertilisers, recycled nutrients can be utilised as raw material for new added value products, e.g., feed (Figure 4). Other fields with growing business opportunity relate to water purification and bioenergy production. Underutilised blue biomass types such as algae, mussels and fish also provide significant opportunities for nutrient cycling and new business (Schultz-Zehden & Matczak, 2012; University of Helsinki, 2018; European Commission, 2019).

Introduction of novel business models can accelerate the transition to an efficient nutrient cycling economy. For example, fertiliser leasing is a rapidly growing new business model in Europe. According to current estimates, the economic net value of fertiliser leasing could reach an annual volume of EUR 70 million in Finland by 2030 (Aho et al., 2015). Further, digitalisation, e.g., block chain technology, provides possibilities for introducing new service concepts and helps tackling issues on, e.g., the logistics and control of side streams.

Focus areas for research and innovation

To ensure the transition to an efficient nutrient cycling economy, techno-economically feasible solutions are needed for utilising wastewater, sewage sludge, biodegradable waste as well as industrial wastes and side streams as sources for nutrients and fertilisers. Research and innovation activities should be directed to the following areas:

- Cost-efficient technologies for the recovery of phosphate and nitrogen from wastewater, sewage sludge, manure, ashes and industrial side streams
  - Anaerobic digestion
  - Biological treatments
  - Chemical treatments
  - Mechanical separation technologies
  - Advanced membrane technology
  - Concentration technologies for dilute solutions
- Mitigation of challenges with contaminants
  - Purification and removal technologies for different contaminant categories (pharmaceuticals, heavy metals, pathogens, etc.)
  - Impacts of the contaminants to health and the environment (i.e. risk management)
- Biogas plants as biorefineries for nutrient recycling
  - Potential substrates for biogasification include food waste, field biomass, sludges from municipal and industrial wastewater treatment plants, and manure
- Deployment of different waste and side streams as nutrient sources
  - Digital control systems for decentralised material streams
  - Value chain development
  - Business model development
- End product (fertiliser) development and related business concepts (e.g. fertiliser leasing)
- Crosslinks with the 1-carbon and hydrogen economies

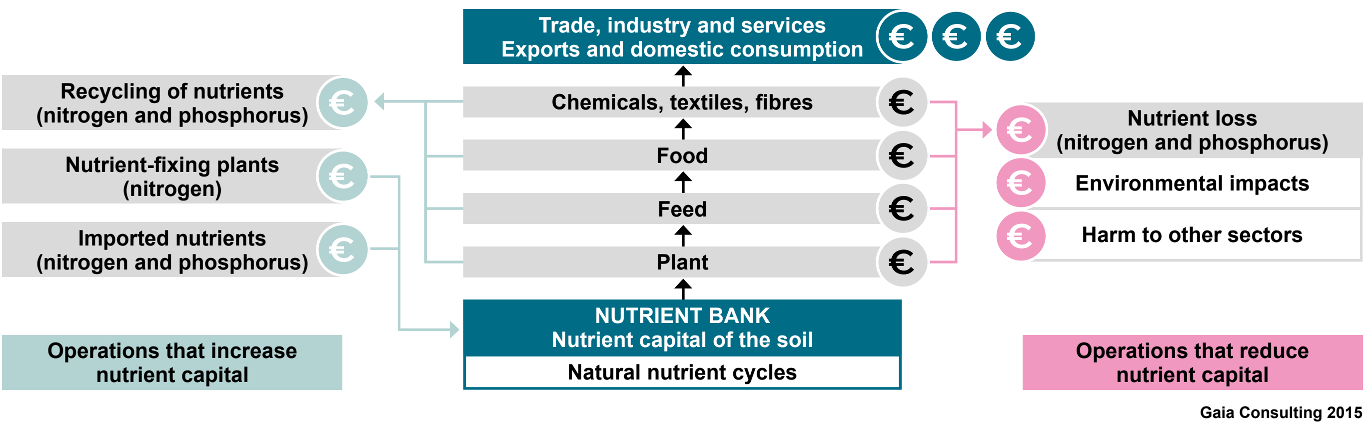


Figure 4. Nutrient economy (Aho et al., 2015)

