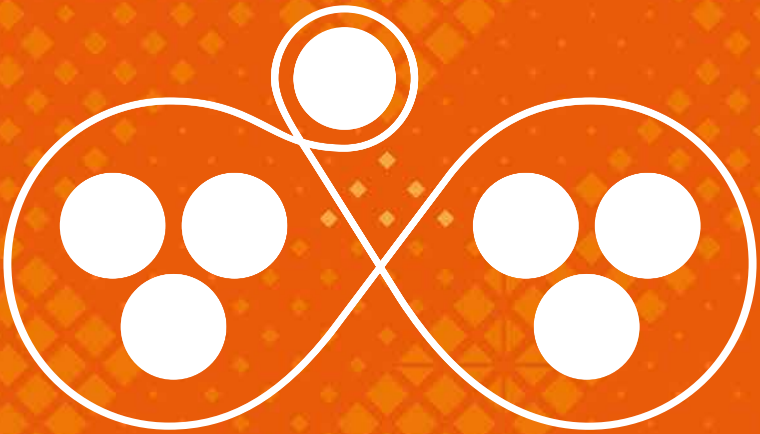
VTT visions

VTT
beyond
the obvious

Going beyond a circular economy

A vision of a sustainable economy in which material, value and information are integrated and circulate together.



GLOSSARY

Big data and open data

Big data refers to the immense amount of data that is the basis of digitalisation, and which is collected by advanced sensors and networked devices. Big data is exploited by analysis, which is enabled by increased computing power and advanced programming.

Open data is data that's available to everyone to access, use and share without restrictions from copyright, patents or other mechanisms of control.

Biocapacity

The capacity of ecosystems to regenerate what people demand from them, i.e. biologically productive land and water on earth.

Carbon capture and utilisation (CCU)

The use of pure CO_2 or CO_2-containing gas mixtures as a feedstock to produce fuels, chemicals and materials. When produced using low-carbon energy sources, these products could be used to displace their fossil counterparts and reduce net carbon emissions to the atmosphere.

Cascading use of components and materials

Efficient use of resources by advancing repeated use, particularly biomaterials or biomass. Cascading use aims at the highest possible value and utilisation as materials prior to utilisation as energy.

Digital platform

An information technology system by which different stakeholders (providers, end users etc.) implement value-adding operations across operational borders.

Earth overshoot day, ecological debt day

The calculated calendar date on which humanity has consumed all the resources earth is capable of producing that year.

Energy recovery

The conversion of non-recyclable waste materials into useable heat, electricity or fuel through a variety of so-called waste-to-energy processes, including combustion, gasification, pyrolysis, anaerobic digestion and landfill gas recovery.

Material recycling

Upcycling. A process of converting materials into new materials of higher quality and increased functionality.

Downcycling. A process of converting materials into materials of lesser quality and reduced functionality.

Mechatronics

Multidisciplinary field of technology combining mechanica, electrical and computer engineering.

Micro-transaction

A revenue or business model based on quick and virtual payments; a well-known example is micro-transactions of virtual goods in video games.

Mineral economy

The understanding of economic and policy issues associated with the production and use of mineral commodities.

Non-renewable

A resource of economic value that cannot be readily replaced by natural means on a level equal to its consumption.

Rebound effect

Rebound occurs when circular economic activities that have lower per-unit-production cause increased levels of production, reducing the benefit.

Regenerative design

Regenerative design enables production and manufacturing processes that restore and renew sources of materials and energy aiming at sustainable and resource-wise systems.

Self-sufficient device

A device that can produce the energy needed for its own functioning.

Servitisation

A business model that creates value by adding a service element to a commodity.

Smart material

Smart or intelligent materials are designed on the material, polymer or molecular level to be communicative and to have such properties that can be changed in a controlled and programmed manner. They can respond to external stimuli, e.g. temperature, electricity, magnetic fields, light or chemical compounds.

Societal stock

Societal stock consists of all human-made physical assets. The built environment quantitatively dominates societal stock. Societal stocks includes materials that are extracted from the environment to make things like products, devices, household appliances and machinery.

Synthesis gas, syngas

A mixture of carbon monoxide, carbon dioxide and hydrogen. Syngas can be produced from any hydrocarbon feedstock using steam or oxygen. Syngas is a resource to produce for example hydrogen, ammonia, methanol and hydrocarbon fuels.

Urban mining

The process of recovering compounds and elements from demolished buildings, spent products, materials and waste, including waste electric and electronic devices (WEEE).

Load following

The capability to adjust power generation according to demand, for example regulating power generation between night and day.

Capacity factor

A ratio that describes the expected capacity of energy output over a period of time compared to the maximum possible energy output over the same period.

Great electrification

A phase when societies start to use electricity as the main source of energy in all sectors, including industry, transportation and agriculture. When this phase has come to an end the main source of energy is directly or indirectly electricity.

AUTHORS

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CONTENTS

FOREWORD

GOING BEYOND A CIRCULAR ECONOMY reflects the authors' fact-based vision of a future economy that transforms from being circular to sustainable. It is a vision roadmap that establishes a path to resource sufficiency, and has been contemplated and written within the frameworks of the VTT strategy, the EU Action Plan for the Circular Economy[1], the UN's 2030 Agenda for Sustainable Development[2] and the Paris Agreement on climate change[3].

The approach of this roadmap is to consider the sufficiency of resources, material and energy. Resource sufficiency is a strong force that drives the transition from a linear economy to a circular one and further still towards a sustainable economy. The present transition from a linear to circular economy is inevitable because the abundance of resources we have enjoyed until now is coming to an end. An increase in production, manufacturing and consumption drives economies towards an ever-worsening scarcity of resources, eventually resulting in a battle for resources, both virgin and secondary. In order to escape this scarcity, we need to intensify not only recycling and reuse of materials and substances, as well as the sharing of commodities, but also the production of affordable and sufficiently renewable energy and fresh water. Loss-resistant recycling, smart mastery of materials, high-performance materials and the use of the atmosphere as a resource reservoir will together enable access to a new era of sustainable resource sufficiency.

Certain technological solutions, which are evident and seem implementable but are presently unrealistic due to cost, industrial feasibility or ethical considerations, do not restrict our vision, and if anything serve to strengthen our resolve. For example, gaseous carbon compounds, nitrogen and water in the atmosphere as well as solar and other renewable energy solutions can all be used as affordable and sufficient resources for the future production of fresh water, food, chemicals and materials. We envision a circular economy and low-carbon economy as enablers when moving towards a genuinely sustainable economy.

This work has been carried out in cross-disciplinary workshops and person-to-person brainstorming sessions with VTT experts from different fields. In addition, experts from industry, industrial associations, ministries, programme owners and funding bodies have been interviewed to share their wisdom and broaden our minds. Our special thanks are due to everyone who has taken their time to give their views on a future sustainable economy.

Espoo, November 2018

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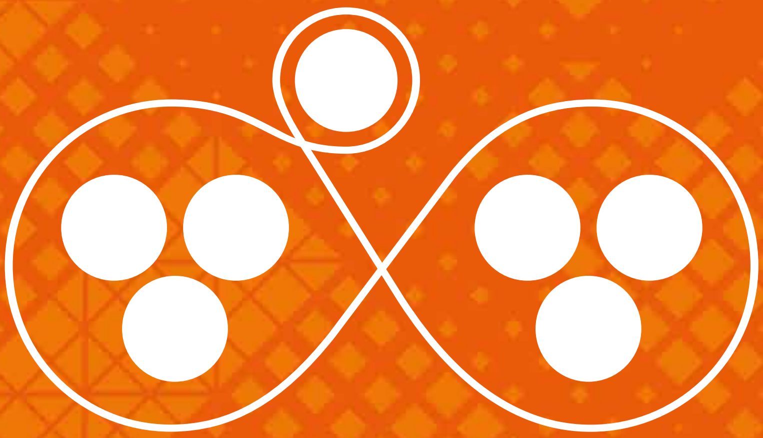


1

TOWARDS A SUSTAINABLE ECONOMY

WE OFFER three visions that establish a path to develop technologies, process concepts and business models as well as ways to produce, manufacture and consume in the future. To partake in the transition from a linear economy to a circular one and beyond requires the courage to abandon established ways of operating on all levels; in society, in business life and as individuals. It requires collaboration that crosses industrial and business-sector borders and engages research and development organisations, civil society, policy makers and education systems. Ministries (such as the Ministry of Economic Affairs and Employment, the Ministry of Agriculture and Forestry and the Ministry of the Environment) need to be on the frontline of this transition, offering background support by easing regulation and assisting in the creation of innovative and collaborative ecosystems that could in turn become thriving business ecosystems.

We propose a platform for collaboration and innovation, open to all dedicated stakeholders, to kick-start planning the concrete steps that need to be taken along the development paths suggested in this publication. The work necessitates impact assessments, feasibility studies and collaborative development projects together with companies across business-sector borders, research organisations, public funding organisations and civil society.

Although sustainably produced, reused products and recycled materials are the core business in a circular economy, digitalisation, information technologies, servitisation and platform economic solutions are enablers that lay the groundwork for the necessary changes. In the future, production, manufacturing and consumption will transform disruptively, entering into a cyberspace in which “everything is connected to everything else” and data creates power by managing with knowledge. What are the possibilities of artificial intelligence (AI), the Internet of things (IoT), digital service platforms, big and open data, as well as blockchain and related technologies to manage trusted digital transactions both for a circular economy and for other economies that may emerge alongside it?

The most tangible benefit of digitalisation is an increase in resource efficiency. Primary and secondary materials and products can be funnelled, used and reused in the most optimal ways by exploiting digital systems, automation and robotisation. Data will become a marked productive means besides concrete resources such as raw materials or energy; management of data will mean management of material flows.

The value of a material increases when a service element is linked to it. We need concrete actions to be taken to push a circular economy from being material and product-centric towards a data-driven and service-centric operation model that significantly reduces the overall use of natural resources and stops further extraction.

Going digital will most certainly create new operational value creation and business models, and eventually a business branch. If we do not do it ourselves, somebody else certainly will. Stakeholders that can see this progress will be the competitive leaders of the economies and capable of staying ahead of the game.

1.1

VALUE CREATION IN A CIRCULAR ECONOMY AND BEYOND

Future business will be conducted in a situation in which a scarce supply of resources and environmental concerns increase prices, cause price volatility and create uncertainty. It should be a trigger for companies to innovate solutions to do “more with less and cleaner”. Many studies have attempted to estimate the value of a circular economy, but with disparate conclusions[4]. This is due to the complexity of a circular economy *per se* and a lack of common indicators and definitions to measure value creation in a circular economy compared with existing economic models.

Disconnecting the economy and business from resource over-exploitation requires innovative technological solutions, firstly to recycle non-renewable and critical materials, and secondly to replace them with renewable alternatives. Renewable material solutions have been seen to gain ground in technical products such as electronic and electrical devices. In addition, future product or process solutions that generate excess material or energy, rather than only consume them, will become more important (see Chapter 5). An existing example is consumer solar panels, which pay back their production and running costs over time, after which they produce excess energy that can be sold to the common energy market. However, these novel concepts face regulatory obstacles that need to be overcome.

> A circular economy is a route into a genuinely sustainable economy in which material, information and value circulate together.

Integrated supply and value chains aim at wasteless and emissionless circulation and **cascading use** of materials and products, thereby optimising resources. The essential objective is to keep substances, materials and products in circulation as long as possible and to keep their value as high as possible. Achieving this objective necessitates actions from all stakeholders throughout the entire material and product life cycle, not only when they are ready for disposal, or to be transferred to the next life via reuse or recycling.

Cascading use of materials is a central topic emphasising end products of high value instead of a direct conversion to low-value end products or end uses, which is often seen as the easiest way to get rid of loss and waste with present technological abilities and in present non-collaborative business environments. Realising longer product life cycles requires premeditated design starting from the material level, covering production and manufacture and ending with the design of products and ways to consume. Resource efficiency becomes a reality, as product lay days are reduced to zero by increasing the number of users benefitting from the same products and sharing easy access to products and services enabled by service platforms. This might also mean a need to update legislation and taxation. In many countries the transition from a linear economy to a circular economy is hampered by outdated regulations that do not support development of technologies or new operational and business models.

1.2

RESHAPING EXISTING OPERATIONAL BUSINESS MODELS

Overall global material extraction has multiplied tenfold since the beginning of the 20th century, starting at 7 billion tonnes per year in 1900 and reaching 84.4 billion tonnes per year in 2015[5,6]. We continuously use more resources than the planet is capable of producing. At the current rate of development, the global demand for materials is estimated to reach 180 billion tonnes per year by 2050[7,8]. The balance between the planet's **biocapacity** and human ecological insatiability already had its turning point during the late 1960s[9]. Eleven years ago, in 2007, the so-called **Ecological Debt Day**[10] was in October. In 2018 humankind had already used nature's annual supplies by August[11].

> According to the law of conservation of mass, material does not cease to exist. Currently, material accumulates in new, unpredictable and difficult-to-reach or challenging locations such as in the atmosphere, in water systems and the deep

sea, in landfills and waste heaps – or is scattered haphazardly in the environment in forms that are difficult to collect and convert for reuse.

The global economy has increased material stock on a macro level 23-fold, and this increase is in line with the growth in GDP, which has increased 27-fold[5]. The amount of primary material used to build up or renew stocks grew from 1 billion tonnes per year to 36 billion tonnes per year over the same period of time, from 1900–2010[5]. The world is not capable of providing this amount of virgin materials at all, much less sustainably. We have become accustomed to using materials and goods briefly and disposing of them when they no longer serve their purpose, and have now reached a crossroads where we must consider alternatives to today's consumption behaviour. The recognised alternative is material and product circulation, which in its purest form means wastelessness and never-ending material cycles. However, keeping materials in never-ending circulation is utopian wishful thinking, even purposeless. Today, material circulation reaches less than 10 %[6], which is alarmingly low. Increasing circularity, for example to 50 %, would require fundamental and visionary changes at all levels of economies worldwide.

The irrevocability and imperative of a transition towards a sustainable economy challenges companies and communities to explore novel ways to thrive and create value. The kick-start moment is at hand. Making profit is obviously an essential element in value creation, but environmental and social sustainability are increasingly important. Circular business models focus on supporting long-life materials and products, reuse, cascading use, renewability and regeneration, integrating production processes and the sharing of goods. "It is about finding ways to move revenue generation from selling physical stuff to providing access to it and optimising its performance along the entire value chain."[12] Business is done in collaboration using integrated systems in which value chains are linked, thereby avoiding loss and leakage.

One of the necessary changes could be concurrent energy production and chemical compound recovery of organic and biological materials and substances that have reached the end of their life. Existing technological solutions enable the recovery of CO_2, CO and H_2 in addition to energy. These gaseous compounds can be returned into circulation as raw materials. They can be refined by chemical and biotechnical means into new materials and substances provided affordable, emissionless energy is available in sufficient amounts.

