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The Circular Economy and Digitalisation: Strategies for a digital-ecological industry transformation

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Executive Summary

A resource-efficient, circular economy will be needed before industrial climate neutrality and sustainability transformations can be achieved. It promises to decouple economic value creation from material resource consumption and promotes an absolute reduction in physical material flows as well as their associated environmental effects.

The circular economy, in turn, will need digitalisation and data availability to be successful. Digital technologies and applications make it possible to improve current procedures, processes and structures **(Improve)** and take the first steps towards new business models and behaviours **(Convert)**. Despite this, digitalisation itself must be effective enough to facilitate a more far-reaching economic transformation and value creation and a complete ecological restructuring of society and lifestyles **(Transform)**. These three levels of impact are interlinked. The influence they have over each other means they must be addressed with a holistic approach.

Improve – Optimize processes and logistics in circular economy

The number of new digital solutions that will become available for optimizing industrial production processes at all stages of production are expected to improve energy and resource efficiency by at least 20%. Digital tools will make component and product design more efficient, while computerized manufacturing processes (computerized numerical control, CNC) and innovative additive manufacturing processes such as 3D printing will make lightweight construction even more effective.

Smart waste management will also dramatically increase efficiency in the waste and recycling industry. Sensor technologies and digital solutions will be able to enable real-time, demand-based route planning and waste collection. Digitally marked materials and packaging will be used to identify and track goods throughout the recycling process (tracking and tracing). Machine-readable codes on plastic packaging and sorting technologies, combined with artificial intelligence (AI), will improve the quality of recycling and digital trading platforms will offer new channels for marketing quality-tested and certified secondary materials (recyclates).

Convert - Restructure business models and user behaviour

Digitalisation will enable new circular business models to meet customer demand for lower resource utilization and resource conservation services. In new usage-based business models (pay per use), products will remain the property of the manufacturer, allowing them to be used multiple times. This incentivizes the creation of more robust and durable product offerings. The same concept applies to the sharing economy and the second-hand market, where devices, tools, and vehicles are shared by a large group of customers and thus used more intensively or for longer periods of time. With the support of digital platforms and smartphone apps, digitalisation will not only reduce transaction costs, it will also scale up and optimize industrial business models.

Increasing the visibility of product information, for example in the form of a digital product passport (DPP) combined with corresponding assistance tools on smartphones, will make it easier for consumers to arrive at more informed decisions regarding their ecological and resource impact.

Transform - Create conditions for digital-ecological industrial transformation

A complete digital and ecological transformation of our economy will only be successful if it is guided by a common agenda. This agenda requires changes at all economic levels:

The role of data in the circular economy: The circular economy must be understood as a data economy. Data from multiple companies must be pooled together. Climate and resource protection must become an integral part of digital management systems through sustainability-oriented accounting.

Systemic transformation for transparency: A successful circular economy requires a shift towards a culture of proactive data sharing. Meaningful data sharing, on the other hand, can only build on common data models and reference architectures to be effective. The transparency that results from such changes will enable individual solutions like DPPs.

Infrastructures and data spaces for the digital circular economy: Reliable and secure infrastructures for data storage and processing (e.g., like those built within the framework of GAIA-X), will require guidelines, fair rules, and trustworthy data governance, as well as standards and interfaces that enable efficient and flexible scaling of use cases to expand the scope of use through interoperability with other systems.

Being digital and circular means being systematic: A successful transition requests a new mind-set for future viability and a conscious self-understanding of one's role in the system transformation. That is to say, it will require a "process within the process" perspective combined with a culture of data sharing and collaboration.

A strategy to act as the guardrail for transformation: A national strategy for the digital circular economy is long overdue. What is needed is an integrated approach that creates an overarching framework for a digital-ecological economic policy across all ministries and provides all actors in the circular economy with a reliable orientation for their own actions.

We are at the beginning of a historically decisive decade in which the plan for securing the world's natural resources must be set together with the international community. The development of a climate-neutral and resource-efficient circular economy will be a key part of this plan. The digital transformations we are seeing in all areas of life and the economy will continue to open up new options for action and thus continuously expand the range for solutions. We must seize these opportunities to harness the transformative power of digitalisation to revolutionize our economies and the way we live.

It therefore falls upon the political community, and in particular the new German federal government, to spend the next few years developing a coherent system of goals and incentives for the digital and ecological transformation of our economy. They must create a reliable and stimulating regulative framework for private and corporate action. This will allow all actors and stakeholders to reach a common and comprehensive understanding of Germany's transformation path towards a sustainable economic and social transformation as an industrialized nation.

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1 Introduction

Climate protection will be one of the most important challenges that German industry will have to tackle in the coming years. The establishment of the new German government's Ministry for Economic Affairs and Climate Action underscored this priority. Germany's 2045 greenhouse gas neutrality goal puts pressure on industrial sectors to update their production processes in order to drastically reduce their emissions in the short term and completely eliminate them in the long term.

And so, a growing number of companies from among the German “Mittelstand” as well as global corporations” have set their own climate neutrality goals and strategies and are calling for ambitious climate policy to support their initiatives. One example of these efforts is the implementation appeal of the 2° Foundation (Stiftung 2°, 2021).

Meanwhile, both the EU Commission's Green Deal with the Circular Economy Action Plan (European Commission, 2020a) and the German resource efficiency program *ProgRess III* (BMU, 2020a) have put resource conservation and the circular economy on their agenda. The broader business community's exploration of the circular economy's economic potential has also continued to accelerate in light of the global supply chain disruptions and raw material shortages caused by the pandemic. Cities such as Munich and Kiel have both announced their intention to become Zero Waste Cities – a move that has been widely popular with their residents. The circular economy is also a priority for the coalition agreement and the new National Circular Economy Strategy is designed to bundle existing raw materials policy strategies.

Both fields of action - climate protection and resource conservation - are cornerstones of global sustainable development that require us to fundamentally change our current private and professional routines. A profound ecological system change will be needed in all "transformation arenas", or central areas of economic and social activities. Only then can the ambitious goals for climate, resource, and environmental protection can be achieved.

Digitalisation will be one of the prerequisites for this ecological change. Digital technologies and applications make it possible to either improve current procedures, processes and structures **(Improve)** or reorient existing business models or framework conditions **(Convert)** (Figure 1). At the same time, digitalisation must also effectively reorient society towards more ecologically-sustainable lifestyles and contribute to a more far-reaching transformation of the economy and value creation **(Transform)**. This last level of impact will be the decisive factor whether these efforts will be effective and must therefore be put into focus of future debate.

These three levels of impact are also interlinked and heavily influence each other, and so we must address them in a holistic manner. Quickly tapping into the potential short-term optimization efforts will be essential as we simultaneously begin to create the prerequisites for a more profound transformation of the structural and framework conditions in the economy and society.

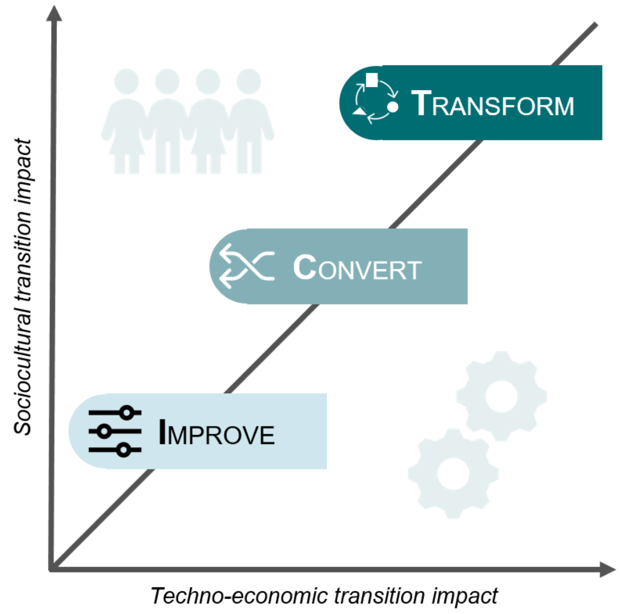

Figure 1:1 Impact levels of digitalisation for sustainability transformation (Source: Own illustration)

This is where Huawei Technologies Germany hopes the "Shaping Digitalisation: Enabling Transformation to Sustainability" project can help the most. Within this project, we aim to highlight and discuss the opportunities that digitalisation can bring to Germany. In particular, we are discussing three stand-out areas where action is most needed to achieve ecological transformation: mobility, the circular economy, and agriculture and food (Ramesohl et al., 2021).