VALUABLES IN INORGANIC STREAMS

Summary

The important inorganic streams with hidden value potential include side streams from mining and metal production, waste electronics, construction and demolition waste, and ashes. Recycling of these streams is complicated because of their heterogeneous content, low concentrations for valuables and the presence of impurities and/or hazardous substances. Many of them would require processing before utilisation. New identification and separation methods and use of real-time data on the material content would enable better management and utilisation of these streams and the value they contain.

Recommendations for future actions

- Developing resource-efficient extraction and separation technologies to improve the recovery of valuable and/or critical minerals and metals from mine tailings, ashes, low-grade slags, dusts and sludges, other industrial side streams and waste electronics
- Introducing novel recycling and reuse concepts for construction and demolition waste
- Developing resource-efficient and scalable technologies for identification, purification and deactivation of harmful and toxic substances in industrial side streams and wastes
- Developing new application areas and better added value for the recycled materials
- Designing new models for data-driven service businesses

Current status

EU has a goal to improve its raw materials security. The digitalisation of life and businesses has created a huge increase in the need for many minerals, such as materials for lithium-ion batteries. For inorganic raw materials, improving material recycling is the key to reach the goal of security of supply.

Extraction of valuable materials from inorganic industrial side streams and wastes such as mine tailings, residues from metal production, waste electronics (WEEE), construction and demolition (C&D) waste, and ashes helps in securing the need of rare earth elements and critical materials for the European industry. In addition, extraction and recycling of the valuables in wastes and side streams may enable reduction of the overall costs of waste management for some waste streams in the future.

In order to make material extraction from wastes and side streams feasible and deployed in large scale, we need to develop cost-efficient extraction technologies both for valuables and harmful compounds. The main challenges lie in the low concentrations of the valuables and the variation in material quality. In addition, the low volumes and high variety of side streams and the content of hazardous substances make their feasible utilisation economically challenging. Therefore, better logistic solutions for storage, distribution and processing of these streams are needed. The utilisation of digital tools based on the Internet of things, block chains and artificial intelligence is crucial to overcome the challenges in logistics and distribution.