Reshaping existing business models is a necessity on the way to change. The impact of a quantum improvement of current models will not be enough. There is a need to revolutionise the economic structure. We will have to forget how business is done today and start anew.

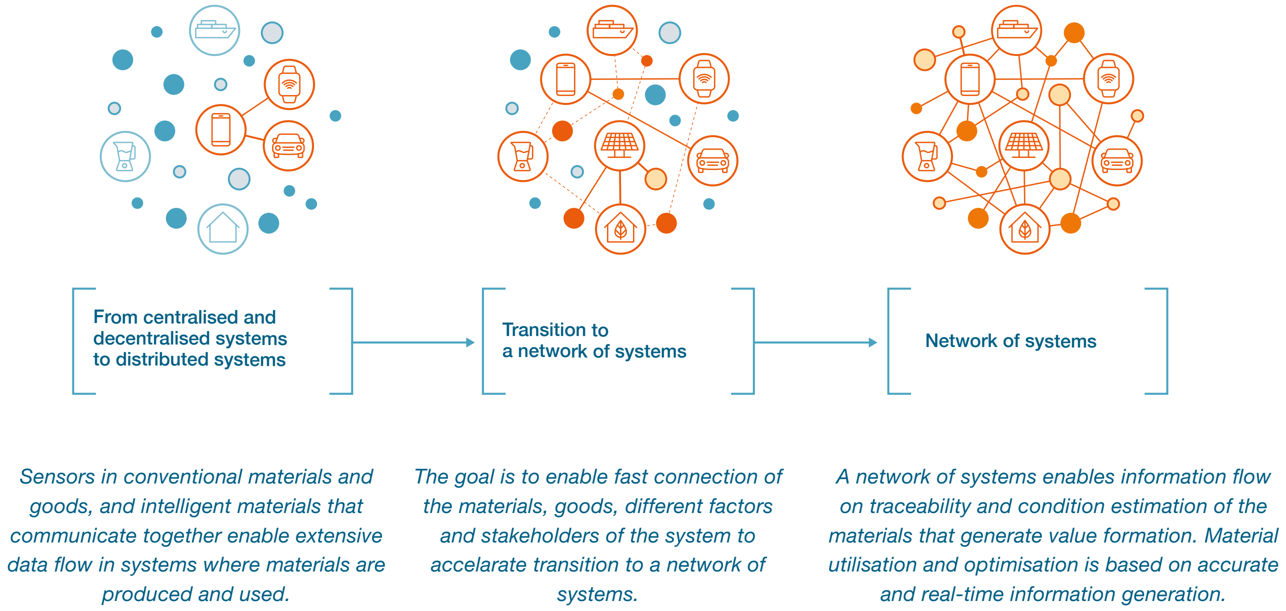
Yet another change is the transition from ownership to sharing or leasing. Material producers and product manufacturers sell services and the right to use them rather than the materials or commodities themselves. A service and leasing element added to a material or product increases its value to both consumer and producer. This new way of operating focuses on optimal use of resources and designing intelligent, high-performance material solutions that enable long-lasting and value-retaining commodities that are easily reused or recycled, provided these activities are organised in a way that does not cause a **rebound effect**[13], such as increased consumption and consequently increased production, meaning that what is thought to be sustainable actually results in an increase in the use of materials and energy. All of these changes necessitate systemic thinking, resilient enabling and on-time regulation, innovative material and product solutions, novel operational and business models, and industrial renewal enabled by diverse digital and **big and open data**-based solutions. For example, starting from integrating intelligence into materials and ending with collecting and analysing big and open data to plan efficient circulation, as well as global **digital platforms** to trace and trade materials and goods in circulation.

1.3

ACHIEVING A SUSTAINABLE ECONOMY REQUIRES MASSIVE DIGITALISATION

The exponential rise in digitalisation has already had a huge impact on our society during the last decade. Digital connectivity has brought with it tremendous opportunities, and one of them is a circular economy. However, the leverage of the digital connectivity level that we are discussing in this vision paper is much more extensive. Traceability, quality information and condition estimation of the materials and products requires massive digitalisation of the material-related operations from extraction to production and end use, as well as the restoration of materials back into use. The goal is to collect data from all stages of material circulation and share it in ecosystems where materials exist and circulate. Added value will be tapped through the information that is analysed from the data that is gathered at different stages of the material circulation. The more the different factors in the ecosystems communicate and share data, the greater the understanding achieved.

Currently, most digitalised environments operate through centralised systems, which is a limiting factor in building informational natural resource management. To realise this vision we need to move from a centralised and decentralised towards a distributed network of systems where all of the crucial assets and operations are connected (Figure 1).



Sensors in conventional materials and goods, and intelligent materials that communicate together enable extensive data flow in systems where materials are produced and used.

The goal is to enable fast connection of the materials, goods, different factors and stakeholders of the system to accelarate transition to a network of systems.

A network of systems enables information flow on traceability and condition estimation of the materials that generate value formation. Material utilisation and optimisation is based on accurate and real-time information generation.

Figure 1. Digital transition accelerates circulation of materials and goods.

Accelerating the growth of distributed networks is vital in transitioning to a network of systems. The goal is to connect all existing separate networks that carry critical information about material flows and assets. By connecting different networks, communication and data access will be dramatically intensified. Data flow provided by this transition will allow precise calculations for all resources used worldwide and enable real-time optimisation of the material circulation. A network of systems will open up a world where all of the critical decisions regarding natural resource utilisation are made based on precise real-time information.

Extensively connected systems will enable, for example, feedback from the consumer directly to the material owner or manufacturer, which in turn enables a fast response to a consumer's needs. Unnecessary or incorrect material use, product variations or manufacturing steps can be avoided. Besides providing information about efficient and deliberate material circulation, real-time information is available about, for example, the real-time state or availability of natural resources. Transparent big data enhances an open dialogue between stakeholders in ecosystems, which in turn creates the shared holistic view that is needed for building a sustainable and resilient society.

The transition to a network of systems has to take place as we move towards 2030 to accelerate the transition from a linear to a sustainable circular economy, and thus have an impactful effect on reducing material use and extraction. This might happen even faster than expected. The transition towards a network of systems is going on already and is taking place in different locations and at different speeds. The faster all of the crucial operations are digitalised and connected, the better prerequisites to enter into a genuinely sustainable economy.

2

MEGATRENDS AND KEY FACTORS AFFECTING THE TRANSITION TO A SUSTAINABLE ECONOMY

THE TRANSITION towards a sustainable economy is influenced by several current and emerging megatrends and drivers (Figure 2). Resource sufficiency, climate change, population growth and the expansion of the global middle class are all creating increasing sustainability challenges for the planet. Increasing resource insufficiency as well as worsening climate change and its implications for the environment raise some important questions: How do we maintain economic growth without compromising the well-being of nature and people, and how do we find solutions to decouple economic growth from the unsustainable exploitation of natural resources with minimal greenhouse gas emissions? The digital transformation of industries and society is a megatrend that supports the transition towards a sustainable economy on all levels, from optimised material life cycles to circular business models.

Global megatrends not only challenge the existing economic model but also have an impact on the development towards a circular economy and beyond. A circular economy evolves gradually from the existing linear economic approach, eventually disrupting it. This process does not take place in isolation. The current and emerging economic models co-evolve along with other economic models, as depicted in Figure 2. A circular economy has many shared goals with a low-carbon economy, which battles climate change by reducing greenhouse gas emissions with non-carbon energy sources (including solar, wind, water and geothermal energy) and aims to improve resource efficiency through energy intelligence and **carbon capture and utilisation (CCU)**. Carbon reuse and CCU, which refers to the separation of CO_2 from flue gases for example, combined with the use of the captured CO_2 either as such, or as a source of carbon for other chemical and biochemical processes, is seen as part of a new materials economy.

A traditional materials economy focuses on the extraction and utilisation of raw materials, both non-renewable and renewable, and operates according to linear economy principles. Just as with a circular economy, a new materials economy strongly emphasises the value of raw materials and waste minimisation. Sustainable extraction, production, use and reuse of both **non-renewables** and renewables can be seen as elements of the new materials economy that should also emphasise recycling critical raw materials over utilisation of virgin alternatives.

The mineral economy and bioeconomy, as part of the materials economy, are also drivers for circular economies. Research, development and innovation are at the centre of a new materials economy. The development of sustainable substituent materials and new, safe materials is driven by scientific and technological advancements, for example in industrial biotechnology and synthetic biology. New technologies for intelligent material circulation, extraction of materials from urban sources (for example the rise of **urban mining**) and accelerated nitrogen and carbon circulation speed up the transition towards a circular economy. Growing urbanisation will increase the importance of cities and their role as economic engines in this evolution.

The evolution of **platform and data economies** is enabled by the fast development of digital and information technology (IT) solutions. Improved processes, materials and product design rely on the use of big data and artificial intelligence to improve resource efficiency. Digital platforms also play a crucial role in the development of service and sharing economies as part of a circular economy. Dematerialisation together with servitisation are important factors in decoupling economic growth from raw material use and its environmental effects: physical items can often be replaced with digital ones or services that significantly reduce overall material use.

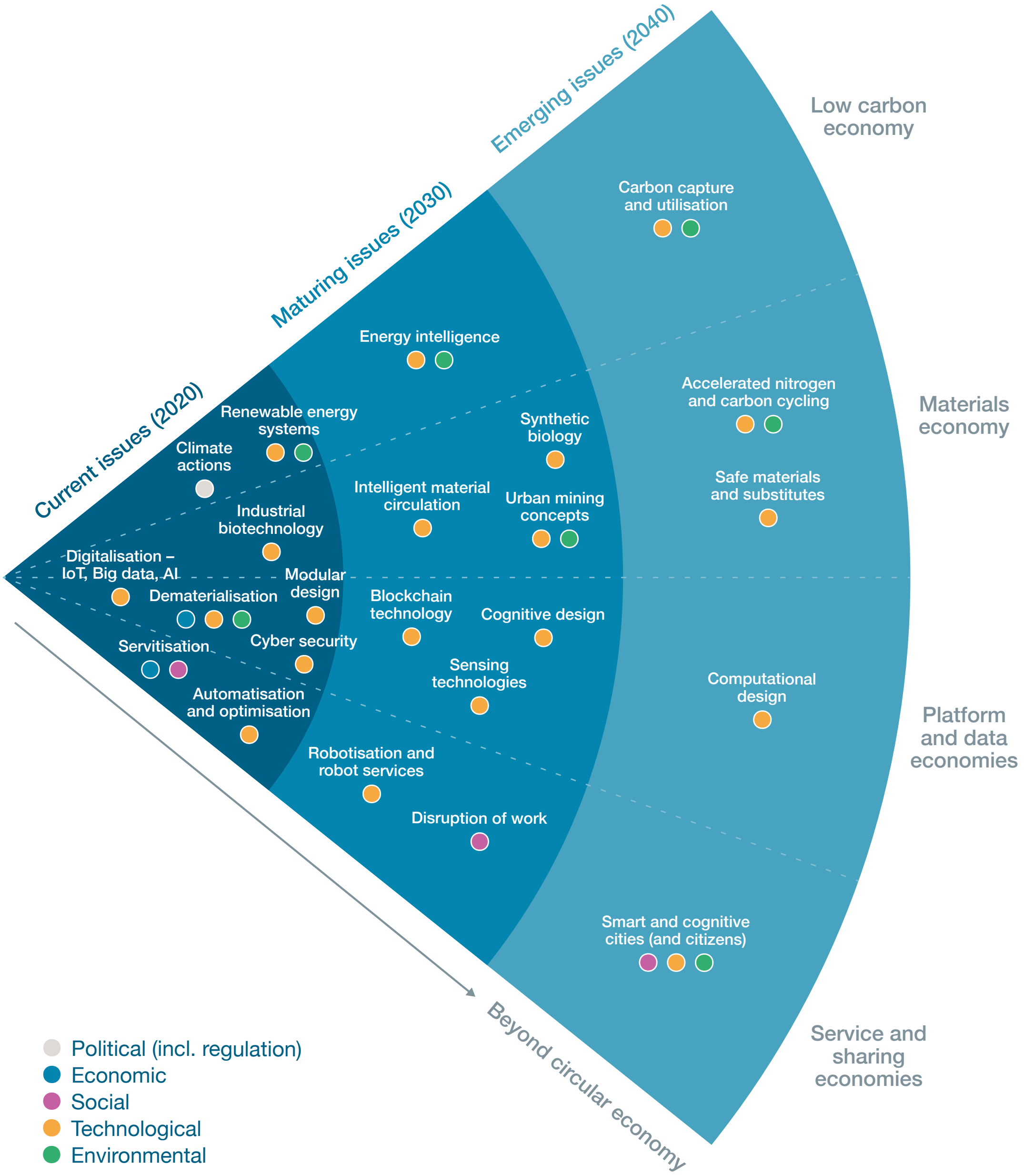


Figure 2. Global megatrends and drivers push the transition towards circular and sustainable economies.

3

THREE VISIONS OF A SUSTAINABLE ECONOMY

THIS PUBLICATION highlights three visions that the authors believe can ensure future resource sufficiency by moving via a circular economy (present situation and near future) towards a sustainable economy in the distant future. The visions (Figure 3) are seen to emerge successively over the next two decades, or even sooner, and all effectively complement one another and enable a future in which resources are sufficient for frugal, sustainable and intelligent production of food, fresh water, materials, commodities and energy. Comprehensive material and chemical compound circulation, value maximisation, energy transition, increasing data accumulation and exploitation, as well as information flow in networks, form the main thread of these visions: 1) Loss-resistant loops, 2) Mastery of materials and 3) The new era of resource sufficiency.