This report addresses the second area in need of action.[1] Up until now, discussions on the circular economy have been limited to recycling and the re-use of materials. We must expand the scope of these discussions to include new, resource-efficient business models and the comprehensive transformation of value chains and industrial structures. Our analysis has found that digitalisation is indispensable for this transformation if used properly.

We hope this report will provide the impetus needed to kick-start a climate- and resource-friendly industrial transformation in Germany. Here, we have incorporated the findings of our interdisciplinary workshop on "Shaping the Digital-Ecological Industrial Transformation - Business Models and Political Framework Conditions for Climate and Resource Protection" that was attended by experts from international research institutes, civil organizations, public authorities, and private companies (for a full list of participants, please see the acknowledgements). The workshop will be hosted again in the future once new research on technological, economic, and political development prospects and the implementation conditions for a climate-friendly and resource-efficient circular economy is complete.

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1 In the following parts, we will use the comprehensive term "circular economy" to describe a systemic transformation across all phases of the value chain, including the use phase. This perspective is thus broader than the understanding of the Law on Closed Cycle Management and Waste (KrWG), which equates "circular economy with a functioning, effectively regulated waste and secondary raw materials management" (Müller et al., 2020).

2 Challenge: Combining the Agendas for Digitalisation and the Circular Economy

A resource-efficient circular economy is at the core of all strategies for industrial sustainability transformation and industrial climate neutrality. The goal of the circular economy is to decouple economic value creation from material resource consumption and to ultimately reduce physical material flows and their associated environmental impacts and greenhouse gas emissions. This will be one of Germany's central areas of action over the coming decades. Like the energy transition, the resource and the industrial transition are two of the most important transformation arenas for the pursuit of sustainable development of the global economy and society. The circular economy has recently received much attention and, together with climate protection and the preservation of biodiversity, must be placed at the heart of sustainability-oriented policies.

Climate protection is only viable with resource protection

Germany has already set a climate protection target to become greenhouse gas neutral by 2045. If they hope to achieve this goal policymakers will need the support of the private sector to transform the German economy over the next decade. It is becoming increasingly apparent that a resource-efficient circular economy will significantly assist in greenhouse gas reduction. Thus, it will support the journey towards industrial climate neutrality (Kadner et al., 2021; Sun et al., 2021). For example, the International Resource Panel estimates that each G7 country can reduce GHG emissions from buildings and vehicles by up to 40% by 2050 (Ekins & Hughes, 2017). Other studies see the potential for cutting up to 60% of GHG emissions from the four most CO2-intensive material streams in European industry (steel, plastics, aluminium, and cement) is possible by 2050 through resource efficiency and circular strategies (Material Economics, 2018). Despite this, the effect resource-saving can have on emissions reduction has still not been sufficiently discussed.[2]

The potential is enormous, and still untapped

There are a wide variety of places where we can reduce primary raw material use in our production processes and value chains by instead replacing them with reused materials (secondary raw materials) or by increasing efficiency. The Circular Economy Initiative Germany estimates that, when compared to the business-as-usual path, dedicated Circular Economy strategies can reduce resource consumption in Germany by around two-thirds by 2050 (cf. Figure 2, Kadner et al., 2021).Figure 2:2

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[2] The study by the Federation of German Industries (BDI) "Climate Paths 2.0", for example, focuses on supplying industry with renewable energies and expanding a hydrogen system. The analysis only deals excursively with individual recycling options such as feedstock recycling of plastics, while further-reaching resource efficiency potentials and corresponding structural change effects in the basic materials industry are not taken into account (Burchardt et al., 2021).

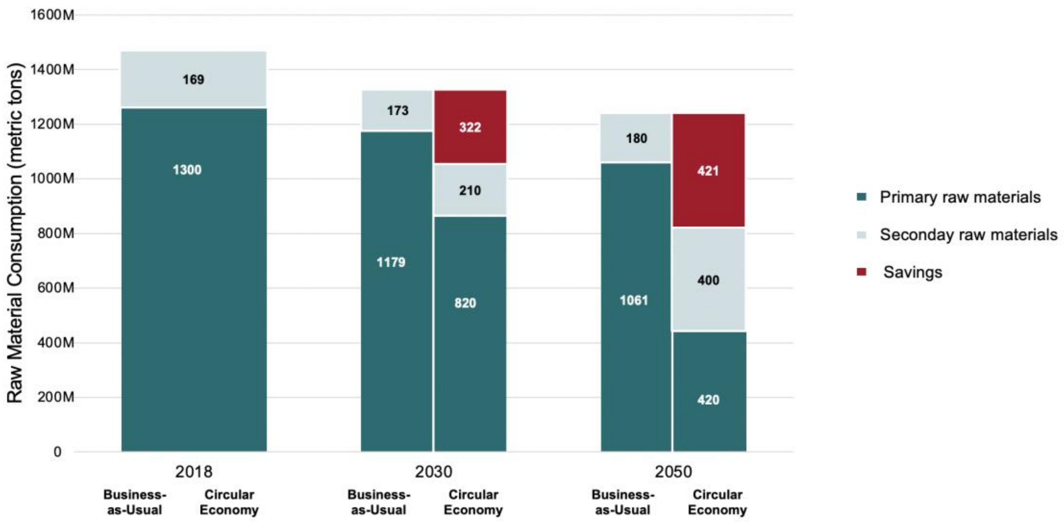

Figure 2:2 *Comparison of the circular economy case with the business-as-usual case for resource consumption (RMC) in Germany (Source: Own illustration according to (Kadner et al., 2021))*

However, we are still quite far from reaching that stage. Compared to other countries, Germany does have a very comprehensive, albeit cost-intensive, system for waste disposal and recycling. It has also traditionally had a very strong environmental technology sector. However, when it comes to the actual circular economy performance indicators, Germany lags behind many other countries. In Germany, secondary raw material use currently only replaces around 13% of resource consumption. Even when taking global upstream savings into account, this figure barely reaches 18% (Steger et al., 2019).

When compared with other European nations, Germany is in the middle of the pack when it comes to the use of secondary materials, while other countries such as the Netherlands or Belgium already show significantly higher rates of recovered raw material use, replacing almost 30% and 25% of resource consumption, respectively (Bahn-Walkowiak et al., 2021). The same trends apply to resource productivity, for example the added value per consumed material, where Germany's performance hovers around the European average (EEA, 2020).

Recycling is important, but it isn't enough on its own

A circular economy is predicated on the idea of circularity and reuse of resources through recycling. There is still great untapped potential in this area. Currently, only about 40% of plastic waste from private households is recycled (Lindner et al., 2020). And yet there are clear limits to recycling: 100% collection and reuse of all raw materials is not achievable. It’s neither ecologically effective nor economically viable. There will always be some loss of material in the conversion process and, depending on the composition of the material, degradation cannot be avoided during recycling. When the structure of a material changes, its performance invariably deteriorates to some degree. In addition, recycling processes themselves consume energy, cause emissions, and pollute the environment. Sometimes, the ecological expenses of recycling simply outweigh the benefits.