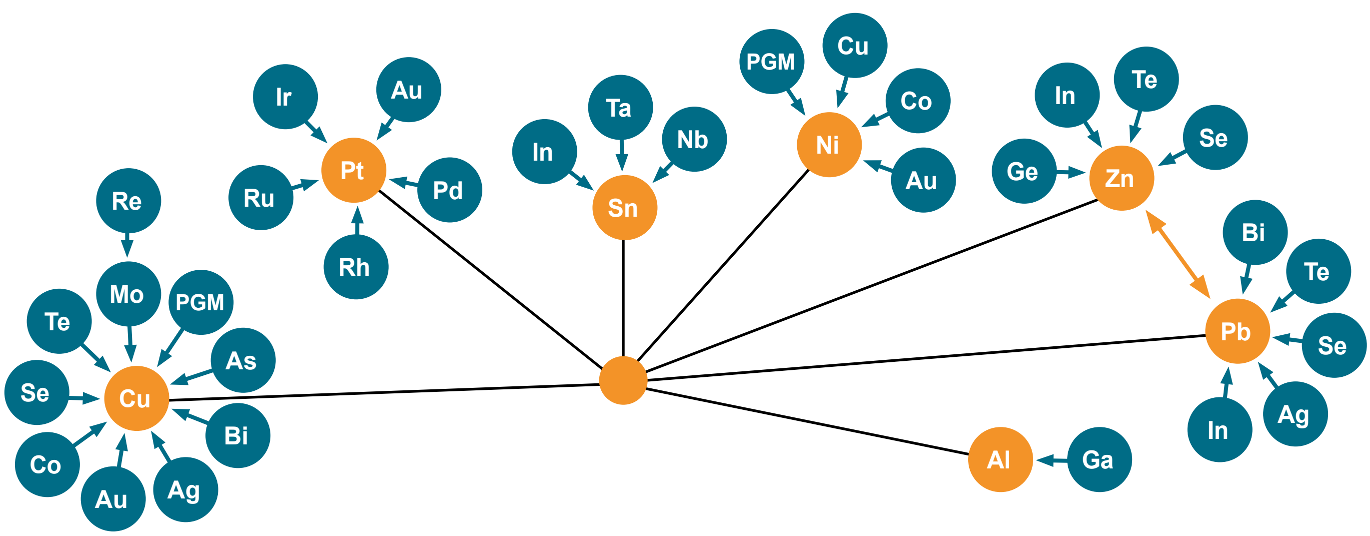


Figure 5. Sources of critical materials and their associated base metals (based on Hagelüken and Meskers, 2010; EASAC 2016)

Market opportunities

Critical materials, mainly metals, are economically important raw materials for a wide range of industrial sectors. Europe consumes 25–30% of the world's critical materials, but only 3% of global metal production is in Europe, leading to a high risk of supply interruption (European Academies Science Advisory Council, 2016). The battery industry, for example, is an important user of metals and a strategic value chain for the EU. The demand for batteries is estimated to increase tenfold in 2015–2020. The European battery market has been projected to grow to €250 billion by 2025. Today, around 80% of the world's batteries are manufactured in Asia.

WEEEs such as computers, TV sets, fridges, and cell phones are one of the fastest-growing waste streams in the EU, with some 9 million tonnes generated in 2005, and expected to grow to more than 12 million tonnes by the end of 2020. Recycling of WEEE creates business opportunities for, e.g., technologies that are suitable for identifying or separating substances in different matrices. Also, methods to improve the flow of information on the material content and harmful substances are needed. Furthermore, there are new business opportunities available in product design and reuse, and in the repurposing of by-products.

In addition to WEEE, tailings from mining and side streams from the metal industry could have a considerable role as sources for minerals and metals. Mine tailings, especially, are an underused source of minerals today. Novel technologies are, however, needed to capture their potential as the tailings are heterogeneous, they contain valuables in low concentrations and often contain impurities. The market prices of minerals have an impact on the profitability of extracting them from side streams and hence may either boost or slow down new business generation.

Ashes and slags are produced in all combustion processes where solid fuels are used. Ashes have been used for years mainly in low value applications such as in earthworks or they have been landfilled. Nevertheless, ashes contain many components that may create value in the future and therefore ashes should be regarded more as sources of valuable elements. The valuables in ash can be, for example, metals, rare earth elements, nutrients or pure mineral fractions. In the future, ashes could perhaps be utilised as raw material for, for example, ceramics and other construction products (Silva et al., 2017). Similar to ashes, green liquor dregs are created in soda recovery boilers when burning dissolved wood material. Utilising dregs has been difficult but according to a recent study, flue gas cleaning may provide potential for their reuse (UPM, 2016).

The construction and real estate sector is one of the largest consumers of natural resources, also producing a vast amount of waste and side streams. Recovery of materials from construction and demolition waste provides growing opportunities globally.

Focus areas for research and innovation

To simultaneously manage the sufficiency of natural resources, mitigation of climate change and changes in our increasingly digital lifestyle, we need to use our resources of inorganic raw materials more efficiently. This can be done by smart design of products to extend their lifetime, through recycling and by efficient material recovery and recycling systems. Utilisation of the full material value of the inorganic side streams and wastes in essential. Research and innovation activities should be directed to the following areas:

- Resource-efficient extraction and separation technologies for old tailings and side streams from mining, construction, metal and manufacturing processes, electronic appliances and incineration, e.g.
  - Scalable and energy-efficient grinding and fractioning
  - Biochemical extraction
  - New pyro- and hydromechanical processes
  - Mobile extraction and processing solutions
  - Cost-efficient concentration technologies for dilute solutions
  - On-line analytics
  - Recovery of the materials in the primary process phase (e.g. battery chemicals)
- Cost- and resource-efficient and scalable identification, purification and deactivation technologies for harmful and toxic substances in side streams and wastes
- Solutions for substituting harmful, critical or scarce materials in batteries and electronic appliances
- New application areas for recycled materials, e.g., new added value from ashes and green liquor dregs
- New models for data-driven service businesses (block chain, artificial intelligence, digital marketplaces)

CARBON RECYCLING

Summary

With climate change progressing, a rapid decrease in greenhouse gas emissions is needed in all sectors. From the perspective of sustainable circular economy, CO_2 emissions and also the CO_2 already in the atmosphere can be seen as raw material. Introduction of carbon-neutral industrial systems catalyses the adoption of industrial CO_2 recycling. Carbon capture and production of synthetic fuels, chemicals and other products using industrial CO_2 emissions as raw material pave the way for building a carbon-neutral or even a carbon-negative circular economy.

Recommendations for future action

- Developing energy- and cost-efficiency of carbon capture
- Developing feasible solutions for CO_2 capture by mineralisation using industrial side streams
- Developing advanced chemical and materials synthesis from single carbon compounds including solutions of biomimicry, synthetic biology, artificial photosynthesis, microbial solutions, and chemical synthesis
- Producing profitable products such as proteins, ingredients for cosmetics, oils and fuels from recycled

Current status

Global greenhouse gas emissions must become negative in the coming decades. All sectors (transport, energy, industry, land use, agriculture, waste) need to eliminate their emissions and partly become emission-negative. On the other hand, the atmosphere is an endless reservoir of CO_2 and other essential elements for life. Simple carbon compounds (CO_2, methane, CO, etc.) provide a feedstock for the production of materials, chemicals, food, feed and energy. Our future resource sufficiency calls for technological innovations which enable cost-efficient and environmentally benign use of such simple carbon compounds in the atmosphere.

From the techno-economic perspective, capturing carbon before it is emitted to the atmosphere and utilising it for the production of fuels, chemicals or other products (CCU) may be more feasible than direct capture from the air, at least for the time being. For carbon-neutral industrial systems, CCU is in fact inevitable as not all processes can be electrified and since certain products, such as cement, can for the moment only be produced from carbon-containing raw materials.

Utilisation of captured carbon compounds for the production of synthetic organic products is interlinked with the concept of hydrogen economy as the synthesis often requires a hydrogen source, too. Renewable sources of energy play a major role in enabling hydrogen