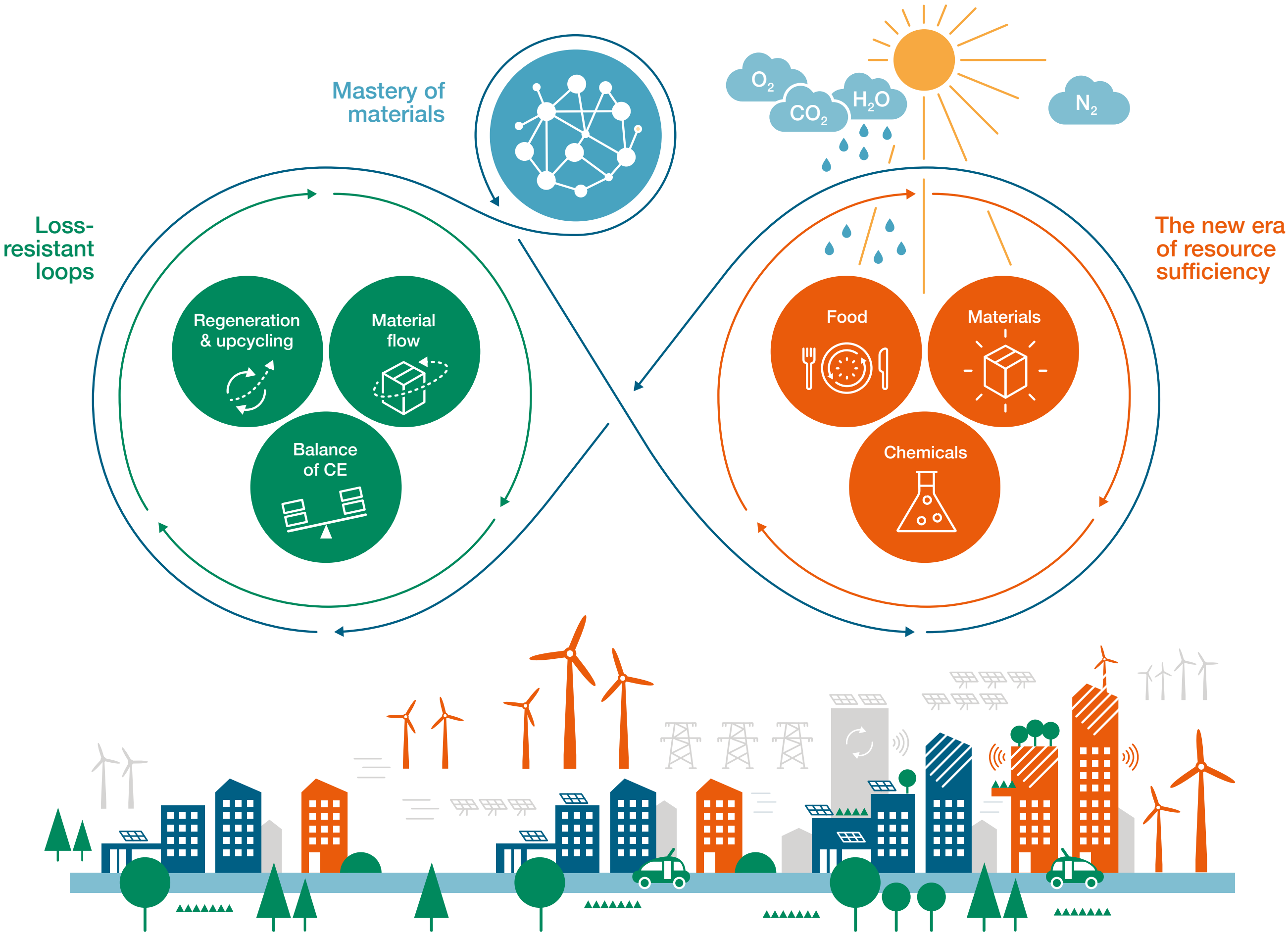


Figure 3.The authors' threefold vision of the future sustainable economy.

3.1

LOSS-RESISTANT LOOPS

Loss-resistant loops describe the prerequisites for the transition from the current linear economy to a circular economy. In today's world, materials are still abundant enough to keep production and consumption going at full speed, accumulating waste and depleting virgin resources along the way. Although resources are available, increasing environmental debt is resulting in severe damage. Insufficiency and eventually a loss of resources are seen, which requires immediate and efficient corrective actions. Production, manufacturing and consumption are therefore integrated to form loops that enable the enhanced circulation of materials and substances aiming at reducing waste and emissions, and increasing resource efficiency. Creating these so-called loss-resistant loops requires solutions for sustainable and clean energy, cascading use of primary and secondary materials, and material design that enables long-lasting reuse of products and full recyclability. Data-driven systems manage efficient material and product production and circulation. The focus is on transitioning from waste management to material flow management.

MORE THAN half of globally processed materials leave society as waste. Almost one third go to built stocks such as infrastructure for long-term use[14]. In 2015 the global circularity of materials was reported to be alarmingly low, at only 9.1%[6]. Given that global production and consumption of materials is constantly increasing, it is painfully obvious that the circularity of materials needs to be dramatically increased. The chilling fact is that if everyone around the world consumed resources at the same rate as we Westerners do today, we would need a couple of extra planet earths to survive in the future. Fundamental changes are needed in food, energy, and material production, material design and use, and the sustainability of the way we do business. Efficient circulation necessitates advanced supply chain management; efficient data gathering, management and use; as well as open cooperation between industrial and societal actors, business players, policy makers and individuals.

Proper end-to-end material flow management is crucial, because the current recycling processes leak both rejects and emissions, and vast amounts of valuable raw materials are lost. As much as half of all materials can end up in landfill or otherwise unavailable for reuse. Traditional material recycling focuses on recovering valuable and easily separable material components – for example, base and precious metals from waste electronics and electric equipment (WEEE) or fibres from paper and cardboard. Challenging materials, especially heterogeneous organic matter, are not currently utilised efficiently due to their complexity and need for multiple recycling loops to prevent **downcycling** and severe loss. In the long run there will be an urgent need to improve the efficiency of the recovery of all materials, not only easily recyclable ones, with the priority being to restore energy-consuming and depleting critical raw materials into circulation.

> More than half of all materials can end up in landfill or otherwise unavailable for reuse.

Accelerated resource unavailability, volatile prices and supply disruptions present a risk to business, bring uncertainty in everyday operations and can attenuate economic growth. In order to stop natural resources from becoming seriously depleted we need a clear increase in circularity and for powerful actions to be taken. In order to have an impactful effect on mitigating climate change and the depletion of natural resources, we suggest that the current focus should be on:

- decreasing fossil energy use by increasing energy efficiency and the gradual replacement of fossil with sustainable energy
- emphasising the role of materials in product design, production and use
- eliminating the use of hazardous substances and complex materials
- providing access to transparent and open data to enable value-creating business

Decreasing fossil energy use by increasing energy efficiency. Energy production solutions need to be clean in order to avoid excess emissions to air; either non-carbon energy or recovery and reuse of emissions from carbon-based (fossil or bio-based) energy and process industries should be implemented. The short-term emphasis, however, should be on decreasing energy consumption in energy-intensive operations. At the same time, materials and commodities need to be recovered back into use with less energy-consuming solutions. Much relies on energy transition, and there is an urgent need to increase the sustainable share of overall energy demand as it ensures a transition to a sustainable circular economy.

In addition, it is crucial to direct the use of energy primarily to the operations that return non-renewable and non-replaceable materials and substances, such as critical raw materials (CRMs), back into use. Circular economy operations should be covered to an increasing extent by sustainable energy to avoid excess emissions. This requires prioritising the recycling of materials, concentrating first (besides CRMs) on materials that consume more energy when extracted from nature compared to restoring by recycling processes.

Emphasising the role of materials in product design, production and use. Design and precise information about demand plays a key role in decreasing material and product production and use. Long-lasting and recyclable materials and products are needed, as is modular design that allows update, repair and refurbishment. Hence, material and product design will have to change considerably to serve circular systems. At the moment this is not the case as materials lose functionality and value during recycling, and thus cannot replace primary materials, meaning there is still a need to extract materials from nature.

Additionally, it should be noted that vast amounts of the produced materials are not available for circulation, even if they are designed to circulate, because they enter stocks that are in long-term use. Besides material consumption, adding to built stocks requires a vast amount of energy not only in the building stage but also in maintaining the existing and new additions (i.e. the built environment). In most cases these stock materials will not be recyclable, or they will lose value in recycling processes, and as such, in most cases they will not replace primary materials. This is due to the fact that materials are not designed to circulate. There is a need to rethink how the newly built stocks are added and maintained to avoid value loss at the end-of-life of the built infrastructure.

Eliminating the use of hazardous substances and complex materials. Today's products are designed and materials formulated in an increasingly complex manner, making it difficult to disassemble them and remove hazardous substances, which is a prerequisite for safe recycling and obtaining safe secondary materials. Many of these substances become enriched and may become even more problematic during recycling processes, eventually curtailing the use of an otherwise good secondary material. In plastics, for example, the hazardousness and diversity of chemical substances should be carefully taken into account when recycling solutions are planned and implemented. Added to hazardous substances, the complexity of materials hinders value-maintaining recycling. For example, food packaging can contain several plastic types as well as cardboard and aluminium, which are all needed to provide functional attributes that ensure proper food preservation. Complex materials are a challenge to recycling. Material design and technological solutions to replace complex multicomponent materials with mono-component alternatives along with process solutions to remove hazardous substances from recycled materials are prerequisites for increasing the circularity of materials.

> In order to truly master material flows there is a need to move from waste management to material flow management.

Providing access to transparent and open data to enable value-creating business. Efficient material recycling is hampered by the fragmentation of industries and production. Players along material supply chains tend to optimise their own part, and significant gaps and inconsistencies in data exist that in turn restrain fluent material flow and value-chain performance. Sustainable and efficient generation of materials from waste and secondary materials necessitates new material and information technology solutions. Shifting the focus from waste management to material flow management involves the collection and use of accurate information about the quality, characteristics, quantity and location of available materials. Safe and economically viable material flows require end-to-end supply chain transparency to enable real-time optimisation and decision making along the entire material supply chain. Open big data will enable the transparency and information needed to design sustainable supply chains. Blockchain technologies, in turn, enable authentic traceability and identification of materials in the supply chains, opening up novel opportunities for businesses.

In frugal cycles materials are being reformed and circulated within and between different supply chains.

Balancing the circular economy structure – creating value from regeneration

Current circular economic models are implemented in ways that focus on end-of-life operations such as reuse, repair, recycling, incineration and disposal. Regardless of the good intentions of current models, they are consuming and loading nature. We have a responsibility to correct this imbalance and start finding regenerative and upcycling solutions.

Correcting the circular economy imbalance requires a shift from recycling to regeneration.

Upcycling means circulating materials in a way that requires low energy and material input to maintain or increase value. Reuse, the most sustainable model in the present circular economy, by itself is not enough to replace the use of virgin materials and avoid excess use of materials, if the value proposition has not been taken into consideration at the very beginning of the material or product life span. We propose balancing the circular economy in the way depicted in Figure 4.

To avoid the nature-burdening imbalance (Figure 4a), there is a need to focus on circular activities that generate value. By putting the emphasis on

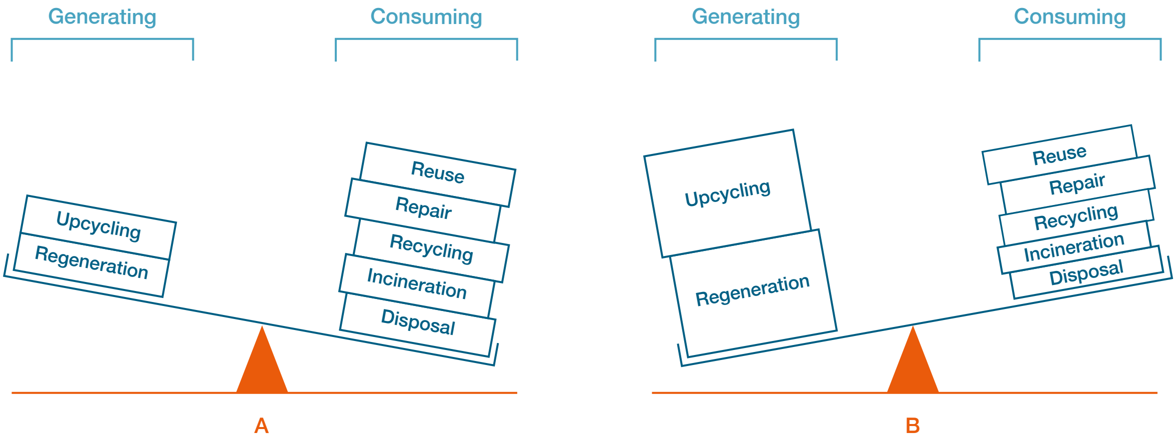


Figure 4. The sustainability balance of the circular economy operations. A consuming circular economy that burdens nature (a). A generating circular economy that enables paying back the debt we owe to nature (b).

CASE EXAMPLES

The cases described in this paper are not actually factual, but possible glimpses into the future. They bring to life the visions described in this paper and provide tangible and insipiring examples about what the future may look like. Our imagination is only limited by the laws of nature.

upcycling and creating regenerative features, we can start correcting the imbalance by ensuring that materials can be used for longer and reducing the need for incineration and disposal as well as intensive recycling. Hence, we suggest reshaping the circular economy model from the consuming model (Figure 4a) to a generating model (Figure 4b). Consumption still takes place in the generating model, but the centre of gravity is shifted from material consumption to generation, which produces value and burdens the environment less due to the avoidance of excess material extraction, which is instead achieved via regenerative and upcycling activities. Circular economic models can operate in both value decreasing and value increasing ways. The more operations are moved to the generating side of the balance the better the outcome in terms of improved sustainability.

There is clearly a need for new innovations that enable a shift from material and energy consumption to regeneration of excess material-based value and clean energy to society. We call these innovations ‘self-sufficients’ (see Chapter 4 for more information).

CASE

Integrated technologies and new business models to promote the reuse and recycling of end-of-life electronics

The present European generation of waste electrical and electronic equipment (WEEE) is about 20 kg[15] per person per year. WEEE is the most important source of critical raw materials (CRMs) after mining. Electrical and electronic equipment is not designed for disassembly, but are composed of multiple parts and materials, which makes them very difficult to recycle. As a consequence, vast amounts of valuable parts and materials do not enter recycling processes and are completely lost. Current WEEE recycling focuses on recovering base and precious metals such as gold, leaving other compounds, especially organic material, unutilised. Present **urban mining concepts** consist of local recycling solutions to recover CRMs from WEEE and other waste, thus guaranteeing a fluent and continuous supply of CRMs, but not other components of the input waste materials.

CRMs such as gallium, germanium, platinum group metals and rare-earth elements are used extensively in electronics and energy industry products, including rechargeable batteries, displays and computers. As the demand for CRMs continues to increase, availability must be supplemented via intensified recycling and regenerative design that allows proper repair and recyclability of WEEE.

For the time being CRMs cannot be substituted with other materials without losing product functionality. On the other hand, demand for CRMs will grow several dozen times compared to the current level by 2030[16]. This situation calls for new recycling concepts based on integrated technologies that can increase the efficiency of material recovery and reduce the use of virgin minerals and fossil resources. Besides mechanical processing, various thermal conversion technologies, for example gasification, can be used to separate metals and organic materials such as plastics from WEEE. Organic material can then be converted into energy or hydrocarbons for plastic precursor and chemical production. Those metals that have until now been left unutilised can be separated from the thermal residues via mechanical and hydrometallurgical means. But more important is to design appliances for efficient disassembly at the end of life to enable fluent and affordable reuse of the disassembled components.