Therefore, preventing resource consumption in the first place when providing goods, services, and infrastructure is more critical that increasing recycling. This is particularly true in areas where new production demand is significantly higher than the generation of waste and residual materials.[3]

Industry transformation through resource-efficient value creation

The challenges that must be overcome to realize a circular economy are urgent and enormous. An important first step that we must take is the continuous improvement of industrial production processes and the optimization of individual technologies. This step alone however will not be enough to enable globally sustainable development. We must rethink the structure and logic of our industrial value chains and move way from energy- and raw-material-based models to better align with climate protection and resource conservation targets. We must reduce resource consumption starting from the ground up and make sure the resources we do use retain their value for as long as possible. This allows them to generate as much added value as possible through new business models with as few physical products as possible. A circular economy thus also requires a change in demand and an increase in more sustainable lifestyles that replace energy- and material-intensive products and services with the satisfaction of non-material needs. The extent to which the virtualisation of our everyday lives and consumption will contribute to this is still unclear. Concepts such as the metaverse, which is intended to be a digital parallel world, are still in their infancy, and so their attractiveness and influence over society and our environment cannot yet be assessed.

A joint agenda on digitalisation and the circular economy

The central challenge facing the circular economy is figuring out how to manage material flows and resource use across all industry, i.e. within the individual links of a value chain as well as between different industries and sectors. In a circular economy, a value chain becomes a value network in which decisions at each process stage affect the options for action of the other players. The materials and design of components chosen by one link determine the durability and reparability of the final products. The type and quality of recycling processes determine the usability of secondary materials in new manufacturing processes and in product design.

The circular economy therefore requires a systematic approach that goes beyond the actions of individual companies. A necessary, but not sufficient on its own, prerequisite for action in the circular economy is therefore access to information on upstream steps and a mutual understanding of the impact of one's entrepreneurial actions on the downstream stages of the value chain. This information, combined with individual entrepreneurial drives, social motivation, and political incentives, can promote a willingness and ability to act.

Thus, linking physical material flows with digital data flows is a key part of many measures and strategies used to pursue a circular economy. This linking requires resources and the products created from them to be labelled. Information on their quantity, location, and condition at the various points in the system *(tracking)* must be recorded so that their life cycle and material flows can be traced throughout the value creation chain *(tracing)*. Only with this data is it possible to analyse and ultimately optimize material flows.

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[3] In 2019, around 5 million metric tons of post-consumer plastic waste was generated in Germany, of which around 1 million metric ton could be reused as recyclate. In addition, there was industrial production waste of the same magnitude. However, plastics processing in the same year was a good 14 million tons, and so recyclates thus covered only one seventh of the raw materials required, and over 12 million tons of virgin, petroleum-based materials were consumed (Lindner et al., 2020).

Therefore, there is no circular economy without data. Only digitalisation can lay the foundations for a comprehensive ecological transformation of our economy. Luckily, a window of opportunity has opened up here in recent years. With the help of Industry 4.0 and the Internet of Things *(IoT)*, the digital transformation of the economy has already begun accelerating and offers multiple starting points for an ecological transformation. The foundation is provided by the interplay of digital solutions in four central functional areas:

- Data collection and connection
- Data merging and sharing
- Data authentication and security
- Data analysis

Digital solutions combine a wide variety of key digital technologies such as connected sensors, IoT, and edge and cloud computing, as well as digital platforms, distributed ledger technologies (DLT) such as blockchain, and analytical methods such as big data and artificial intelligence (AI).

In addition, digitalisation is increasingly changing production processes, value chains, competitive positions as well as relationships with customers and partners. Companies are building data ecosystems, and industrial competitiveness and technology leadership are increasingly defined by the ability to coordinate and shape data relationships. This is where strategies for the development of the circular economy can and must start. Digitalisation and sustainability must be thought of and acted on together as part of the "Twin Transition".

The next chapters will go into these aspects in greater depth:

Chapter 3 (Improve) will outline the broad spectrum of options for optimizing the existing economy. The digital solutions required for this are already available and being used, and must therefore be systematically developed further and used more intensively.

Chapter 4 (Convert) will go one step further and examine how digital solutions can help realign value creation, business models, and our usage behaviour. This will be indispensable for achieving the objectives of a circular economy. There is a need for action here, and these approaches must be quickly scaled up and out.

Chapter 5 (Transform) will identify five key starting points to create the conditions for this scaling-up and the profound digital-ecological transformation the economy must undergo to achieve a circular economy.

Chapter 6 (Prerequisites) will highlight the environmental impact of digital end-devices and hardware components, and why the circular economy must also apply to digitalisation.

3 Improve: Optimize the Processes and Logistics of the Circular Economy

The broad portfolio of digital solutions available today creates new opportunities to optimize industrial processes at all production stages, waste management and collection logistics, as well as sorting and recycling facilities (H. Berg et al., 2021). All actors along the entire value chain can contribute to resource efficiency by improving individual processing steps and material flows. This chapter outlines several starting points from which digitalisation can make a real difference for sustainability.

Making products more resource-efficient with circularity by design

Digital solutions can already help minimize the use of resources in the product design process. The digital tools and processes used to design components and products can make them more lightweight and optimize their material use before production even begins. By assessing the actual quality of material flows, usage patterns and recycling processes, we can gather important information that can be used to help prioritize resource conservation during product design (Circularity by Design, also cf. (EEA, 2017)). For example, the recycling business models we describe in chapter 4, as well as future reparability and even disassembly are already considered during design and can be simulated using digital twins. Two aspects of product design should be highlighted here:**Fehler! Verweisquelle konnte nicht gefunden werden.**

First, digital processes such as computer-aided design (CAD), which enable digital design and 3D modelling of components and products, are the basis for established computer-aided (CNC) manufacturing processes as well as for newer additive manufacturing (ADM) approaches, such as 3D printing or laser melting. They are characterized by a high degree of flexibility, allowing for even super small production runs with batch sizes of N=1. This makes efficient design and small-batch material production possible. Building Information Modelling (BIM), which creates a digital image of buildings, is also increasingly being used in construction, reducing energy and resource use throughout the building's life cycle, from construction and use to subsequent deconstruction.[4]

Second, material choice is also a key factor in product design. In many areas such as packaging, it is important to further exploit the possibilities of recycling-friendly design, for example, by abandoning composite materials and developing equivalent solutions based on homogeneous monomeric materials that can be better recycled. Material flow data from entire process chains can be used to model and balance recyclable alternatives, ultimately increasing the use of recycled secondary materials. Examples of completely 100% recycled materials can already be found on our supermarket shelves in the packaging of cleaning agents and detergents, while the first 100% recycled sports shoes illustrate opportunities to the sports and fashion industries.

Improving production to increase efficiency and reduce environmental impact

Digital technologies are increasingly being used to control and optimize manufacturing methods and production processes. Within the Industry 4.0 framework, a toolbox of digital solutions that can make new contributions to energy and resource efficiency is emerging. Machines and systems are increasingly controlled with greater precision and operated with more flexibly

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[4] In some cases, BIM is also defined as Building Information Management.

(Plattform Industrie 4.0, 2020), and depending on the application, an efficiency potential of 20% or more can be achieved (Schebek et al., n.d). Digitalisation not only reduces energy and material use and the associated CO2 emissions, but also reduces the consumption of auxiliary and operating materials while guaranteeing quality, thus reducing incorrect production and scrap. Ultimately, this also reduces production costs and strengthens competitiveness.

Planning ahead to optimize sales and logistics and avoid returns

Data analytics can be used to better plan and forecast material requirements, production volumes, and shipping capacity. AI-based processes improve demand forecasting and facilitate demand-driven, just-in-time deliveries to retailers and consumers to reduce stockpiling. By better matching the actual supply of goods to actual customer demand, these tools can also help to avoid or reduce return shipments. Particularly in online retail, digital tools such as recommender systems or "virtual try-ons" that use VR/AR technologies can help customers to make better choices on their first try, particularly with textile products.

Machine-readable codes for products also help to further automate tracking and monitoring goods flows across all stages of retailing and distribution. New solutions are continuing to emerge to track the use and whereabouts of goods, thus limiting the - sometimes illegal - destruction of still-usable goods.