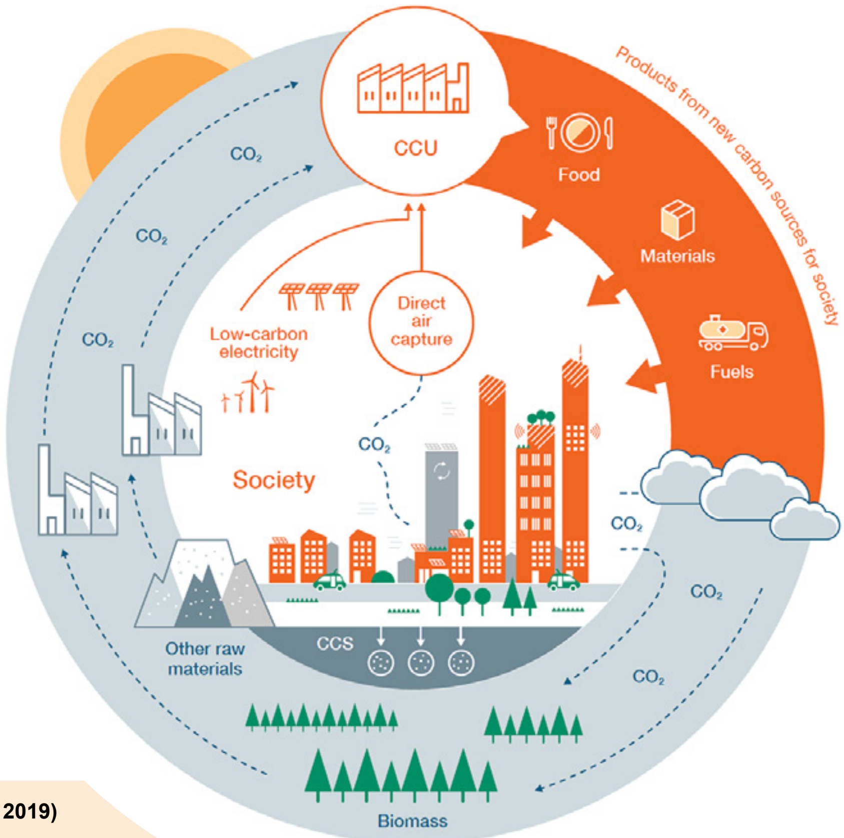


Figure 6. Carbon Reuse Economy (Lehtonen et al., 2019)

economy. Transforming the energy sector into emission-free requires utilisation of all renewable energy forms including hydro, wind, solar, and bioenergy.

Market opportunities

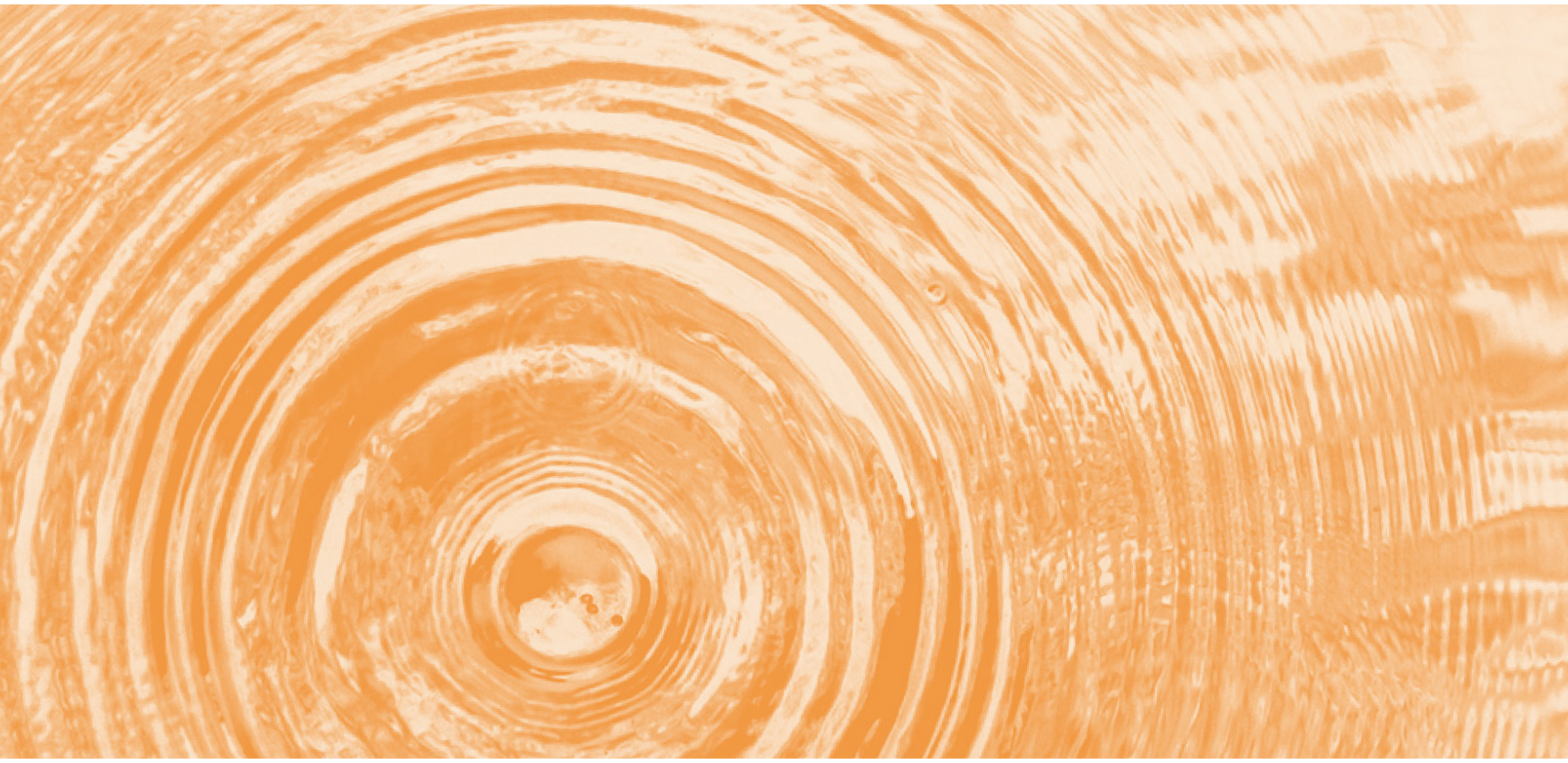
The European Union aims to achieve carbon neutrality by 2050 (European Commission 2018b). To reach this target, CO_2 emissions in all sectors need to be reduced, large-scale investments in renewable electricity production must be made and capabilities for utilisation of carbon emissions need to be developed. The speed of the transition to a carbon-neutral circular economy largely depends on the adapted policies and social acceptance. In addition, the declining costs of renewable energy sources fosters the transformation towards a low-carbon society.