Currently most electrical and electronic appliances and devices are particularly challenging from a durability and recycling perspective, from two points of view: 1) they are not designed for disassembly and recycling, and 2) certain group of electronics, like smart communicating appliances, develop rapidly, so there is no point in making them too durable. Design and information based optimisation is the key element in managing all the materials that are contained in these appliances in order to return the materials back into loops. Current business models do not support or incentivise repair or refurbishment.

What if there were autonomous recycling and novel incentives to return end-of-life devices and their components back into use?

The big challenge in WEEE and battery reuse and recycling is related to safe and smooth disassembly of end-of-life devices into components and reassembling them again. Proper disassembly is key because it determines component and material flows and ensures safety in handling. The shift from disposal and mechanical, non-selective crushing of WEEE towards disassembly of devices requires an emphasis on designing modular devices and developing intelligent recycling processes that would selectively sort disassembled components from heterogeneous hard-to-recover material fractions. A non-destructive recycling model would promote reuse and recycling along the whole value chain, and would also enable information flow and transparency throughout circular supply chains.

The deployment of autonomous recycling calls for a new business model. It should be integrated as an essential part of the business strategy and supply-chain management. In this type of business model loss is created only if a device or component is not returned to the manufacturer for reuse (Figure 5). In this model the commodity, and therefore the material, is the property of the manufacturer. The consumer has temporary ownership of the commodity but not the material. Value decrease is related to the loss of material or components from circulation. The incentive for a user to return a device after it reaches the end of its expected lifetime would be adjusted by dynamic pricing that can be related to, for example, time of use, condition or even location. If the user does not return the commodity for update, repair or recycling the monthly costs rises.This incentivises the consumer to return the commodity for necessary updates or repairs that at this point are less costly to the brand owner and producer and which ensure that its value is preserved with minimum effort. The update-repair-recycle service is free of charge to the user. Additionally, this also means better value for the user and improved customer loyalty. If the user does not return the commodity at the expected end-of-life, the cost continues to rise until the commodity is returned for recycling. This model is based on restoring commodities in order that they can be used again and again, and ensures the return of the materials back into use through the use of dynamic pricing. If the commodity is lost completely, the user pays a one-off payment, agreed in advance, and starts a new programme. The later the commodity is returned to the manufacturer the greater the cost rises for the manufacturer due to the increased effort, materials and energy required to restore the lost value.

Business models can be based on information about product use and lifetime. Information is used to optimise the lifetime of devices and make them last for a favourable time. Ideally, devices are returned to the system multiple times by users for an upgrade and when needed for refurbishment. Devices need to be designed to be recyclable and easy to disassemble to avoid value loss and excess costs (Figure 5). Also, all the components and parts need to be durable and designed to last. Information gained from the use phase is also extremely valuable to the manufacturer and to all stakeholders along the value chain. The more data gained from cradle-to-grave, the better the understanding is achieved to plan operations and to design for purpose and

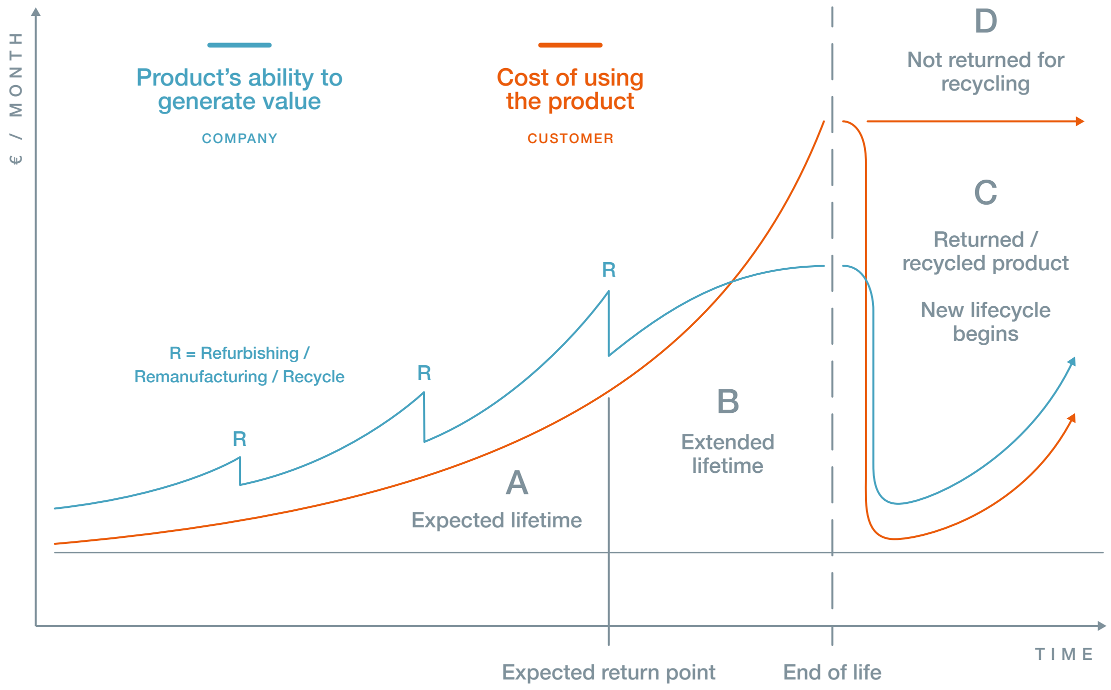


Figure 5. Dynamic pricing to incentivise material return back to the manufacturer and preserve value.

durability. First glimpses of this kind of a business model exist already, such as car tyres as a service.

To be competitive in the market, a service business model has to provide value to the consumer. Value increase is based on the service and the data gained from the product use phase. Product use phase data is valuable to brands as it allows better design and management of the resources without value loss, which in turn means better business and improved competitiveness.

CASE

Trackable material flows – autonomously communicating products and devices

The circular economy relies on managing the lifecycle of material flows and products. It requires large amounts of data to be collected at various points during the material and product lifecycle. Smart items (i.e. items equipped with sensors) collect such data. For example, hyperspectral cameras could be utilised to support recycling to detect items and their components and analyse material compositions as well as the condition of components. Smart items can also be tracked, if not for the entire lifecycle, at least whether (where and when) an item has been returned for recycling. Communication can be an opportunity for new data-driven business models around smart items and new digital platforms and applications that make use of product lifecycle data.

Mastery of materials (see Chapter 3.2) relies on the information of material flows based on the data gathered from the flows. Data is transformed into information by analysis of the big data. This means that there has to be a systematic way to collect data from all material flows, and this is currently lacking.

Most of the materials that are in use are not traceable. It means that after procurement there is no information available on where the materials or products are located, how long they have been in use or what condition they are in. This makes it very challenging to optimise the material use and circulation, for example planning the best possible ways to collect materials for recycling.

What if all products and devices could be traceable with the capability to communicate?

For the purpose of enabling traceability and data collection, materials and commodities can be divided into two groups: smarties (products and devices with the capability to communicate) and dummies (products and devices with no capability to communicate) (Figure 6). Both are equally needed to fulfil the demand of accurate information for decision making in the circular economy.

Smarties – communicating devices

Smarties are devices that have the capability to measure and observe their surroundings. These devices, for example mobile phones, are nodes that transfer data from uncommunicative products and devices (dummies) to an open database of material data. This makes it possible to transfer data efficiently in units that are designed for this purpose, and mobile phones serve this purpose well. In addition, smarties gather data on local conditions – like noise, temperature, humidity and so on – that can be hard to reach or hard to measure, and they also capture behaviour-related information. Additionally, smarties autonomously provide information about measurements relating to the human body, such as movement. Smarties are communicating units and thus intelligent in nature. They can communicate with their close surroundings by sending and receiving information, and thus impact their own behaviour. The traceability and information-gathering features of smarties are the backbone of the mastery of materials, supervising materials, products and goods around **societal stock** (see Chapter 3.2 and 4).

Dummies – devices with no capability to communicate

Dummies are commodities that have value, but these devices or products themselves are not capable of communicating actively with data clouds. Examples can include products that are locally used durable commodities such as a table or a dresser. Dummies can be equipped with smart tags or sensor beacons that record and broadcast data to smarties, providing the possibility to follow valuable goods and products that don't have inbuilt intelligence for communication and traceability. This data can contain information, for example on temperature, pressure, humidity and movement. By transmitting information via smarties to the clouds,

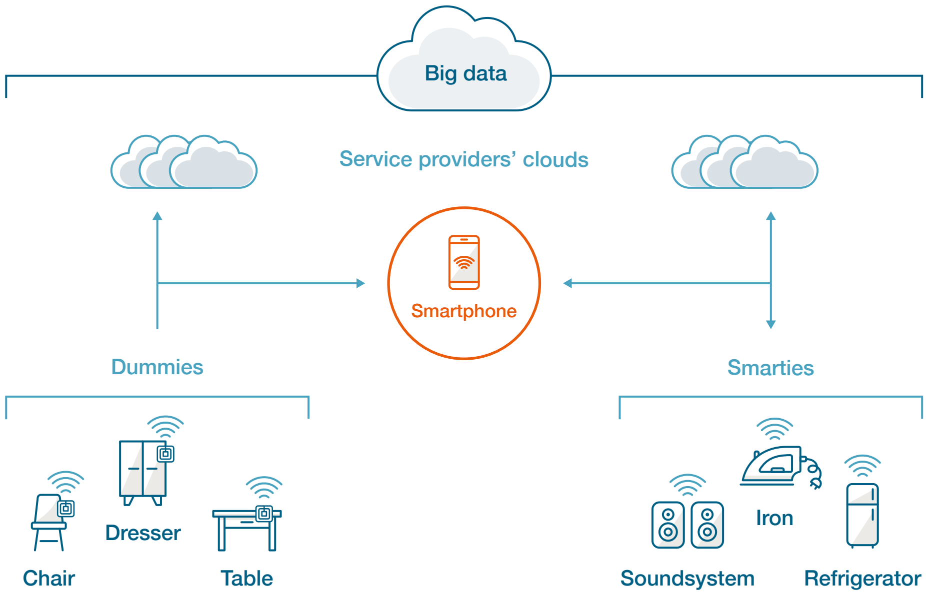


Figure 6. Extensive data gathering by products and devices with the capability to communicate.

new information on these types of commodities can also be obtained. In this way it is possible to gather data for product-lifecycle analytics from a commodity group that was not available for value and condition estimation. Information about these products allows better design for purpose and proper recycling at end of life. In addition, it opens up opportunities for business models related to renting and sharing.

With this type of data collecting, for instance, information on household products inventory can be obtained easily without user intervention. Since we have our mobile phones constantly with us, the smarties in the home will communicate constantly with the cloud, providing information on their own use and also information about the rest of the products that are located in the home. This will allow massive generation of information on the products, allowing better design of these products that will serve the needs of the users more precisely.

For instance, dining table sensors will provide information about the material the table is made from, how many people have been around the table and for how long by measuring, for instance, body temperature and movement, and thus be capable of estimating how often the table is in use. With this type of information and by using AI, it will be possible to estimate the condition of the table and generate information on how a table for that specific location and purpose needs to be designed considering, for example, the surrounding conditions and the profile of the family, so it doesn't need repair or refurbishment for a long time. Data gathered about surroundings will allow precise design using the most suitable materials for the purpose, which will reduce material use drastically. For example, data gathered on surroundings of the apartment based on, for example, the chairs, sound system and refrigerator can estimate the best material selection for a family dining table.

In future all the data gathered about surroundings and the material or product itself will be utilised for optimising features that ensure the optimal preservation of commodities. Products will last longer with the help of self-controlling features to enable better durability. There are already examples of self-healing and self-controlling materials and products. We see development in this direction to be a growing trend that will prolong the useful lifetime of commodities.

Privacy

Whenever real-life data is refined as information there has to be discussion on privacy. There is always the possibility to pinpoint users based on data that is gathered, for instance, from communicating devices such as smartphones. There are already several solutions for detaching this type of personal information from the gathered data that do not jeopardise personal information. There is still a need to have a proper privacy policy, otherwise security issues may end up being showstoppers in digitalisation. And it is evident that digitalisation provides many as-yet-untapped opportunities for the circular economy that we cannot afford to lose. Permissive legislation and regulation will play a crucial role in both protecting privacy and opening up opportunities for the digital traceability of assets.

CASE

Food is a basic human need and requires wasteless agricultural and food production systems

The world is bipolar in terms of food sufficiency; while there are 815 million malnourished people, one third of food is wasted[17]. The surplus between the available food and the required food is food waste. In the southern EU, the majority of the food waste occurs during harvesting, storage, transport and primary processing, whereas in the northern EU the waste is generated mainly during distribution, home-meal preparation and catering. Food and agricultural losses and waste have important implications for resource insufficiency, which ultimately causes poverty and malnutrition and limits economic growth. The fight against food loss and waste is as essential as reducing the environmental footprint of food systems and improving global food security. If half of the loss and waste were cut throughout the food chain, this would account to a saving of 25% of current global agricultural production[18]. A wasteless food and agricultural system not only means greater efficiency, but also increased productivity in the manufacturing and retail industries as well as direct savings for consumers.

Agriculture is the largest user of the world's freshwater resources[19]. Globally, there is enough water to produce food for everyone, but sources are unevenly distributed. The largest producing regions suffer the most from climate change and population growth-induced water scarcity. Non-conventional water sources are needed as well as technological solutions for food production in general.

The transition to wasteless food and agriculture will happen through applying agile and smarter production systems from farm to fork, "just-in-time", "just-in-place" and based on individual needs. We also need to create ecosystems that close the loop of nutrient flows from microorganisms and plants to animals and *vice versa*. Advanced sensory systems, automation, robotics and mechatronics-integrated farming systems should be the backbone of the production systems. Plant factories should be coupled with their process digital twins to manage the food production and distribution cycle more efficiently. Platform economy-integrated food distribution will also ultimately reduce waste generation. (For more information see Food Economy 4.0[20])

What if food production challenges could be solved by closed-loop food factories?

Before technologies are mature enough (and people are free from prejudices) to use atmospheric compounds as raw materials, food production moves from natural waters and arable land to compact closed-loop factories that minimise the need for nutrients, feed, clean water, agricultural land and energy. For example, an integrated and closed-loop fish, insect, plant and algae factory essentially mimics nature's own ecosystems found in ponds, lakes, rivers and their banks. In the factory, fish and insect farming is integrated into plant production in greenhouses and photosynthetic algae cultivations in reactors. At the heart of the integration is solar energy as well as water that circulates in a closed-pipe system between the fish tanks, greenhouses and algae reactors, which in turn enable cross-use of O_2 generated by the plants and algae, and CO_2 and nutrients generated by the fish and insects. Insects are fed by the excess fresh biomass produced in the system. (Figure 7).