Optimizing waste management and recycling to keep raw materials in the system

The insights provided by data analyses are crucial for effective and sustainable waste management. At the end of a product's use phase, all waste should be collected and sent for recycling. Digitalisation solutions, and in particular the extensive IoT solutions designed for so-called smart waste management, offer many optimization opportunities for waste and recycling management (Piel et al., 2018). Existing use cases include digital applications for optimizing waste collection logistics through daily or real-time data-based route planning, and the use of smart (i.e. sensor-equipped) waste and collection containers, which detect when they need to be emptied.[5]

Overall, these telematics and logistics solutions can reduce the number of collection vehicles needed by an estimated 5-10% and the number of collection vehicles by 25% (H. Berg et al., 2020). Other examples include autonomous street sweepers or (partially) autonomous collection vehicles, which can be used in increasingly dense street spaces. Robotics solutions improve vehicle and treatment plant operations, which will in turn help cope with the increasing pressure caused by demographic changes and predicted worker shortages in the waste management industry.

The above-mentioned digital information on materials and packaging facilitates the tracking and tracing of material flows in the recycling industry. For example, machine-readable codes on plastic packaging make it possible to recognize different types of packaging in mixed waste streams so that they can be sorted out selectively. This will increase the yield and quality of the material recovery at recycling and reclamation centres.

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5 A challenge here is how to use personal waste management data in accordance with the privacy requirements of the GDPR. Data anonymization enables data owners (e.g. waste management companies) and (external) data consumers (e.g. statistical offices, cities and municipalities) to ensure data protection while guaranteeing an appropriate level of residual data utility and insight. Various approaches to data anonymization are available, such as k-anonymity and Differential Privacy (Dwork, 2006; Sweeney, 2002).

AI-based sorting technologies have also improved the quality of recycling and work conditions. Image recognition technologies can be used to automatically detect certain packages or products after they are scanned, and advanced plant controls and robotics can improve the performance and accuracy of sorting plants (EU Recycling, 2021; Flemming & Balthasar, n. d.; Hayes, 2021; RECYCLING Magazine, 2019).

When it comes to preparing and further treating recycled materials, digital control and optimization of process technologies are also opening up new opportunities for transparent and reliable documentation of process parameters such as residence time, temperature, and pressure. Proof of these process parameters is necessary for many functions, including the certification of certain recycled materials. This information about the upstream recycling process makes marketing recovered material easier, as they can be advertised as quality-checked recyclables.

Finally, functional and scalable markets for marketing quality-tested and certified secondary materials (recyclates) must be established to replace the highest possible share of the natural resources used with recycled secondary materials. Quality secondary materials must be available in sufficient quantity and appropriately distributed to meet demand. Digital trading platforms offer new channels for these materials which are, in turn, gaining in importance and helping to overcome previous barriers. They bundle what is still often highly fragmented and regional supplies, thus enabling the recycling industry to network with producers and scale up. However, new quality standards, such as DIN SPEC 91446 which classifies plastic recyclables through data quality levels for use and (internet-based) trade, still need to be developed for these digital markets to reach their full potential. To this end, policymakers can make important contributions to the development of these markets and close-loop material cycles by setting product-specific minimum quotas for the use of recyclates and secondary raw materials - as envisaged in the coalition agreement.

4 Convert: Realign business models and usage behaviour

Digital technologies can help improve resource efficiency throughout many aspects of the circular economy. However, such improvements alone will not be enough to alleviate the negative environmental impact of our raw material consumption or realise ambitious climate protection goals. Both the ways in which industries use resources to create economic value and the ways consumers use products to satisfy their needs must change. This is where measures derived from the Convert-Strategy come into play. These measures focus on starting points from which business models can be realigned and from which users, and their behaviour, can be more heavily involved in the circular economy.

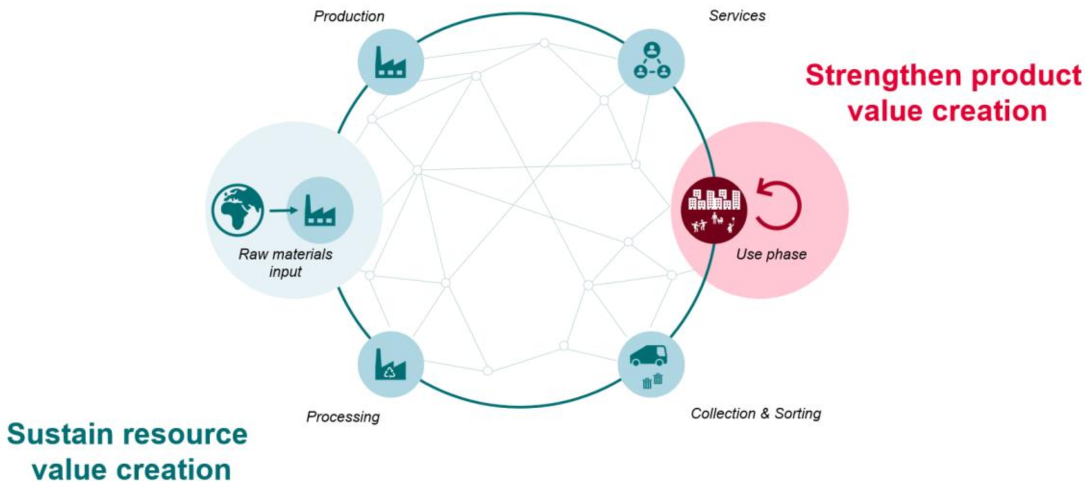

Figure 3:3 Strategies to increase value creation (Source: Own illustration)

Rethinking value creation

Digitalisation opens new opportunities to circular business models that focus on serving customer requirements with minimal resource use, utilise products designed for durability, and have strong links to product-service systems (Engels et al., 2021). Currently, companies that are committed to resource efficiency still focus on measures that can optimise the production processes or energy savings addressed in the previous chapter (Figure 4, cf. also (BCG & WBCSD, 2018)). This leaves a huge need for development, as less than half of these measures relate to product design, and very few companies are working on product-service systems.

Figure 4:4 Expected increases in company resource efficiency, according to different measures (Source: Own illustration according to (Engels et al., 2021))

Circular business models are those that can translate the so-called "inner R-Strategies", such as Re-Think, Re-Use, Repair, or Re-Manufacturing, into entrepreneurial action and business opportunities (cf. Figure 5). The basic idea behind such models is simple: Decouple value creation and the satisfaction of customer needs from the possession and consumption of raw materials. Therefore, climate and resource protection can be seen as a catalyst for a paradigm shift in value creation and industrial production logic (Plattform Industrie 4.0, 2021).

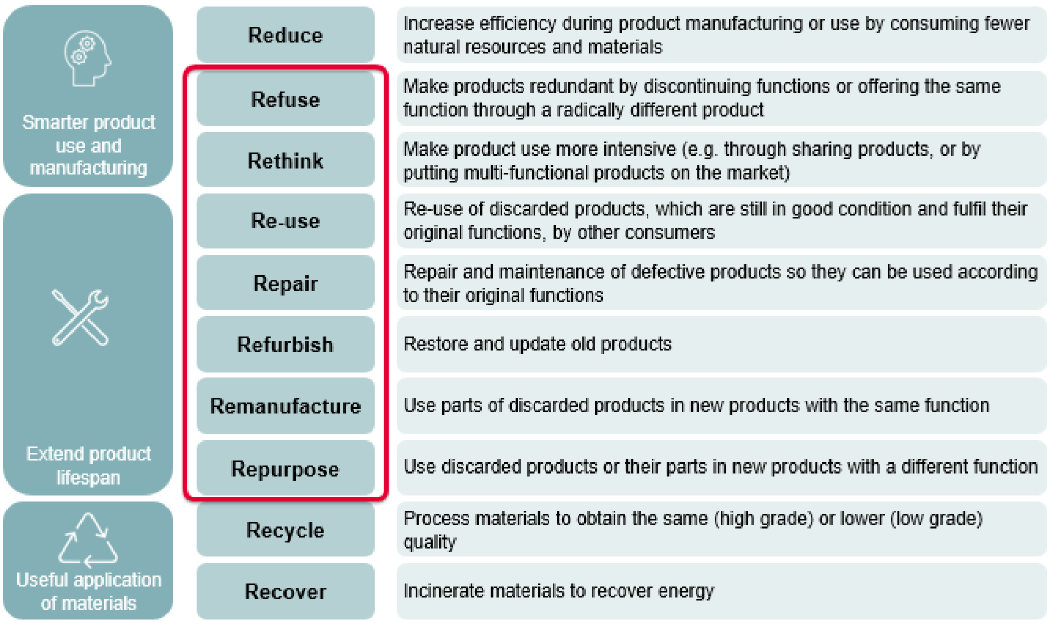

Figure 5:5 10R strategy elements of the circular economy (Source: Own illustration according to European Environment Agency et al., 2020)