In the future, it is likely that the CO_2 and other C1 compounds will provide an important feedstock for materials, chemicals and food. However, despite the growing interest of companies, capturing the new business opportunities still requires development of long-term policy frameworks as well as research and development work on technologies. Mitigation and recycling of CO_2 produced from the steel, concrete and chemical production processes are burning challenges that need to be solved with new technologies. Further, synthetic biology and future agile biorefineries that combine biology to engineering and information technologies pave the way to disruptive innovations for advanced CO_2 utilisation.

Focus areas for research and innovation

To boost the transition to a carbon-neutral circular economy, viable and cost-effective solutions for carbon recycling and utilisation of single carbon compounds for the synthesis of chemicals and materials need to be developed. Research and innovation activities should be directed to the following areas:

- Improved efficiency of carbon capture solutions
  - Improved energy efficiency
  - Concentration technologies
  - Utilisation of gasification technologies
- CO_2 capture by mineralisation using industrial side streams, such as metallurgical slags, ashes and mine tailings
- Advanced chemical and materials synthesis from single carbon compounds
  - Solutions of biomimicry, e.g., technologies that convert CO_2 into sugars and other products using similar approaches that appear in nature
  - Synthetic biology
  - Artificial photosynthesis
  - Microbial solutions
  - Chemical synthesis
- Profitable and viable products from recycled carbon
  - Ingredients for cosmetics
  - Proteins
  - Oils and fuels



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About CLIC Innovation Ltd

CLIC Innovation is an open innovation cluster with the mission of facilitating creation of breakthrough solutions in three areas: bioeconomy, the circular economy and energy. The cluster operates as a public-private-partnership. CLIC Innovation Ltd is owned by 30 leading international companies and 16 research organisations committed to creating sustainable solutions for the world. The company is based in Helsinki, Finland. For more information visit www.clicinnovation.fi

Finnish areas of strength in circular economy

Finnish industries have strong competences in the management of environmental issues, such as emissions to air, wastes and wastewaters, in resource-efficiency, and in cross-cutting cooperation. The circular economy provides great opportunities for Finland's traditional key industries, such as technology, but provides potential for the emergence of new businesses as well.