Putting a closed-loop food factory into practice necessitates multiple technologies such as automation, robotisation, AI, IoT, data, sensor, water and food technologies. It also requires expertise in chemistry, biology, cultivation as well as integrating and optimising diverse production systems to be compatible with each other. Once these challenges have been resolved, closed-loop factories will be scalable, flexible, convertible and free from regional and climatic boundaries. The environmental sustainability of a closed-loop food factory is guaranteed by clean energy and by collecting and using rainwater and condensed atmospheric water vapour. Establishing waste and emission-resistant closed-loop factories in densely populated areas supports food production through improved energy efficiency as well as reductions in raw materials, packaging, storage and transport costs.

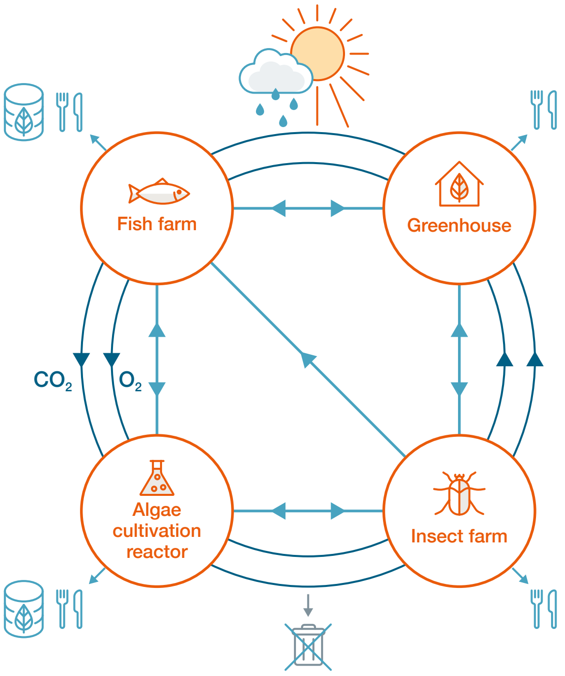
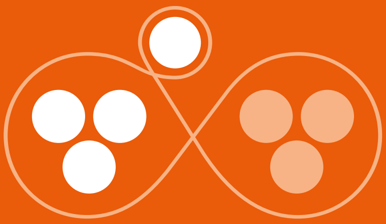


Figure 7. A scalable and convertible closed-loop food factory is resource efficient and independent of regional and climatic boundaries.

Recap of loss-resistant loops – a change path from a consuming to a regenerating circular economy.

	PRESENT SITUATION 2018	REQUIRED CHANGE	FUTURE VISION 2030 and beyond
MATERIALS	Virgin resources are depleted and waste accumulates. Recycling processes leak rejects and emissions, and focus is on easily separable material components. Materials and products are increasingly complex in design. Materials and products are resource consuming.	Loss-resistant recycling concepts for heterogenic waste. Design of materials and products for reuse and recycling, in this order. Recycling solutions focusing primarily on critical materials and substances. Feasible solutions for carbon capture and storage. Regenerative design of products.	Waste generation is minimised. Circularity target of 50 % is reached. Critical materials are fully restored and in continuous circulation. Fully recyclable and functional material solutions enable long life and reuse of products. Circulation of value together with products is enabled by regeneration and upcycling.
ENERGY	Energy is mainly fossil-based. Progress of renewable energy production is increasing, but too slow.	Acceleration in development of feasible renewable energy solutions. Enhanced energy efficiency in energy-intensive operations Development of advanced energy storage technologies.	Global energy is significantly renewable and energy production is emissionless. Industrial processes are energy saving and emissionless and primary focus is on energy-intensive operations.
DATA	Massive digitalisation is going on, but lack of consistent material information prevents development of end-to-end material supply chains across industry borders.	Transition from siloed to holistic thinking in production and manufacturing. Building of open data platforms to enable fluent material flow and ecosystem creation.	Ecosystems are formed based on open data. Digitalised supply chains reduce resource loss due to on-demand production. First steps towards material flow management.
SERVICE & SHARING	Waste management sector is the main service provider. Partnerships with other industries are lacking.	Development of data-driven material, market and service platforms. Accelerated transition to decentralised systems.	Waste management is an integral part of material circulation. Material-as-a-service concepts start to emerge.

3.2



MASTERY OF MATERIALS

In the vision of mastery of materials, data and materials are fused together. Materials become intelligent, safe, traceable and identifiable. The need for intelligent materials and products is a consequence of the predominant resource scarcity. This development leads to volatility of raw material prices and the emergence of new business opportunities such as ‘material as a service’. In this vision, masters of raw materials have control of supply and value chains, which is possible only when the mastery can be authenticated. Information fuses with materials to make them identifiable and traceable during endless flows from cycle to cycle and transforming anew along the way. Open data clouds help to ensure that material supply and demand are more evenly matched. Fluent data-driven material flow management is the focus.

OUR FIRST actions in moving towards a genuinely sustainable economy were to concentrate on *loss-resistant loops* – decreasing the loss of materials during extraction, manufacturing, use phase and at the end-of-life by transitioning into circulating business models and systems. Another focal point was to diminish energy use (especially fossil), remove hazardous substances from the loops and reduce overall material use by adopting regenerative design of materials and products and moving to service and sharing economy models that are enabled by accelerating digitalisation and open and big data.

Many estimates show that the global population will still continue to grow for several decades. At the same time living standards are improving and developing economies continue to grow, increasing overall production and consumption. Over time the imminent scarcity of resources will start to show in the form of even more volatile prices and unavailability of raw materials. Uncertainty about the supply of raw materials will increase and the security, and safety of all global supply chains will be at stake if the exploitation of natural resources continues at the same pace. The primary question is how to avoid the battle for resources from arising in the first place? One answer is through efficient material flow management. We believe that creating an optimal system in which materials, value and information can flow together is the solution to keep materials in use for longer and circulating effectively. For the mastery of materials, traceability and condition estimation require intelligent material design, connectivity between items and digital systems.

Intelligent products supported by digital solutions will play a crucial role in enabling the efficient and optimised usage of materials. This was discussed already in connection with the first vision, ’loss-resistant loops’, in which information flow is enabled by smart appliances and various connected devices. In the mastery of materials part of this vision, information about the location, condition, characteristics, composition, availability and ownership of materials will change the game in unprecedented ways. Information fused with materials themselves, not only smart appliances in which the materials are used, will enhance material usage and promote looping materials back into the systems. Reliable mastering of the data will play an essential role in managing material flows and the promotion of new services.

Information is intrinsic in commodities; in the future it will also be intrinsic in materials. This enables follow-up of materials in commodities or as such during the entire lifespan, even if the material ‘visits’ various products during its life cycle. Material data from all stages of the lifespan can be fed back to the design phase where material life extension and full recyclability are the main targets. Analysis of the data in materials will also provide information needed to optimise production. Through this process, designed-on-demand materials will precisely meet the desired performance. (Figure 8).

> What if we could have materials that can circulate freely within and between in any loops without losing value, and regenerate excess value to the existing surroundings?

In order to avoid the production of excess and incorrect materials and products, data must be utilised in every material-related industry and business. Data gathering and analysis will provide accurate information on the amounts and desired specifications and performance for materials and products, which will reduce unnecessary production; in some cases it may even call into question the need for production with the right information obtained from the data. For instance, some goods need to be designed to last longer while others are intentionally made to serve for a shorter lifetime. A significant amount of energy and materials can be saved if the optimal lifetime of the goods is taken into account at the material design and production phase. Lifetime optimisation will be provided by the constantly evolving data analysis and AI that turn the material's data into useful information and knowledge, which in turn ensures that systems can be optimised effortlessly and without generating waste. These evaluation and estimation tools will help to direct each resource to the right place, where they are non-substitutable and needed the most, like metals and other non-renewables. Precise estimation tools will evaluate the need for substituting the critical materials that are currently non-substitutable and depleting. This will activate massive research on substituting critical metals and minerals with renewable alternatives.

As a consequence of the limited amount of materials circulating in the future economy, material ownership will become highly desirable. Brand owners will also become raw material owners in order to guarantee continuation of their operations in a business environment suffering increasingly from resource scarcity. Thus, in addition to the value-gain models described above, we propose yet another model called material as a service (Figure 8). In this model, business is based on the right to use the materials rather than the materials themselves being sold. This model generates profit for the material's original owner at every step of the supply chain, as well as when the material enters the next supply chain. The more value the material can preserve during its lifetime, the more profit the original material owner can gain.

> Material as a service will change the game of ownership.

Unique information in materials acts as proof of ownership. It helps to identify, locate, quantify and qualify materials, thereby enabling 'from local to global' leasing and trade as well as the creation of material-as-a-service business models where material is leased rather than sold. Digital

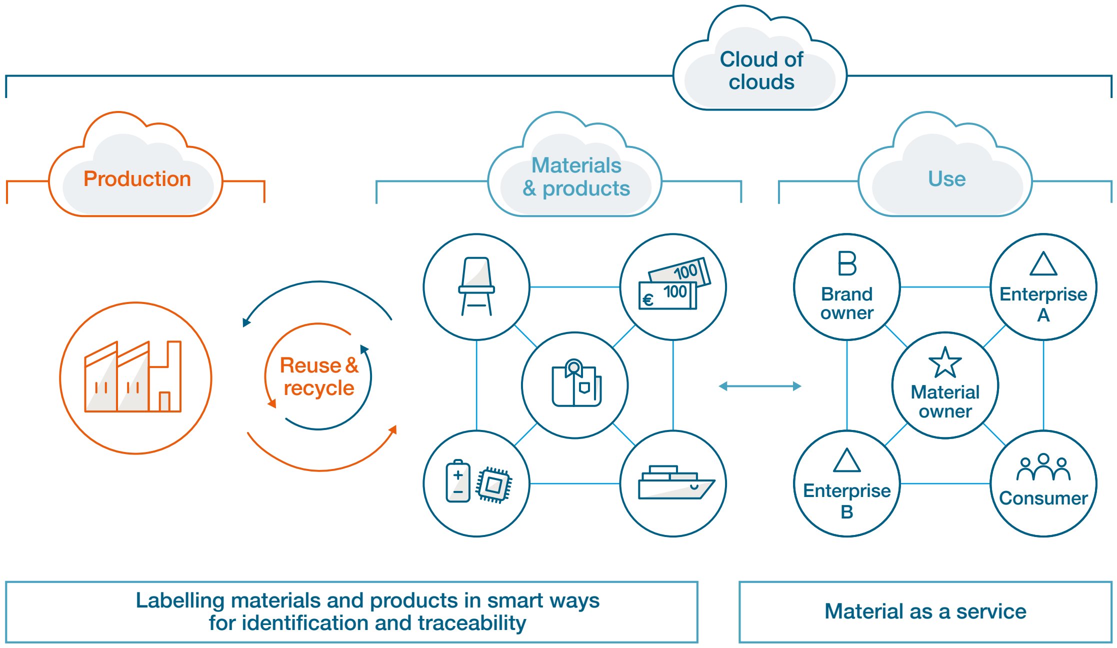


Figure 8. Mastery of materials becomes possible with intelligent labelling and traceability as well as material-as-a-service business models. The digital systems needed for the mastery of materials necessitate efficient data and information management and processing in a 'cloud of clouds', where information about resources, products, productions, logistics and consumers will be merged.

follow-up of materials in circulation will enable a material owner to decide in which loop their material cycles. Mastery of materials will enable value maximisation and offer many novel possibilities to the actors of the business environment. Besides enhanced material management and business possibilities, mastery brings with it a responsibility for the material during the whole of its lifetime, which at present is passed to the second actor when a purchase is made. In the future, the original owner of the materials has an interest in keeping them in different cycles for as long as possible due to the better economic value gained. This model works when a material is traceable and identifiable, and is free to take new forms as it circulates; in other words it can jump from a lower to a higher value level. This model requires technological disruptions that enable programmable and intelligent materials, platform economy solutions that enable traceability and identification of materials, as well as open and reliable platforms for material exchange.

Intelligent materials

The flow of information is managed by sensors and other IT solutions that connect computing devices and machines to each other, enabling the transfer of data without human interference. This system is the Internet of Things (IoT). Today IoT connects machines to people provided they are carrying a smartphone or, for example, wearing smart running shoes. IoT enables the identification of smart objects and determines their location. However, the materials these objects are made of are non-communicating and therefore out of reach of IoT when an object is disassembled for recycling.

> In the future circular economy, information is deeply embedded into materials.

Embedded information enables traceability, authentication and condition estimation during the whole life span of a material. The information tells whether, when, where and how much material is in primary use, recycling or removed from circulation. Material identification will become a central issue in the future economy as materials remain in value-maintaining circulation for a long time and may transform during circulation. Intelligent and self-sufficient materials will be the assets that enable a shift from the present production-centric operation model to material circulation and material-as-a-service business models.

Fusing information into material can be performed in many ways, the most ingenious and most practical of which are obviously still to be discovered. It is done by labelling material either on the internal, external, structural or molecular level. Combining labelling with sensors makes it possible for materials to communicate and react to external stimuli. Various labelling methods exist, starting from molecular-level solutions and going all the way up to bar codes and radio frequency identification (RFID) tags on everyday commodities such as keychains and wristbands used in public swimming pools or rock festivals. Labelling is used to brand and prove ownership of products. However, external labelling is no longer workable when commodities and appliances are disassembled into components and further to material fractions during the recycling processes, and yet further still when separated materials are fractionated to smaller components, polymers for example, and modified once more for another use.

Although materials fused with intelligent and communicating components and molecules may sound like something from science fiction, rapid technological development in robotics, mechatronics, printed intelligence, material science and technology, biotechnology and synthetic biology will offer us the means to create smart material solutions sooner than we can imagine possible today. When it comes to making materials intelligent, common sense is a wise adviser. A bulk material destined to last a short period of time and serving a single and simple service, toilet paper as an extreme example, is not the target for embedding information; it is scarce, highly valuable and high-performance materials that need information to keep them in long-lasting and value-preserving use.

CASE

What if smart labelling could enable materials to communicate autonomously with owners, users, each other and the surrounding environment?

Nanorobots or nanomachines, still lurking in the future when it comes to material applications, may become everyday labelling options. They arrange themselves inside or on the surface of a material matrix and carry out programmed functions during usage. They can prove or change ownership, collect and store data regarding usage, and update the characteristics of the material as a response to changes in the surrounding conditions.

There is no doubt that it will be necessary to harness nature's power in order to convert non-communicating materials into communicating ones that are also adaptable to external changes. Nanorobots communicating and operating closely together with living organisms multiply the amount of data content in the form of the DNA the organisms carry in their genome. Future 'nano cyborgs' are highly functional combinations of nano-scale biological and mechatronic parts that may serve multiple functions in materials that are yet to be discovered.