A number of different approaches exists for circular and resource-efficient business models:

With the **usage-based business model**, providers charge only for the actual use of their products[6]. The product remains in the possession of the manufacturer and can be made available to customers for use when needed. This model gives manufacturers an incentive to provide the most robust and durable products possible, in order to maximise revenue during the lifespan of their products. It is vital to constantly receive information during product use, especially when dealing with high-value products or cost-intensive capital goods. Therefore, machines can be networked together through the application of sensors to assess the condition of any product at any time, quickly detect potential faults or malfunctions, always guarantee operational capability, and minimise follow-up costs through predictive maintenance. These strategies offer the German mechanical engineering industry the opportunity to expand its value creation via operator models, and strengthen its customer relationships.

The sharing economy follows the same approach. Equipment, tools, and vehicles are shared by customers and thus used more intensively. This makes it possible for the same amount of resources to create more value and satisfy needs to a higher degree. Digitalisation lowers transaction costs and enables organisations to scale new approaches through platforms and smartphone apps, both as private initiatives and commercial business models. However, the sharing economy is not limited to everyday life, and can also be applied to manufacturing plants in the sense of *Shared Production* or *Production-as-a-Service*. Within industry, especially in SMEs, machines often stand idle for considerable periods, when they could instead be used by other companies. Digitalisation makes it possible to define machine modules with specific functions (such as drilling, milling, or cutting), and then offer and deploy them in networked systems (SmartFactoryKL, 2021). Another example, with over 60-years of history, are "Maschinenringe" associations in agriculture. In such associations, farms join together to share expensive agricultural machinery for short-term operations. A comprehensive digital ecosystem of services has developed alongside these associations, facilitating digital document management, forecasting with agricultural weather data, and much more.

New potential for value creation is also arising from the **extension of the useful life of products** during and after the initial use phase. Through careful repair and maintenance, users can continue using their products and goods for as long as possible. This is the starting point from which political action should be taken, such as obligating manufacturers to give users the right to repair, provide spare parts, and guarantee a minimum product life span (e.g. EU Eco-design Directive or the *Sustainable Products Initiative* (SIP) of the EU announced for 2022). The digital availability of repair information and instructions, alongside required software downloads, are other examples of possible key requirements. Access to digital design data, in combination with technologies such as 3D printing, offer new ways to supply spare parts and can contribute to the reparability, and thus longevity, of products. Digital-product information also supports the identification and proper handling of components and products during return and redevelopment.

Another ideal area for a circular economy is the **marketing of second-hand goods** by private individuals or commercial actors. Through re-use, products can be used for longer periods or even have new functions added. In the case of cars, this is an area with a long-standing tradition, and the same is true in industries where durable capital goods are reused for second-hand machinery and equipment. In addition, everyday objects in our homes offer huge potential in this regard. It is estimated that an average German household owns fully-functional but unused goods and objects worth almost 1,300 euros (Figure 6, (Schwilling et al., 2021)). This

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[6] Chemical leasing is a special field for the application of this model. Here, washing agents or solvents are used on a rental basis, then returned to the manufacturer and reprocessed to be used again (the German Environment Agency, 2021).

equates to a total value of over 50 billion euros in Germany alone. Therefore, it would be beneficial for these goods – which are also considered raw materials - to at least partially flow back into a circular economy through second-hand use. In support of this, digital platforms and smartphone apps can facilitate direct sales between private individuals and enable virtual flea markets or exchange platforms.

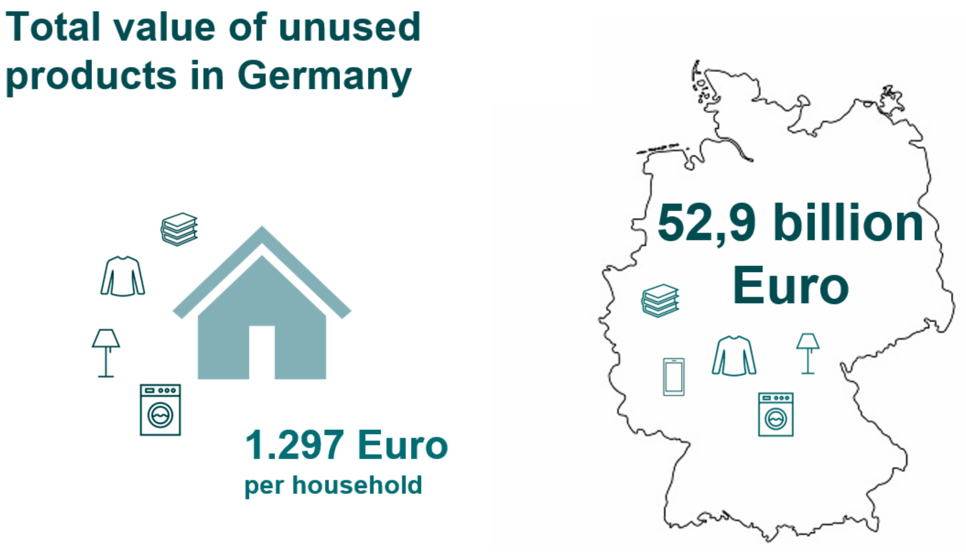

Figure 6:6 Estimated total value of unused products in Germany (Source: Own illustration according to (Schwilling et al., 2021))

Changing usage behaviour

The use phase is becoming increasingly essential to a circular economy. Consumers now influence the selection, use, and disposal of products, which is enhancing the influence of individual behaviour on resource consumption.

Accessible product information, such as that seen in the form of a digital product passport (DPP), makes it easier for consumers to make decisions related to climate and resource protection. This primarily affects the selection and evaluation of ecologically-advantageous alternatives during purchase decisions. Information from a DPP, in combination with assistance tools, gives consumers the opportunity to take many more ecological criteria into account, and weigh up all relevant interactions or conflicting goals according to their own individual preferences. Such information can also be used to verify the ecological footprint of a product, according to emissions incurred in the upstream chain or indicators of durability, reparability, and recyclability. Similarly, decisions made based on waste prevention can be facilitated. To maximize the impact of these elements, information on the correct operation, care, and repair of products can be easily provided or given as reminders through smartphone apps and networked with service providers in the vicinity. Therefore, complex information and contexts can be illustrated during and integrated into everyday life. Ultimately, this will empower consumers in their ability to make decisions and take action.

Digital technologies can also offer us guidance towards the end of a product's lifetime and support the correct collection and separation of waste. Sensors and image recognition technologies in bins, containers, and collection vehicles can provide data on waste composition and quantities, and thus also identify misdirected waste. Based on this, users can be offered new incentives for correct waste disposal, as well as new options for related feedback and learning, ultimately helping to avoid unnecessary waste through the application of approaches like nudging or gamification. Such behavioural strategies complement the solutions for the logistical and technical optimisation of waste collection and disposal outlined in the previous chapter.