Companies within CLIC's network have identified especially the following areas as their strengths:

- Closing industrial material loops internally, and utilisation of side streams
- Technological knowhow
  - Processing technologies
  - Components for sorting and technologies for automatic identification of materials and substances
- Cross-sectoral cooperation
  - Cross-industry collaboration
  - PPP collaboration: industry, research, authorities
- Ambition to do things in a sustainable, responsible way

In the forest and chemical industries, new bio-based products are expected to be re-usable and recyclable throughout their life cycle. Finland has strong traditions and competence in forest-based biomaterials. Products that offer global market potential include bioplastics, packaging solutions, biocomposites, and textiles manufactured using cellulose and recycled raw materials.

In the plastics sector, Finland was the first country to set and adopt a Plastics Roadmap in 2018 (Ministry of the Environment, 2018; Business Finland, 2018). The roadmap identifies 10 key actions that promote the circular economy in the plastics sector, including measures for both reducing the harm caused by plastic waste and litter, for improving the efficiency of plastics recovery and recycling, and for reducing the dependency on fossil raw ingredients by increasing bio-based and biodegradable solutions (Ministry of the Environment, 2018). The implementation of the suggested actions is underway.

The Finnish mining and metal processing sectors are crucial to the national economy and strong also in the EU scale. From the circular economy point of view, there is a growing need for closing the material loops and improving mine waste valorisation in the global mining business.

The Finnish stainless steel, shipbuilding, battery, vehicle, and electronics industries further refine the metal and mining sector´s products. These sectors account for 20% of Finland's GDP and major part of Finnish export activities. Currently, Finland is investing heavily in building a significant battery cluster in the country (Business Finland, 2019). Finland is one of the few countries where all the essential minerals that are needed for lithium-ion batteries are found in the soil: cobalt, nickel, lithium and graphite. Moreover, Finnish industries master the entire battery value network including mining, extraction and refining of raw materials, technologies and services related to battery manufacturing and use, recharging technologies and recycling. The recycling and substitution of the critical elements that are needed in electronics and batteries provide new business opportunities.

Concerning electronic waste, the collected amount was 11.0 kg per inhabitant in Finland already in 2016, ensuring Finland´s position within the 18 EU Member States that have surpassed the WEEE collection target of 45 percent (Eurostat, 2016). Eco-design of electronic products would support better recycling of their components and materials.

In the Finnish construction and real estate sector, the objective is to extend the life cycle of buildings and construction materials. The development of digital tools and the transfer of knowledge across the value chain contributes to the circular economy. In addition, better recovery and reuse of construction and demolition waste is under active development.

The nutrient cycle provides international market opportunities for, for example, recycled fertilisers and water purification solutions. Finland aims to be a model country for nutrient cycling and Finland's nutrient vision for 2030 includes an active market for recycled nutrients. However, currently, nutrients are not being recycled effectively, even though the added value of the efficient nutrient cycle in Finland is estimated to be EUR 510 million per year (Aho et al., 2015).

In the trade sector, consumer behaviour is expected to change with ownership being replaced by services and sharing. In a service economy, completely new earning patterns will be seen in various sectors, such as housing, mobility, food and industries. Digitalisation and AI give rise to new business models in the form of data-as-service and material-as-service approaches.

Circular economy in Finland: potential and prerequisites

Circular economy fosters Finland´s carbon neutrality targets

Finland is one of the first countries to set a national roadmap to a circular economy. The roadmap was published in 2016 and updated in 2019 (Sitra, 2016, 2019). The objectives of the Finnish roadmap are in line with the EU's Circular Economy Package, UN's SDG, and targets of the Group of Seven (G7) on resource efficiency. The circular economy is currently well presented in the agenda of the Finnish government, and is an integral part of Prime Minister Sanna Marin´s government programme for 2019–2022. Finland has set an ambitious target to achieve carbon neutrality by 2035. Reaching this target requires a transition in which circular economy plays a crucial role.