There is one potential obstacle on the nanorobots' road to becoming reliable information carriers within materials: they might be too big when the information has to dive deep into molecules. As nanorobotics may provide added functionalities and intelligence to otherwise non-communicating materials, biotechnology and its spearhead synthetic biology offer a means to synthesise and produce molecules, non-existent in nature, with built-in functionalities and intelligence. Materials composed of or containing these molecules incorporate entirely new and unique features that are exploited to perform special functions, to prove the material ownership down to the molecular level, and to enable material flow management in its broadest sense (Figure 9).

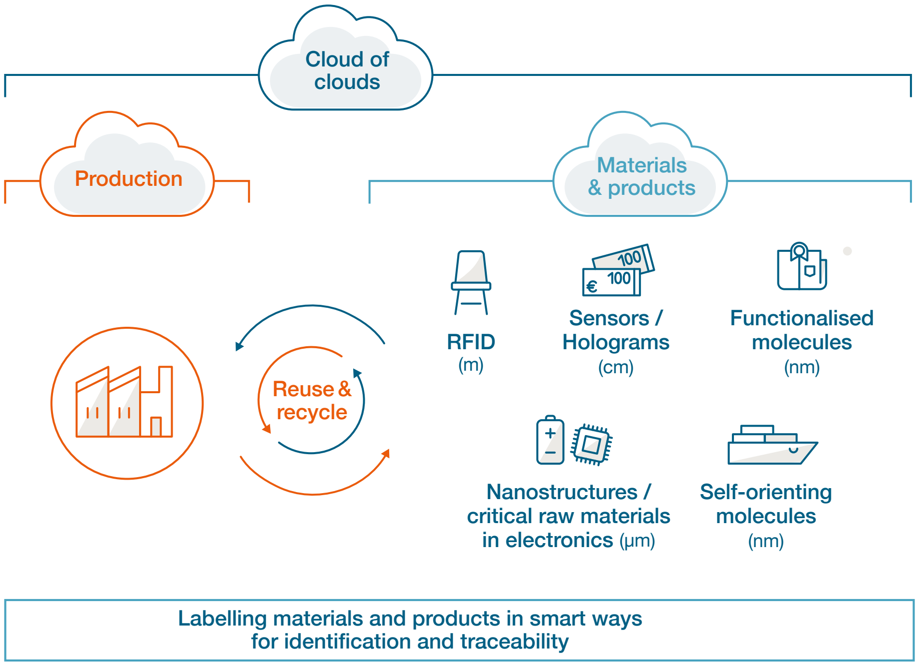


Figure 9. Intelligent materials are capable of communicating with their owners, users, the surrounding environment and each other. Materials will be labelled with different magnitudes of accuracy.

Molecular-level labelling will enable traceability of materials and even molecules.

CASE

What if all trade could be automated by micro-transactions?

In an accelerated circular and sharing economy, commodities will be reused and recycled multiple times during their lifetime, changing hands between users much faster and more often than today. This change will require much more agile data processing, which will call for autonomous trading with micro-transactions.

Micro-transactions will enhance a circular and sharing economy by making trade fast and easy. In future we will be able to just simply pass a product to the next user; there will be no need for manual money transactions or any kind of contracts between trading parties. The system will detect the identity of the trading parties and the transaction will happen autonomously. There will be no need to worry about contracts because smart contracts will govern common rules and an individual's rights within the system.

> Micro-transactions will enable real-time optimisation of material circulation due to fast data exchange and gathering.

Data obtained from the commodity use phase will be exploited to optimise the production of materials, the manufacture of products and the supply of services. Fast micro-transactions will enable data gathering about the circulation of commodities that is presently lacking, and this data can be used to plan better circulation of the commodities back into use. The reuse of commodities can thereby be more effectively managed, monitored and encouraged, for instance through a compensation system or via regulatory incentives. A good example of an incentive-based system could be metal recycling. A customer returns used metal cans to a recycling unit, which detects the cans and the customer, and pays the recycling deposit directly to the customer's account. For instance, if the recycled item is an old kitchen appliance, the transaction can include the history data of the device, which can in turn be used to optimise design and manufacturing to make better appliances. The customer benefits financially from recycling the device while the service provider benefits from the material and data gained, resulting in improved service and commodities for customers in the future.

Another example could be a car driving via a ring road and visiting a market. Car sharing can be charged directly from the account based on time and travel to the market. The user is directly invoiced a road toll fee based on the kilometres driven on the ring road. For instance, if there are three persons travelling in the car, parking-related costs are charged to all passengers in the car. The car itself can make payment transactions at charging stations or at specific electricity producers. Transactions can take place every minute, and the value of the service is directed to the service provider's account in seconds.

In this kind of trading system the customer can decide how the data is utilised, and in so doing affect the value creation of the data. The value of the data can be automatically evaluated and invoiced. There are already demonstrations of data marketplaces for sensors. The quantity of transactions increases rapidly when machines make transactions, so transaction technology needs to have good scalability. One major challenge of a proof-of-work blockchain is scalability and transaction costs, which are important for micro-transactions.

Fast micro-transactions will also change how digital platforms operate. In future, digital platforms for materials will contain real-time information on the location, condition, quantity and availability of materials by creating an 'automated valuation of unused commodities'. Data from commodities will be able to interact in the system using AI and the system will be able to define a reasonable global price for all commodities. These novel platforms will enable autonomous global trade in commodities without human interaction or precise decision-making.

CASE 6

What if there were incentives to maintain and increase the value of the commodities?

There are already service models in our society, like leasing tools or a car, where we benefit from the on-demand performance of the commodities instead of the ownership itself. In the future there will be only a few commodities that we will own in the traditional meaning of the word. Novel business models will provide easy access to commodities without the need to actually own them. Most of the commodities that we need during our lifetime will be available for intermittent ownership through leasing, renting or other novel business models. Users will pay for the performance of commodities in the same way as they do today when they stream movies from Netflix.

Today, private ownership does not necessarily incentivise users to take care of the commodities because they are owned as private property and the owner gets to decide how the commodity is sustained. When the commodities are available only for performance use and the commodity itself will not be available for ownership, this will lead to better stewardship of the commodities while they are, for instance, leased for use. For this to become a reality, the trade system must identify the user in real time in order to be able to transfer the intermittent ownership and therefore the responsibility. The user can be quickly identified if the trade is done via micro-transactions.

The idea of this type of system is to initiate a business model that regenerates value for both the business owner and society as a whole, and promotes the responsibility to maintain commodities in such a way that their value is preserved or even increased. Evaluation of the value is based on the current market, in a similar way to stock markets.

Recap of mastery of materials – changing path from material production to a networked management of material circulation.

	SITUATION 2025	REQUIRED CHANGE	FUTURE VISION 2040 and beyond
MATERIALS	Resource insufficiency is a serious threat. Material circulation and flow management are not realised as materials are not traceable. Products are designed for reuse and recycling, but materials are not.	Development of fully recyclable and traceable materials with desired performance. Development of self-sufficient and regenerative materials and products.	Critical and valuable materials are traceable and fully recycled. Self-sufficient materials are increasingly used.
.ENERGY	A moderate proportion of global energy is sustainable, but progress needs to be accelerated.	Exploration of novel solutions to increase renewable energy. Adopting energy-efficient, energy-conserving and renewable energy-powered technologies that have a short energy payback time.	Disconnecting from fossil energy is focused but not yet total. Renewable energy solutions are diverse and increasingly decentralised.
DATA	All critical operations are digitalised. Most critical and valuable materials and products are tagged and data gathered. Blind spots of untagged resources are filled with information from data.	Investing in sovereignty, reliability and cyber security of data. Blockchain technology applied to enable authentic traceability of materials. Transition from distributed networks to a decentralised network of systems	Real-time material flow management is fluent.
SERVICE & SHARING	Value of materials has increased dramatically due to exhaustion of raw material reservoirs.	Solutions to transform value generation from selling physical items to providing services. Accelerated transition towards a network of systems.	Materials are used for as long as they contain value. Material-as-a-service business models are in full use.

3.3

THE NEW ERA OF RESOURCE SUFFICIENCY

The new era of resource sufficiency will rely on radical innovations enabling sufficient access to affordable, sustainable and renewable energy as well as life-supporting and life-facilitating compounds and materials made extensively of gaseous raw materials and fully recycled minerals without compromising the capacity of the planet. In addition to industrial exhaust gas and traffic emissions, the atmosphere is a significant reservoir of CO_2 together with other essential elements such as nitrogen and compounds such as water. The new era of resource sufficiency will rely on technological innovations enabling the use of atmospheric raw materials. Instead of being restricted to selected locations, resources will be available everywhere.

MAN-MADE, intelligent and programmable molecules are synthesised of fully recycled substances. We can fight the battle for resources, forcing resource scarcity and climate change to fall by offering high-performance compounds and materials based on biological functionalities or, beyond this, materials which are produced as needed, on-demand and with features non-existent in nature. By this point the boundary between non-renewables and renewables will blur. The possibilities are limitless. Materials are designed to be assembled and disassembled on a molecular level, thus making them reusable in multiple applications.

Insufficiency of nutritional food is a serious problem due to concomitant population growth and declining food production because of failing cultivation conditions caused by climate change and the reduction of arable land in areas where the need for food is the most urgent. Although moderate warming and CO_2 level increase is mostly beneficial for agriculture, severe warming followed by erosion, floods, drought and other natural calamities is becoming more common. Livestock is at risk because of diminished fresh water supply and edible feed is primarily fed to people. Although measures are being taken to limit GHG emissions through the use of technological solutions and regulative actions, they are not enough. Climate change and the deprivation of land have already had a negative impact on nature. Disruptive new innovations in primary and industrial production emerge to overcome these challenges.

The capability to use atmospheric raw materials enables access to sustainable, life-supporting and life-facilitating compounds and materials without compromising the capacity of the planet. Population growth is predicted to increase the need for food by 70 % towards 2050[18]. To tackle this threat, the sufficiency of sustainable, renewable and emissionless energy must first be secured. By this period, if not before, carbon-based energy production is experiencing radical change as there might not be enough of even the lowest-value organic or biomaterial available for energy production. Turning back to fossil is not an option. Businesses will evade the CO_2 risk and invest in non-carbon energy solutions such as solar, wind, geothermal, wave and nuclear power. By definition, the sun is an infinite source of energy. Technological solutions are approaching such readiness levels that enable feasible and sufficient solar energy supply together with wireless electricity transfer solutions. Novel technologies for energy storage will evolve to mitigate the variations in the solar energy availability on a seasonal and regional basis.

Gasification and other thermal processes are increasingly used to produce simple carbon compounds and hydrogen from end-of-life organic and biomaterials, and these compounds serve as feedstock for chemical compound and material synthesis and production. Minerals and metals are recovered from ash and other fully recycled sources. Apart from non-carbon solutions, energy is generated in thermal processes as a co-product together with CO_2, CO and H_2, the capture and utilisation of which are common practise. Energy-self-sufficient and energy-regenerative material and product solutions are increasingly in use to ease sustainable energy sufficiency (see Chapter 4 for more on this topic).

In the first phase of carbon capture and utilisation (CCU) CO_2 will serve as a starting material for a number of chemical compounds, some of which are converted to materials by biological and chemical means. This phase is followed by food production provided other necessary components, such as nitrogen and phosphorus, are sustainably available. Although biomass reserves are used in a cascading manner, population growth and an increased need for food necessitate novel raw material reserves to be taken into use to provide food for all people. Traditional agricultural and aquacultural production will not be enough to feed the human population and livestock. In the future sufficient and affordable sustainable energy makes it possible to direct CCU to produce food and offer clean, fresh water to all people and livestock and for the irrigation of plantations. Agriculture, water systems and nature in general can recover in dried and wasted areas. This development strengthens climate change mitigation and eases the evident geopolitical pressures caused by increasingly uneven distribution of fresh water, food and bioresources. Nevertheless, turning back to the present-day overproduction and conspicuous consumption will no longer be an option.

Nature has amazing capability to convert atmospheric CO_2 into sugars and further still into a plethora of other compounds. Photosynthesis also requires water and an energy source – the sun. The man-made conversion of CO_2 into chemical compounds and materials mimics nature's own way of producing multiform biomass. Currently, the most promising synthesis routes include the exploitation of microbes using CO_2 and sunlight, microbes using CO_2 and hydrogen and microbes using reduced one-carbon molecules (carbon monoxide, methane, methanol) as nutrients for growth[21] (Figure 10).

In the new era of resource sufficiency, no distinction is made between bio-based and fossil feedstocks as the original source of CO_2 is irrelevant. By definition, the utilisation of fossil resources is reduced significantly from the present state. The newly generated CO_2 emissions come from the thermal conversion of biomass and organic end-of-life products as well as iron, steel and cement production, deforestation and land clearing for agriculture. As gaseous emissions

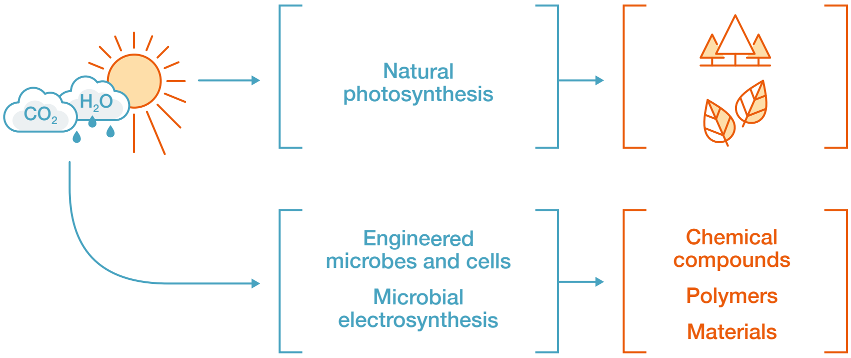


Figure 10. There are several technological possibilities to utilise CO_2 as a raw material. Photosynthesis and man-made syntheses will be all in use when flue gas and atmospheric compounds are converted to chemicals, polymers and materials.

from industry are increasingly captured for use, at some point in time we will witness a tipping point. The worldwide renewable biomass growth and CCU together will exceed CO_2 emissions, eventually leading to a negative carbon balance. CO_2 will not dilute out from the atmosphere altogether, but return to natural levels.

Carbon, hydrogen, oxygen and nitrogen together make up 96 % of living matter – all these elements are available in the atmosphere.

Nature's synthesis power supports the return to the era of resource sufficiency. Microbes convert organic waste to desirable products via biotechnical and biological processes. They also exploit CO_2 and N_2 by nature. Biological and biotechnical processes are combined with chemical ones. In thermochemical processes heterogeneous and fluctuating organic matter is converted to simple carbon compounds, which natural and engineered microbes use for biosynthetic reactions. Living cells are factories that produce a variety of products ranging from chemicals and materials to food.