However, it is not only private consumers who need to change their behaviour to achieve more sustainable consumption and lifestyles. With a total purchasing volume of 500 billion euros, public procurement in Germany is a key factor in demand and represents the largest customer group in many markets (Fischer & Küper, 2021). Therefore, this group has a huge responsibility due to its enormous impact on climate protection and the development of a circular economy. Digital solutions can support the implementation of sustainability-oriented procurement by public institutions (*Green Public Procurement*) in numerous ways. For example, through the creation of central user-friendly platforms that facilitate searches for legally-compliant, pre-qualified, and ecologically-oriented suppliers during procurement procedures.

The foundation is laid, scaling is needed

In recent years, more and more initiatives for circular, resource-efficient business models have emerged. However, these initiatives are always opposed by emerging trends, such as fast fashion. This trend has fuelled increasing clothing and resource consumption due to constantly changing fashion collections. Clothing production doubled from 2000 to 2014, to more than 100 billion garments, and annual production is expected to reach 200 billion by 2030. On average, German consumers buy 60 items of clothing per year - but wear them for only half as long as they did 15 years ago (Kopp et al., 2021).

This shows that the creation of a circular economy is by no means an organic process. The key to success lies in the large-scale expansion and dissemination of the business models and behavioural changes outlined in this chapter. This requires political action to define ambitious and binding targets, consistent incentive systems and regulatory frameworks to trigger and guide the transformation processes needed.

We must move beyond individual, fragmented approaches and trigger broad, self-reinforcing and dynamic scaling. At the same time, the many opportunities for optimising individual process and material flow management mentioned in the previous chapter must be constantly exploited and expanded through new and innovative technologies.

The self-reinforcing scaling and technology-enabled exploitation and expansion closely influence each other, and are key to a system change. Digitalisation can facilitate and drive this change if it is understood as an integral element of the ecological industrial transformation.

The next chapter will discuss the pillars and prerequisites for this transformation.

5 Transform: Create conditions for a digital-ecological industry

Digitalisation and sustainability have set the framework for the coming decade. They place similar demands on all involved entities: It is necessary to adapt to an increasingly networked world and to develop a systemic way of thinking and acting. We must be adaptable to a dynamic range of innovations, rapid changes in the environment, and major challenges. Possible solutions are also required. In both digitalisation and sustainability, life and actions are embedded in higher-level change processes and Change Management is set to become a permanent key task, while neither area has a fixed end point.

The digital and ecological transformation of our economy will only lead to success if it is understood as a joint task. The transformation requires change at a number of different levels: Companies must reposition themselves internally, develop further, and build new capabilities; relationships between companies within value chains or sectors are changing, and partnerships and cooperation are becoming increasingly important, meaning new structures must be created to support digital interactions and data flows between actors; and political framework conditions and incentive systems must adapt to new challenges and tasks.

The framework for a successful digital and ecological transformation can be established through the following five pillars and action fields. These must be at the very heart of the agenda over the coming years (Figure 7).

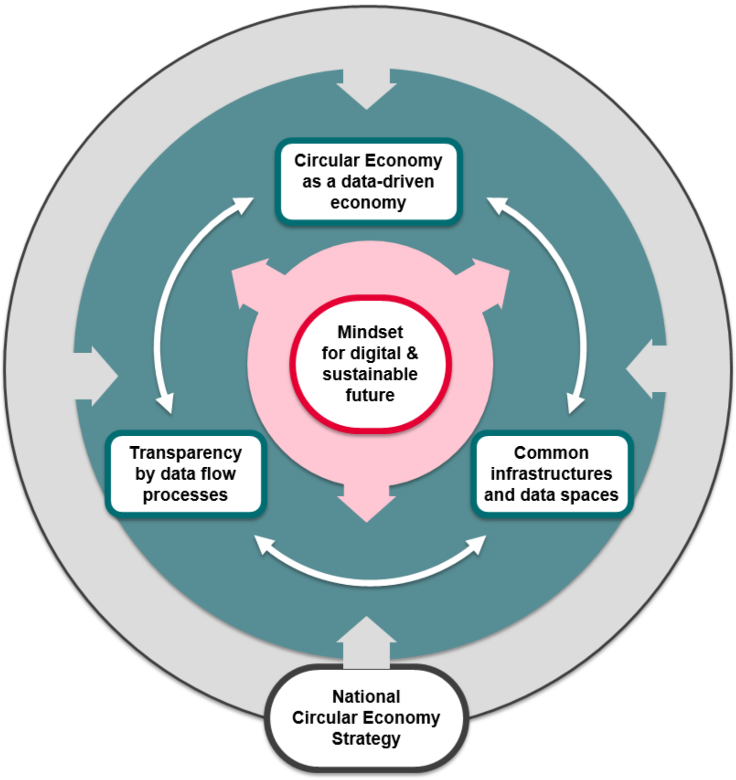

Figure 7:7 Prerequisites for the digital-ecological industrial transformation (Source: Own illustration)

5.1 The role of data in the circular economy

The ability of any company to optimise resource use is related to its degree of digitalisation, which, in the sense of a circular economy, is the ability to fully exploit the potential of data. Empirical studies give us a clear picture (Engels et al., 2021): The more digitalised a company is, the more successfully it can save materials (Figure 8).

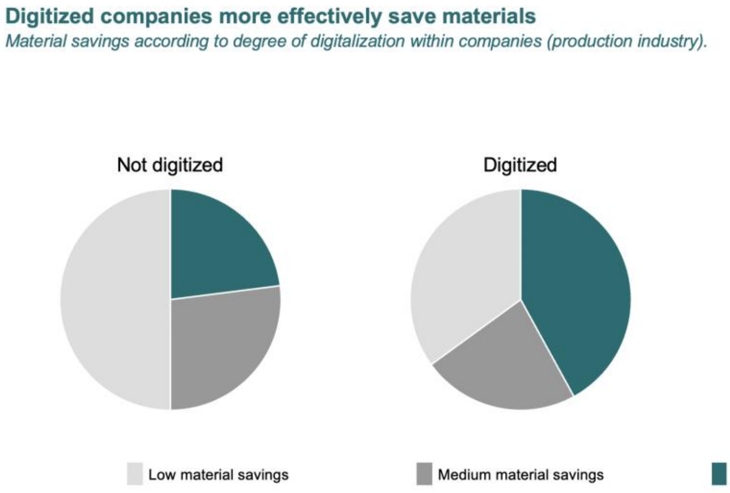

Figure 8:8 Material savings in German companies according to degree of digitalisation (Source: Own illustration according to (Engels et al., 2021))

The degree of digitalisation within companies must be continuously increased. Data and digital processes must be used more consistently during internal actions, decisions, and interactions with external parties. It is not enough to simply collect data. Data must also be merged and integrated for further analyses (Figure 9). Raw data and measured values originating from smart sensors or other data sources can be processed as knowledge and unlock new possibilities. The highest level of knowledge, so-called "digital wisdom", allows the understanding of the past to provide insights into the future.