Currently, circular economy covers only around 5% of the national GDP in Finland, but according to cautious estimates, the circular economy is expected to provide the national economy with 2 to 3 billion euros added value by 2030 (Sitra, 2016; Ahola et al., 2020). The added value potential is considered to be most significant in the following areas: the machinery and forest industries, food waste reduction, altering the use of real estate, private consumption and second-hand trade, and nutrient cycling (Sitra, 2016; Berg et al., 2020). In order for the circular economy to properly fulfil its promises, coherent actions are needed in all societal sectors, especially in energy, transport and food systems due to their strong interconnections.

Transition to Circular Economy requires seamless public-private cooperation

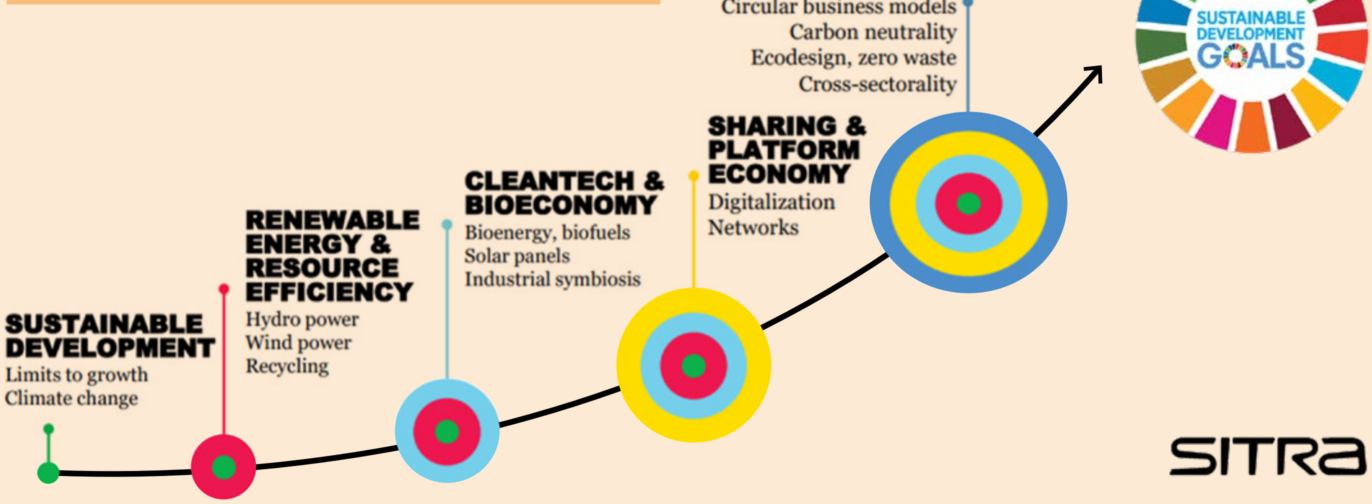
Due to the cross-sectoral and multi-disciplinary nature of the circular economy, the successful implementation of circular economy requires close and cross-sectoral cooperation between industries, academia and the public sector. A transition of this scale needs to be led via and in a public-private partnership, and the prevailing culture of trust and cooperation in Finland is an important asset when driving the kind of systemic change (Figure 7).

The basic research on recycling technologies, new processes and materials should be performed in close cooperation between universities and research institutes. Open research infrastructures and pilot facilities are pivotal to speed up the creation of new scalable solutions.

The industrial partners are responsible for turning the public research results into commercial products and new businesses. While new sharing economy models may enter and conquer the market very rapidly, for product and process innovations, pilots in different scale and demonstration plants are usually needed, as the path from laboratory to markets is often risky and long, from 5 to 40 years.

When it comes to the role of the public sector, funding to research and innovation activities as well as to piloting and demonstration projects is the key to promoting the circular economy (Sitra, 2019). In addition, there is a need to promote and support the start-up activity throughout the reshaping value chains. Further, open dialogue between the industries and the public sector on the essential regulations for the circular economy is crucial for successful management of the transition.

Figure 7. Finnish vision of circular economy



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