CASE

What if there would be no need for oil, arable land or fresh water to produce nutritious food and functional materials?

In addition to optional routes for capturing and producing chemicals and materials from CO_2, fixing atmospheric nitrogen to ammonia (converted further to amino acids and proteins by either natural or engineered microbes) enables food production from 'thin air' (Figure 11). The atmosphere is also a notable reservoir of water. The ability of certain autotrophic microbes, with the help of electricity to reduce CO_2 to simple hydrocarbons, such as methane or methanol, has been known for many decades.[22, 23] Harnessing the microbial ability to fix nitrogen for industrial use is an alternative to be reckoned with, as the industrial nitrogen fixation process (Haber-Bosch synthesis of ammonia) is an energy-intensive process that emits significant amounts of CO_2.

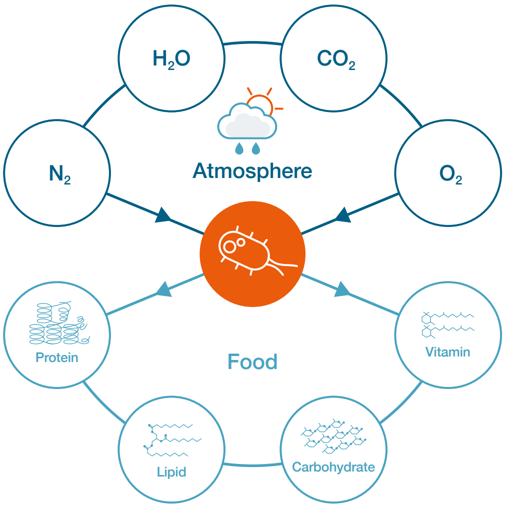


Figure 11. Essential food components are synthetised by natural or engineered microbes from atmospheric elements and molecules using sunlight or electricity as an energy source.

Food production is decoupled from agriculture, livestock husbandry and aquaculture. In turn this will partially solve the challenges related to land use, eutrophication of water systems, over-fishing and climate change. The environmental impacts are minimised to zero, and eventually solutions for producing personalised and nutritious food at home will be realised, although centralised closed, controlled and optimised food production "farms" will also emerge. Food production is no longer dependent on any specific temperature, humidity, soil type or region, and as such a food source can also be provided in locations that suffer from famine and lack of arable land due to drought and erosion.

Synthetic biology will revolutionise future production.

Industrial biotechnology is revolutionised by **synthetic biology**, a combination of biology, engineering and information technologies[21]. Synthetic biology paves the way for multiple applications responding to requirements caused by climate change, resource scarcity and waste accumulation. It enables 1) the development of powerful biocatalysts targeted to convert challenging heterogeneous organic and biomaterials into useful chemicals and materials with minimal environmental impact; 2) design and synthesis of high-performance molecules and materials, existing and non-existing in nature; 3) design and construction of production microbes needing less carbon and energy compared to their natural counterparts; 4) design and construction of microbes capable of synthetising predetermined molecules and building blocks for information-containing and high performance materials; as well as 5) modelling and design of resilient microbe populations capable of converting a vast array of heterogeneous and transforming waste streams into defined molecules. Synthetic biology is a disrupting technology that will blur the boundary between renewable and non-renewable materials.

> The boundary between non-renewable and renewable will blur when we enter the new era of resource sufficiency.

Critical raw materials (CRMs) are economically and strategically important but have a high risk associated with their supply. They are particularly important in electronics, environmental technologies and the automotive, aerospace, defence, health and steel sectors, but are currently lacking feasible substitutes[24]. Synthetic biology focuses on synthetising materials having similar (or better) functionalities as their natural analogues, for example spider silk. No doubt synthetic biology will possess the power to create molecular solutions that can be used to replace, for example, precious metals in electronics.

Information technologies, bioinformatics and computational design of organisms and molecules together enable the synthesis of a limitless variety of compounds and materials essential to life. Biosciences in many application fields generate huge amounts of data. This data is converted into mathematical models and algorithms as well as further to programmed organisms that produce predetermined compounds. Biological compounds and materials have excellent life-supporting properties due to billions of years of development carried out by nature itself through evolution. Nature is a mastermind in creating high-performance materials, such as feather, mother-of-pearl, spider silk and cellulose, to name just a few. Even so, synthetic biology can beat nature when it comes to bringing completely novel functionalities to materials and how these materials are produced. Nature provides an abundance of materials in impressive packages, such as cellulose in trees, feathers on a peacock, or pearls in shells. Going synthetic liberates us from these packages, which have essential tasks in nature's grand ecosystem but are unnecessary and extravagant from the efficient and frugal chemical and material production viewpoint.

CASE

Future agile biorefineries – creating speciality and high-performance materials from CO_2

> What if we could produce high-performance materials based on solid knowledge of what society needs?

To avoid the production of unnecessary and excess materials we need technological and business solutions to produce the right materials for use; at the same time we also need accurate information on what is needed. Information gained by taking advantage of big data and digital solutions will allow us to design production based on precise information on what is needed and what the specific criteria are for production and manufacturing to be able to answer the demand precisely using resources optimally.

Cellulose is one of the most important raw materials for future product applications (see VTT vision paper 'Cellulose goes digital'[25]). New building blocks (nanocellulose, hemicelluloses, dissolving pulp) are already replacing oil-based and non-biodegradable plastics in consumables. Digital data management

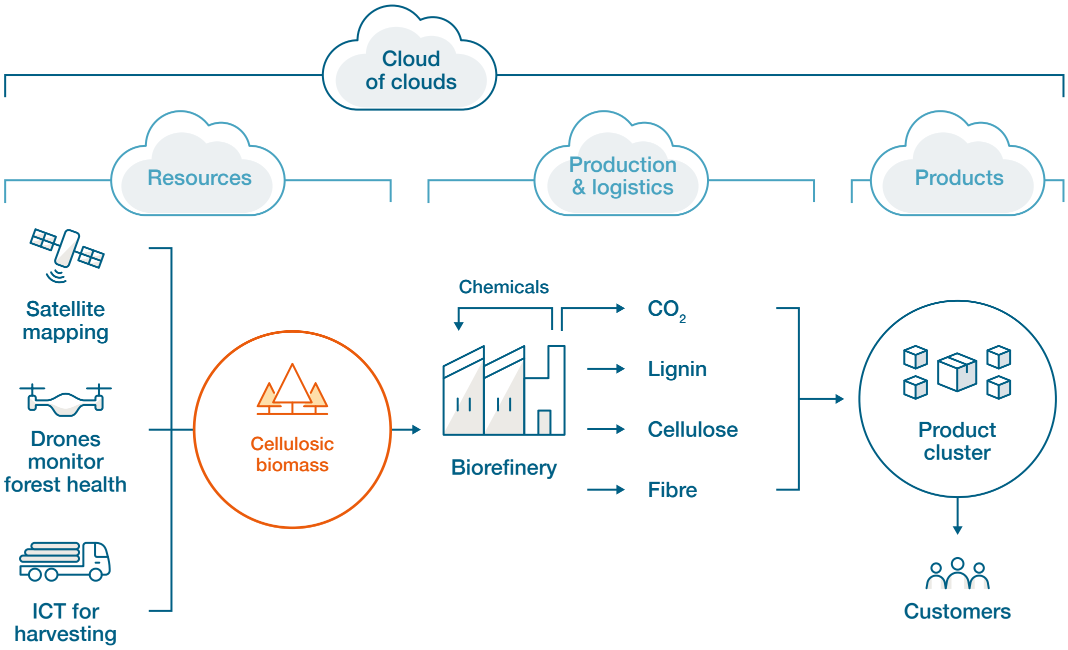


Figure 12. The future biorefinery produces high-performance materials from CO_2; the supply chain is loss-resistant, material efficient and resilient due to a digitalised service network.

and transfer makes it easy to predict the market need and to react in real time to the production of different products.

Currently, cellulosic pulp production in modern biorefineries is a carbon-neutral process that does not require fossil raw materials or energy. In addition to cellulosic pulp, biorefineries produce many other products, such as lignin and ash that are valuable intermediates for chemicals or fertilizers. The pulping chemicals are recovered by combusting the dissolved organic matter, and the amount of energy produced during this process exceeds the needs of the biorefinery.

The chemical recovery cycle of pulp biorefineries produces significant amounts of CO_2 and will continue to do so in the future. However, instead of emitting CO_2 into the atmosphere as happens at present, it will be captured and transformed first into commodity chemicals and further to materials and even food. This will be achieved by artificial photosynthesis or other synthesis routes that convert CO_2 and water in the presence of carbon neutral energy into carbohydrates and oxygen, just like nature does in photosynthetic plants. In the biorefineries of the future, engineered microbes will produce speciality cellulose and other high-performing materials from the exhaust gas. Biotechnically engineered microorganisms will allow the production of entirely novel types of cellulosic polymers that are free of the functional limitations of plant celluloses. They embrace information needed for identification and traceability in whatever product the cellulose is used. Alteration of the cellulose degree of polymerization, nanofibril width, crystallinity, crystal structure and sizes as well as embedding information and novel functional groups is used to tailor cellulose properties, enabling applications in which plant cellulose does not meet the requirements.

The new era of resource sufficiency – the path for change from a battle for resources to resource sufficiency.

	SITUATION IN 2025	REQUIRED CHANGE	FUTURE VISION, beyond 2050
MATERIALS	The carbon balance of industrial ecosystems is at a tipping point. Material loops are loss-resistant. CO_2 capture and storage is commonplace in industry. The battle for resources, particularly in relation to critical raw materials and water, is being won.	Substituting critical non-renewable materials with renewable alternatives. Development of high-performing materials. Development of solutions to convert captured CO_2 and atmospheric compounds into food, chemicals and materials.	Food, chemicals and materials are produced in an environmentally friendly way. Everything physical circulates in a way that imitates natural circulations, but in an accelerated and controlled manner. Renewable materials are largely replacing exhausting non-renewables.
ENERGY	Carbon-based energy production is undergoing radical change; there is not enough organic or biomaterial available for energy production. A significant proportion of global energy is sustainable, but it is not sufficient to cover all needed operations.	Acceleration of self-sufficient devices that use and provide sustainable energy. Flexible and scalable solutions to capture sustainable energy from different resources.	Most energy is sustainable. A substantial amount of devices are self-sufficient and provide sustainable energy.
DATA	Big data is exploited for all critical activities, such as resource management, health and wellbeing, and education.	Development of a network of systems to manage massive digitalisation of all critical assets.	The world is managed by data, enabling resource sufficiency. Data is exploited to produce nutritious food and high-performance materials.

4

CIRCULARITY AND THE ENERGY DILEMMA

ENERGY IS one of the critical challenges of our time. Together with the digital transition, a world where all materials circulate without generating waste and emissions necessitates a transition from fossil to sufficient sustainable energy. The dilemma of consolidating energy and the circular economy can be expressed simply: demand for energy is growing, meaning there is a need to generate more energy, but this energy must be produced in an emission-free way.

The growth rate of the sustainable energy share is promising, though the pace is not rapid enough to combat climate change. Approximately 80 % of the energy consumed is still from fossil stocks, the rest being from renewable sources like biomass, solar, wind, hydro, tidal, wave and geothermal heat[26]. There is an urgent need to increase the capacity of sustainable energy. Nuclear power is considered as one of the sustainable energy sources in mitigating climate change.

The economy today consumes a vast amount of energy and materials, resulting in emissions to air and land-use deprivation. The circular economy provides sustainable solutions to today's operative models. However, circular operations, such as logistics, separation and enrichment of the materials can backfire in the form of emissions and material loss if the operations are not designed and implemented from a system-level perspective.

When it comes to evaluating the impact of extraction and recycling, there should be sustainability assessments. Without accurate calculations it can be challenging to prove which operations are burdening the environment more than others. Thus, the sustainability of circular activities cannot be taken for granted. If fossil or other carbon-based energy is used, in general, most of the circular operations result in emissions. The energy demand of circular economy operations should be covered by sustainable energy to a growing extent. Without sustainable and emission-free energy, the principles of the circular economy are not built on a healthy foundation in the long run. However, in reality this is a transition, and despite the fact that today's circular operations generate emissions they must be continued if we are to succeed in changing the dominant (non-sustainable) state to a sustainable one.

> Low-carbon energy is a necessity for a sustainable economy.

Currently, the energy transition is slow compared to the extensive need for energy that needs to be sustainable, but at the same time there are limited options for emission-free and sustainable energy. The use of biomass or waste as energy contradicts the cascading use of resources in the circular economy. Thus, utilisation should be focused on the material, not the energy use. As for replacing fossil energy, the quantity of available biomass or waste is not enough to fulfil the growing energy demand. However, at the present stage of the transition from fossil to sustainable energy all possible sustainable energy sources should be utilised to accelerate the energy transition.

In order to substitute fossil resources there is a need to increase energy production capacity by thousands of gigawatts, depending on the capacity factor of the technology used. Capacity scalability plays a crucial role in solving the urgent need for energy, and it favours photovoltaic (PV) and serially constructed nuclear technologies (standardised plants built by experienced crews assisted by established supply chains). PV technology has shown rapid growth in terms of production and installation capacity. Standardised serial production of nuclear power plants has happened historically, for example in France, but has stalled globally. Small modular reactors (SMRs) are an attempt to gain the benefits of serial production quickly, and are well under development and have other advantages for the energy system such as load following, a high capacity factor and suitability to locations where renewable energy production is not feasible. Intensive electrification of the energy system together with an increase in energy demand may create massive capacity increase-related challenges. Total energy, and especially electricity demand is anticipated to increase due great electrification and circular economy-related material processing or substitution.

Due to the urgent need to increase energy capacity it is vital to direct resources (investments and natural resources to produce sustainable energy solutions) to places that ensure maximised sustainable energy yield. But this alone is not enough if, for example, geographical conditions are not taken into account properly. To utilise available PV capacity most efficiently, it should be located where capacity factor can be maximised.

Upcycling aims to circulate materials in value-preserving and increasing ways, and aims to use less energy and material inputs compared to traditional recycling. At the same time, there are some materials that are irreplaceable, and they need to be processed despite their high energy input. This might direct investments for material reuse and remanufacturing to areas where the energy cost is lowest. In these cases upcycling will be focused on products and materials that are energy intensive, for example, chemicals with high hydrogen content. Potential limiting factors to this path are, for example, material logistics and related expenses.

Intermittent energy sources such as PV and wind, both of which have a relatively low capacity factor, may result in the production of excess energy that can be used in intermediate products. These intermediate products do not act as energy storage, but rather as rational energy investments to attain value. These can be, for example, pure water, commodity chemicals, alloys or composites, which need a significant amount of energy to be produced, but also have multiple uses. Intermediate products can be processed and shaped on-demand locally where excess energy is available and then distributed further. This also supports exploitation of the locally produced energy for self-consumption. However, there are inconsistencies in where sustainable energy is available and where production is located. Thus, demand and supply does not necessarily meet from the energy perspective, which means that there is need to decrease energy consumption, increase energy efficiency and rationalise material use.