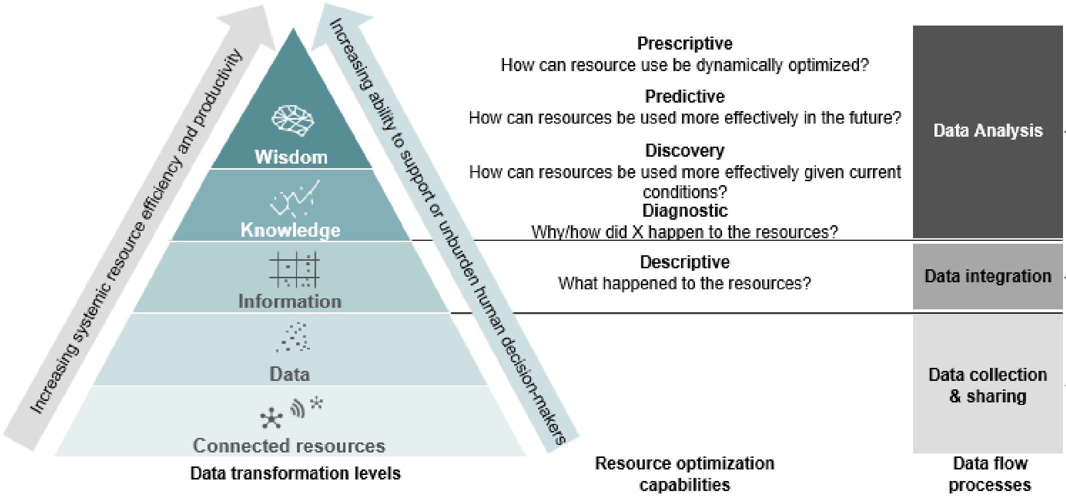

Figure 9:9 Smart circular economy framework (Source: Own illustration according to (Kristoffersen et al., 2020))

Within the context of digital wisdom, the sustainable use of resources within a company can be gradually increased. The first step in this process involves understanding and describing the current status and patterns of resources used in a company and its business areas. Based on this, companies can conduct diagnoses, obtain explanations, and discover optimisation potential. In addition, learning systems can be utilised to model future developments and derive predictions. These actions will strengthen a company's ability to act and react within complex, dynamic environments. Today, many companies still see themselves as latecomers in this area (A. Berg, 2021). Therefore, they must expand and strengthen their digital capabilities over the coming years.

New production processes, accelerated innovation and production cycles, more platform-based business relationships, and growing customer demands are all driving digitalisation and data orientation in businesses. However, companies cannot focus solely on these factors, as they must also assume more responsibility for greenhouse gas emissions and environmental protection. Therefore, data centricity, climate-protection requirements, and resource conservation must be thought of collectively from the very outset of a transformation to a circular economy, which must also be understood as a data strategy.

The different dimensions of data in a company must grow as one. Sustainability-related data and potential actions will then become an integral part of digital management systems in the sense of a "*Sustainability Ledger*", alongside classic methods for overseeing financial and production (Plattform Industrie 4.0, 2020). The demand for such sustainability-related information is currently on the rise. Therefore, over the coming years, the capital market and institutional investors are expected to increase pressure to be able to evaluate the sustainability impacts of companies in their portfolios, in order to reduce ecological risks.

5.2 Whole system transparency for transparency

A data-based circular economy requires data to be available throughout every step of the entire cycle. This means breaking down existing data silos, reducing boundaries between involved actors, and establishing a mutually-beneficial, data-sharing culture.

The concept of a DPP centres on tools effectively exchanging data within the circular economy. Information about a product and its environmental impact is made available across company boundaries throughout that product's entire life cycle. This serves as the prerequisite for a number of the strategies and measures discussed above. Following EU initiatives (European Commission, 2020a; Götz et al., 2021), numerous concepts, implementation modules, and pilot projects are being developed for various use cases. In support of this, it will be crucial to work with relevant stakeholders, such as industry stakeholders, to find a pragmatic and flexible approach that enables easy entry to this challenging process and applies learned experiences to achieve continuous improvement and development. Such an approach is already being piloted for ongoing activities under the EU Battery Regulation, related to a product passport for electric-vehicle batteries (Kadner et al., 2021).

Policymakers must define a framework that considers the goals of DPPs, supports the ecological effectiveness of a circular economy, and ensures companies' implementation efforts can be managed effectively. In this context, it is important that interfaces with existing or emerging information systems or databases[7] are defined and synergised, and free from redundancies or inconsistencies. We see this as a core element of resource and economic policy for the coming years. The new federal government must play a more proactive and formative role within these processes at the European level.

5.3 Infrastructures and data spaces for the digital circular economy

The fundamental idea of the digital circular economy is that companies and actors share and pool data, feed it into relevant tools, such as DPPs, and then develop circular business models based on the pooled data. To achieve this, the following goals must be realised:

- Reliable and secure infrastructure for data storage and processing that preserves the sovereignty of users
- Clear guidelines, fair rules, and trustworthy governance for differentiated data access and use according to the respective roles of stakeholders
- Standards and interfaces that enable efficient and flexible scaling in different use cases, as well as the expansion of the application field through interoperability with other systems

Achieving these goals will require diverse stakeholders to take coordinated, collective, and concentrated action in order to avoid a patchwork of individual and fragmented stand-alone solutions. Examples of such action can already be seen in the development of next-generation cloud infrastructures and services in Europe, within the Important Project of Common European Interest (IPCEI-CIS), and the ongoing international initiative GAIA-X and its application-specific project CATENA-X for the automotive industry[8].

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7 Examples at EU level are the SCIP database on critical substances (Substances of very high concern (SVHC) in products) of the European Chemicals Agency (ECHA), and the EU Product Registration database for Energy Labelling (EPREL), cf. (Götz et al., 2021; Sipka & Hedberg, 2021)

8 https://www.bmwi.de/Redaktion/DE/Artikel/Industrie/ipcei-cis.html,
https://www.gaia-x.eu/,
https://catena-x.net/de/

This concept has recently been gathering steam and a number of the most important prerequisites are being realised. We must now further develop these prerequisites into fully-fledged requirements, with consideration for the idea of a European data space for the circular economy. Over the next few years, horizontal structures will gradually become available and operable in vertical application fields. For example, the CATENA-X initiative targets companies in the automotive value chain and pursues a vision of creating the "most user-friendly environment for the establishment, operation, and collaborative use of end-to-end data chains along the entire automotive value chain". Such building blocks are essential to the circular economy, and material flow management and resource efficiency must therefore be carefully considered within the emerging data ecosystem. However, other application fields are still lacking when it comes to such concepts, structures, and initiatives. Therefore, a roadmap must be created to ensure their systematic development over the coming years.

Individual companies cannot develop the necessary horizontal structures and ecosystems as self-owned, separate solutions. Openness to technology, flexibility and individuality during application, widespread trust, and acceptance of governance and regulatory frameworks are all prerequisites for success. In addition, the dissemination of large-scale investment and high-quality technical know-how will be required to develop efficient solutions.

According to the principle of "industry-led, politically framed, pioneer-driven", we have achieved the broad and effective coordination of stakeholders from science, industry, and politics. The development of the reference architecture model of Industry 4.0 (RAMI 4.0, cf. (Arnold & Liebe, 2018)) and AUTOSAR (AUTomotive Open System ARchitecture) serves as a framework for software development in cars, and displays the true value of collaborative approaches. Through such approaches, substantial scale can be reached quickly, while parallel developments and repeated costs can be avoided.

Science and industry must take on the challenging task of designing viable and future-proof solutions. Meanwhile, politics is responsible for initiating processes, (co-)funding development and set-up costs, especially during initial phases, defining overarching social and political goals, and ensuring ecological quality standards are upheld.

5.4 Being digital and circular means being systematic

Digital transformation and the circular economy are reshaping the roles of companies and stakeholders. These actors are becoming more interconnected than ever before in regards to value creation, material flow, interactions, and data relationships. Data is gaining new value within the exchange of services and laying the foundation for data-driven business models, such as when machine or building data is analysed to provide better services, optimise operations, and increase user satisfaction.

Traditional boundaries between companies, and even within company divisions, are steadily dissolving, with company activities increasingly becoming part of larger, digitally-organised ecosystems. Such ecosystems may be based on partnerships and collaboration, or created through the strategic expansion of a company's business activities. We have observed that both companies and industries are placing greater strategic importance on access to recycling capabilities and high-quality secondary materials. Leading companies in the retail sector are heavily involved in the collection, sorting, and recycling of packaging waste and are expanding these activities to every part of a circular economy. In the automotive industry, the switch to electro-mobility is bringing vehicle batteries and the related raw materials into strategic focus. Through corporate commitments or strategic partnerships in both battery production and recycling, manufacturers are strengthening their competitive advantage and securing access to valuable raw materials and competencies.

Consequently, this development demands that enterprises rethink their individual role within the system, and adopt a mindset of "consolidation for maximum optimization" that promotes a culture of data sharing and collaboration. Traditionally, fragmented data silos - especially within organisations – need to be broken up and rendered usable for the common good. Progressive digitalisation requires actors in society, administrations, and the economy to develop new competencies, as well as a systemic understanding. Transformation skills are a universal prerequisite for both shaping digital transformation and effectively meeting the challenges of climate change and resource conservation. Sustainability and digitalisation demand the engagement of all actors, and should be understood as a single, common transformation task rather than being treated as separate elements.

We must create an agenda for building digital-ecological transformation competence in both business and society. It is vitally important to support the political promotion of information offers, digital innovations, and the development of technical competence, especially for SMEs. In addition, market trends, such as software-as-a-service solutions, can significantly reduce the costs and qualification requirements for the use of complex tools and AI solutions, and thus facilitate their widespread use. It is crucial that the development of digital competence is properly oriented towards simultaneously tackling climate and resource problems, and is embedded within strategies of the circular economy from the outset.

5.5 A strategy to act as the guardrail for transformation

When we carefully consider the challenges described at the beginning of chapter 2, and the need to build a climate-neutral and resource-efficient economy, it quickly becomes clear that the goal is not simply a "green", clean economy, but a different economy. Unlike the substitution of fossil fuels with renewable energies, the decoupling of value creation and need satisfaction from resource use will cause structural changes within sectors, in the form of circular business models and customer behaviour. Upstream stages of material provisioning and processing will become less important, while providers of use-related, often digitally-supported services to increase resource efficiency will grow in importance.

With an increased attention on digital transformation, climate protection, and resource efficiency, a profound transformation to a digital-ecological industry lies ahead. This transformation must show us the way to climate neutrality, while contributing to the robustness of global supply chains and resilience against raw material crises.

None of this will be possible without proactivity and political leadership. We need an overarching circular economy strategy that outlines the transformation path for the coming decades. The complexity of material flows and (international) industrial interdependencies certainly make this a daunting task. Fortunately, the German resource efficiency programme ProgRessIII already offers a broad spectrum of starting points and required actions, and it is already clear that small-scale and specific measures must be carefully thought out in order to improve their effectiveness.

However, tasks must no longer be fragmented into individual ministerial responsibilities. The time is more than ripe for an integrated approach that creates an overarching framework for a digital-ecological economic policy across all ministries. Similar to climate policy, the ambition of such a policy should be to define – to the extent possible - targets and timeframes, specify sectoral contributions, and determine intermediate steps in conjunction with the EU framework. This will create common guidelines for the elaboration, coordination, and implementation of sector-specific tasks across the various ministries and action fields involved.

These guidelines help all actors within a circular economy to gain a reliable orientation, better position themselves according to their potential and responsibilities in regards to the upcoming transformation, develop roadmaps, and establish success-critical partnerships and ecosystems for the implementation of their circular economy strategies.

After readjusting and strengthening its climate policy, the new German government, alongside all stakeholders, will have the opportunity to comprehensively combine the two core topics of digitalisation and sustainable economy to develop an outlook for an internationally-competitive, sustainable, and digital future economy.

6 Risks: Unsustainable and non-circular digital solutions

The previous sections have outlined the key role that digitalisation will play in economic transformation towards a climate- and resource-friendly circular economy. It is crucial that these opportunities are seized. At the same time, it must be remembered that digitalisation itself can negatively impact the environment.

These negative environmental impacts arise primarily from **energy consumption** and the associated **greenhouse gas emissions** during the operation of devices, systems, and infrastructures. Various private and political initiatives related to the digital economy are aiming to achieve climate neutrality in the coming years[9]. Starting points are the use of new, more efficient technologies, intelligent energy management (e.g. through the use of AI processes) and, above all, the switch to a renewable energy supply (Bieser et al., 2020; Gröger et al., 2021; Hintemann et al., 2020a, 2020b; Masanet et al., 2020).

In addition, extracting and processing the raw materials needed to **manufacture physical end devices, facilities, and infrastructure** have numerous social and environmental impacts. At the same time, disposal issues are being exacerbated worldwide by mounting electronic waste. The recycling rates of end-of-life devices remain inadequate (less than 20% (globally) or 45% (Germany)) (Baldé et al., 2020; Forti et al., 2020; Umweltbundesamt, 2020). The principles and strategies of a circular economy outlined above must therefore be consistently applied to all digital products and end devices.

In the case of private households, the increasing number of digital end devices with typically short service lives is a significant driver for the increased resource consumption of digitalisation, even if offering a range of functions on one end device can partially compensate. Focus must be placed on extending the useful life of raw materials through improved durability, repairability, and recyclability of end devices. This will require increased modular construction and more refined interchangeability of individual components. Key starting points include the development of strategies for software updates, in order to avoid software-related obsolescence or the potentially time-delayed release of hardware licences, as well as software codes (open source) for alternative providers of repair solutions and update offers.

Within the industrial IoT environment, the number of electronic components and digital technologies is increasing faster than ever. In stark contrast to private use, complex ecosystems of diverse hardware components and software modules, from a wide range of providers, are emerging from production plants and logistics systems. Approaches for IT governance, lifecycle management, and the ecological optimisation of system architectures still need to be discovered (Wurm et al., 2021). A new action field is represented by the increasing use of sensors and networked digital technologies in everyday life, for example, RFID chips in products or microelectronics in textiles (smart textiles) and wearables. However, this mixing with other material flow makes the proper disposal and recovery of electronic materials difficult (Köhler et al., 2018).

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9 For example, the EU Digital Strategy (European Commission, 2020b), the BMU's Environmental Digital Agenda (BMU, 2020b), and the European Green Digital Coalition (EGDC, (European Commission, 2021).

7 Conclusion

Germany as a highly-industrialised country facing a historically-important decade. Together with the international community, we must set a course to secure the natural resources that are fundamental to life. In the coming years, businesses and society must create the conditions for effective climate, environmental, and resource protection, as well as for the preservation of biodiversity. In pursuit of these goals, the development of a climate-neutral and resource-efficient circular economy is key.

A holistic digital transformation is occurring, constantly presenting options for new actions and continuously expanding the scope for possible solutions. We now have the opportunity to utilise the unique advantages of digitalisation to transform our economies and lifestyles. This is possible through key actions:

- The permanent improvement and optimisation of individual processes and activities at all stages of the economic cycle, which is essential to decrease costs, increase efficiency, and reduce environmental pollution.
- A reduction in the overall demand for raw materials through circular, material-efficient business models and more sustainable consumption behaviour, which will serve as the foundation for climate neutrality and sustainable, future-oriented resources.

The interplay of digital solutions and the mutual reinforcement of the aforementioned actions will lead the German economy and society towards a digital-ecological future.

A comprehensive digital transformation is possible if companies and actors develop a new awareness of their roles within changing, increasingly networked value-creation systems. Alongside this, it is vital that an understanding of the importance of open, collaborative data relationships develops and that a culture of data sharing and collaborative data use emerges. Powerful and trustworthy infrastructures, widely-accepted rules, and institutions for data relationship governance are all prerequisites for effectively scaling and implementing a data-based circular economy. Much has already been set in motion, and the ongoing development of data spaces, cloud infrastructures, and cross-industry information systems must now be promoted and consistently applied to tasks related to climate protection and resource efficiency.

Throughout this report, it is clear that both the development of digitalisation and tasks to build a circular economy are moving in the same direction. However, in most cases, these two elements run parallel but lack sufficient connections, and this must change. Therefore, politicians must take responsibility for formulating ambitious goals and corresponding incentives systems for the digital and ecological transformation of the German economy over the coming years. It is also essential that they create a reliable and ambitious regulative framework that incites private and entrepreneurial action. Ultimately, all actors and stakeholders must share a common overarching understanding of the transformation path towards a sustainable future for the economy and society of Germany.

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