Entering the second stage, Mastery of materials (Chapter 3.2), and the third stage, The new era of resource sufficiency (Chapter 3.3) of our vision is dependent on a transition towards CO_2 emission-free energy. Without sufficient sustainable energy, most of the developments outlined in this vision paper cannot be realised without generating excess emissions. The technologies used to solve this challenge will be solar (photovoltaic and concentrated solar power, CSP), wind or other new energy production technologies. Nuclear energy is seen as one of the potential alternatives in the energy transition. Realisation of these investments is related to the cost of increased capacity and valuation of end products. Without intensive investment in emission-free energy climate change cannot be mitigated. This means that there is a need to markedly increase the amount of these sustainable energy sources in society, starting now. Thus, all sustainable energy production methods should be used at the beginning of the energy transition, even if some of the used technologies will be the dominant ones in the long-term. In this transition, local conditions, geopolitics, legislation and the economy will guide the regional energy mix.

CASE

What if we could harness sustainable energy that is regenerated by the societal stock?

Today, the majority of energy production is related to material resources such as coal, gas and oil. Figure 13 depicts the flow of material resources and energy in the current linear economy, where materials are being extracted from nature and energy is obtained from fossil sources. **Societal stock**[27], mentioned in the figure, consists of all human-made material physical assets. The built environment dominates quantitatively societal stock. Societal stocks include materials that are extracted from the environment to make, for example, long-lasting products, devices, household appliances and machinery. Eventually these materials and products accumulate in societal stocks, and at the end-of-life are discharged to the environment as waste and residuals. Each year a considerable amount of materials are used as net additions to stocks in form of long-lasting or durable products ('stock building'). A significantly smaller amount of materials are leaving the societal stock than entering it. The amount of 'demolition and discard' is much smaller than the amount of new material added to societal stock each year. As a consequence it is continuously growing, and a bigger societal stock' tends to trigger more materials and energy for 'maintenance and repair'. At the moment, the energy needed to sustain these activities and products is mainly covered by fossil sources.

> We need to rethink the energy and performance features of societal stocks. Intelligent and communicating self-sufficients have a crucial role in reshaping the current state.

As shown in the Figure 11 with the dashed line, only a small proportion of the activities are covered by sustainable energy. Of all of the commodities and materials exploited globally, only 9.1 %[6] returns to societal stock through reuse, repair, remanufacturing and recycling activities. In order to enable a transition from a linear economy to a sustainable economy there is a need to reshape the current linear model and its activities from a consuming to a regenerative one.

During the *loss-resistant loops* stage (Chapter 3.1), as suggested in our vision, energy efficiency in material circulations need to be enhanced significantly. In addition, there is a need to develop alternative solutions to generate sustainable energy while at the same time reducing energy use in energy-intensive areas. A first glimpse of solutions for this could be devices and components that generate their own energy and even more energy during their lifetime than is required for production and disassembly combined. We refer to these devices, units, components or functionalities as '*self-sufficients*'. There are already great examples of self-sufficients in societies that, for example, produce sustainable energy for society and operate on self-produced energy, such as windmills and solar panels. We refer to self-sufficients such as these, which are capable of producing larger amounts of energy, as '*macro self-sufficients*'. Another example of self-sufficients are things like the glass surfaces of buildings that generate energy for micro-grids that power, for example, the building's air conditioning. Self-sufficients like glass surfaces can produce sustainable energy in smaller and limited amounts, and we refer to them as '*micro self-sufficients*'. The examples discussed in this section demonstrate the possibilities that regenerative design offers.

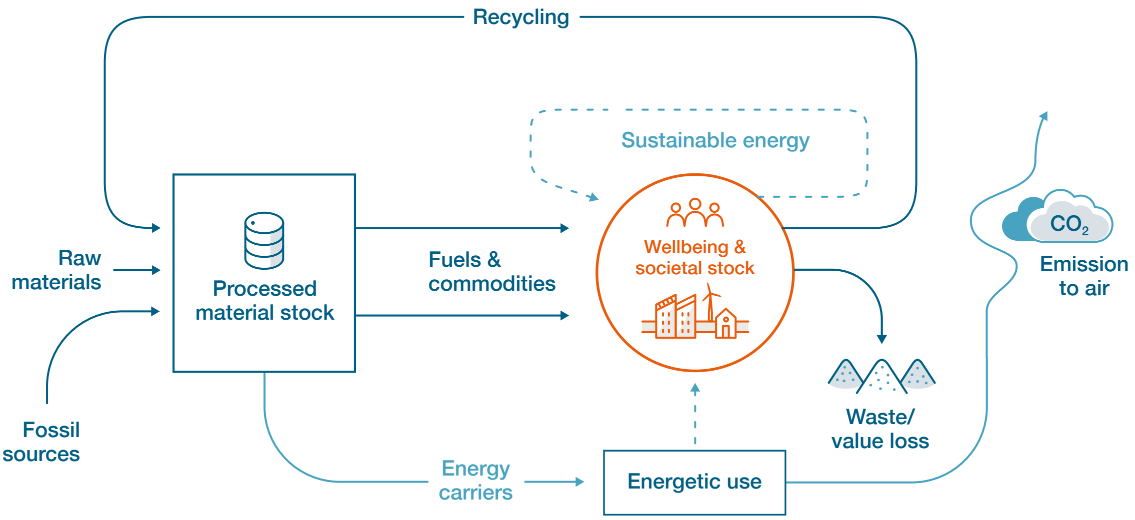


Figure 13. Present energy circulation in a linear economy.

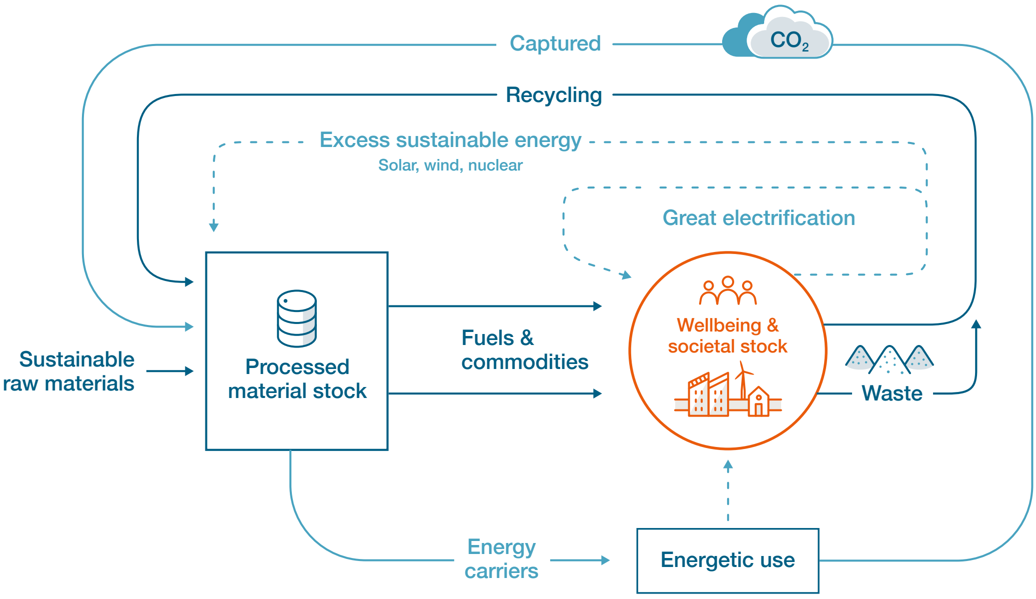


Figure 14. Future energy and material circulation in a sustainable economy.

The idea of regenerative design is to move from away from devices and materials that only consume energy towards devices and materials that generate sufficient energy to meet their own needs while also providing excess energy to the societal stocks where they are located. There is a great need to utilise sustainable energy from resources that aren't yet being exploited, like built infrastructure. However, it must be noted that regenerative design is not a foregone conclusion of a sustainable solution and should not be taken for granted. Regeneration is a sustainable option when it is calculated from the impact perspective of the whole entity that is under consideration. There are limitless opportunities in terms of how regenerative design could be implemented. For instance, a wider range of the different structures of the societal stock could be designed to harness energy whenever it is beneficial and creates value.

Figure 14 shows the circulation of materials and energy in the future sustainable economy, where materials are sourced via upcycling and energy is produced sustainably. In this new model, societal stocks will be responsible for self-producing the energy that is required for the maintenance of the existing infrastructure. Great electrification in this process will enhance the operations more efficiently based on electricity. In addition, in future societal stocks will produce sustainable excess energy to cover the energy demand that is required for the excessive share of the operations, like recycling processes and carbon capture and utilisation, thus ensuring the use of resources from sustainable sources of CO_2 and other upcycled materials without emissions.

Macro self-sufficients like wind and solar-power devices are in a defining position in the energy transition. It is evident that micro self-sufficients like energy-generating glass surfaces of buildings are not capable of producing enough energy to cover the sustainable energy demand. However, the amount of energy produced by them can play a vital role in making local infrastructures self-sufficient and thus less dependent on outside energy input. Together, applied successfully, these two types of self-sufficients will speed up the energy transition.

5

CONCLUSIONS AND SUGGESTED ACTIONS ON HOW TO REACH A SUSTAINABLE FUTURE

THIS WORK wishes to attest that although global resource sufficiency and sustainability challenges are immense, they are beatable. We need to be open-minded enough to accept that increasing resource insufficiency will inevitably lead to a situation where we must be dauntless in pursuing radically ambitious technological, business and societal innovations to enable recovery and a return to resource sufficiency. Mere recycling of materials, however efficient, as well as carbon-neutral energy solutions, will not save us from making resource insufficiency and climate change worse. Starting to beat the challenges necessitates pragmatic 'first things first' solutions:

- investing in resource and energy-efficient processes
- prioritising energy saving in the most energy-intensive production and manufacturing processes
- keeping critical non-renewables in circulation
- developing feasible carbon capture and storage solutions

It is nevertheless clear that radical 'propeller-head' inventions and innovations in the form of technologies and operational models in societies and business life, as well as among individuals, will change the direction of the progress we are being confined to follow. Some glimpses of these innovations have been presented in this paper. Servitisation concepts need a nudge towards materials. Efficient material flow management and intelligent materials would be a significant factor in terms of intensifying resource efficiency, material circulation and material performance. At the same time, development in energy and other production should result in process and business concepts that enable emissionless production by capturing off-gases for use as raw materials.

The rewards of success belong to those who have the courage to quickly make the first radical moves. This requires broad-minded collaboration, new networks and new ways of thinking. We need flag-bearers and forerunners in disruptive technology development and application, and we should support industrial sectors to connect with each other and jump out of the 'linear inertia' towards circular activity and further – beyond the obvious!

WE SUGGEST YOU to take a glance at the roadmaps and scenarios written by experts of VTT on the future food economy (Food 4.0[20]), future renewable materials (Cellulose goes digital[25]), digitalisation of bioeconomy (Bittejä ja Biomassaa[28], in collaboration with the Institute of Natural Resouces, only in Finnish), low carbon bioeconomy[29] (Growth by integrating bioeconomy and low carbon economy ref) and synthetic biology[21] in which many of the themes discussed in this paper are contemplated more deeply and from different angles.

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APPENDIX: FLOW OF THE ROADMAP WORK

We started the roadmap work during spring 2017 as part of the VTT strategy process. We soon realised that the framework of the roadmap must be sufficiency of resources and envisaged three development paths concentrating on seeking solutions for material and resource sufficiency for future economies. To establish a solid base for the work, we acquainted ourselves thoroughly with international and national strategies, action plans, articles and reports on the circular economy, platform economy, digital economy and energy disruption, present and future regulatory framework in Finland and within the EU, and trends and drivers pushing the change out of the present economy.

The roadmap work was carried out in collaboration with VTT experts and experts outside VTT. In the first workshop, the trends and drivers triggering development and change were identified under the topics of mindset, technologies and production, as well as key competence areas contributing to the change. In the second workshop, three tentative visions perceived were acid-tested with VTT researchers from various fields of expertise and development steps were created. During this work, experts outside VTT were interviewed about how the circular economy appears from their field of expertise and about the expectations for future development. Also several VTT experts were challenged in one-to-one brainstorm sessions to assess the tentative visions and polish them further.

We, the working group, reviewed and processed the materials created in workshops, discussions and interviews and together with the reference literature compiled the roadmap as it is now, containing suggested visions for the future and development paths within the visions.

The following experts have participated in workshops, brainstorming discussions and interviews.

Interviewees:
Nina Elomaa, Fazer Ltd.
Tarja Haaranen, Ministry of the Environment (YM)
Anu Kaukovirta-Norja, Valio Ltd.
Matti Rantaniemi, Martela PLC
Maija Heikkinen, Finnish Forest Industries
Tuula Savola, Business Finland
Irina Simola, Finnish Food Industries' Federation (ETL)
Marja-Liisa Tapio-Biström, Ministry of Agriculture and Forestry (MMM)
Sari Tasa, Ministry of Economic Affairs and Employment (TEM)
Niklas von Weymarn, Metsä Fibre Ltd.

VTT's brainstorm troopers:
Workshop, 15 May 2017, "Building VTTs visions for a circular economy":
Maria Antikainen, Mona Arnold, Maija Federley, Ali Harlin, Juha Honkatukia, Anna-Stiina Jääskeläinen, Johanna Kohl, Pertti Koukkari, Jutta Laine-Ylijoki, Raija Lantto, Juha Lehtonen, Tiina Nakari-Setälä, Tiina Pajula, Merja Penttilä, Lauri Reuter, Anu Seisto, Nesli Sözer, Henna Sundqvist-Andberg, Katariina Torvinen, Matti Tähtinen and Maria Åkerman

Workshop, 16 January 2018, "Concretising development paths within the visions":
Maria Antikainen, Maija Federley, Katja Henttonen, Vafa Järnefelt, Anna-Stiina Jääskeläinen, Tiina Koljonen, Jutta Laine-Ylijoki, Raija Lantto, Anja Oasmaa, Tiina Pajula, Juha-Pekka Pitkänen, Anu Seisto, Nesli Sözer, Henna Sundqvist-Andberg and Matti Tähtinen

One-to-one discussions:
Maria Antikainen, Antti Arasto, Mona Arnold, Ali Harlin, Tiina Koljonen, Tiina Nakari-Setälä, Merja Penttilä, Juha-Pekka Pitkänen, Lauri Reuter, Anne Ritschkoff, Anu Seisto, Tuomo Tuikka and Riikka Virkkunen