Digitalisation and natural resources

Analysis of the resource intensity of the digital transformation in Germany (DigitalRessourcen)

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Wörlitzer Platz 1
D-06813 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Internet: www.umweltbundesamt.de

/umweltbundesamt.de

Conductors of the study :
Ramboll Germany GmbH
Jürgen-Töpfer-Straße 48
D-22763 Hamburg

Fraunhofer Institute for Intelligent Analysis
and Information Systems IAIS
Schloss Birlinghoven 1
D-53757 Sankt Augustin

Institute of Economic Structures Research mbH (GWS)
Heinrichstraße 30
D-49080 Osnabrück

German Institute for Standardization e. V. (DIN)
Burggrafenstraße 6
D-12623 Berlin

Authors:
Katharina Milde, Anna Klose, Mareike Böbel, Daniel Lückerath (Fraunhofer Institute for Intelligent Analysis and Information Systems IAIS, Sankt Augustin)
Veronika Abraham, Roman Kirchdorfer, Joachim Aigner, Nina Albus (Ramboll Germany GmbH, Munich and Hamburg)
Mark Meyer, Alice Philippi (Institute of Economic Structures Research (GWS), Osnabrück)
Daniel Haack (German Institute for Standardization e. V. (DIN), Berlin)
Christopher Manstein (German Environment Agency)

On behalf of the German Environment Agency

Editor:
Section I 1.1 Fundamental Aspects, Sustainability Strategies and Scenarios, Sustainable Resource Use
Christopher Manstein

Design:
Eva Jüssen, Achim Kapusta (Fraunhofer Institute for Intelligent Analysis and Information Systems IAIS, Sankt Augustin)

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DIGITALISATION AND NATURAL RESOURCES

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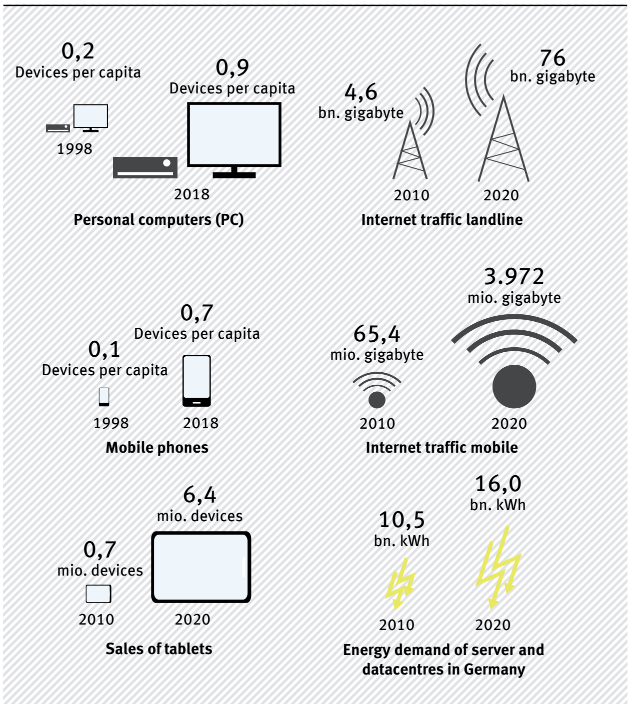
1 The research project “digitalisation and natural resources”

The digital transformation as a megatrend is evident in many current developments, such as the digital transformation of industrial production, the rise of online trade, the growing dynamics of sharing platforms and the Internet of Things (IoT), developments in autonomous transportation, Big Data, ICT, AI, or applications like cryptocurrencies. Digitalisation fundamentally changes how we live, dwell, learn, work, and communicate with each other, how we produce and consume, and how we organize ourselves as a society. It presents us with new political, economic, social, ecological, cultural, and ethical challenges that need to be discussed in society at large.

The **ecological impacts** of the rapidly advancing digitalisation currently receive too little attention in the debate. On the one hand, digitalisation is believed to have enormous potential for the reduction of environmental burdens, especially in the field of “Industry 4.0.” There is no doubt that individual digital applications already contribute to efficiency gains and reduced energy and raw material consumption. However, digital products and techniques themselves also require natural resources and have corresponding environmental effects. For example, the Scientific Advisory Council of the German Federal Government on Global Environmental Changes (dt. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, WBGU) expects that three times as much copper will be demanded in 2050 as in 2010 (WBGU 2019). The extraction of metals and rare earths can be associated with significant energy expenditure, the use of chemicals, and often poor working conditions (Buchert et al. 2019).

Figure 1

Development of information and communication technology in Germany



Source: Lutter et al. 2022 (p. 50)

The resource intensity of the digital transformation has not been sufficiently researched so far – especially considering current and future developments (Figure 1). Therefore, in 2020, the German Environment Agency commissioned a research project (Abraham et al., 2023a; Abraham et al., 2023b) to examine the **resource intensity of the digital transformation** in Germany at both the micro and macro levels.

The goal of the project “Digitalisation and Natural Resources” (abbreviated: **DigitalRessourcen**) was to improve knowledge about the resource intensity of the digital transformation in Germany. Additionally, it aimed to derive options for action regarding a sustainable, environmentally friendly, and resource-efficient design of digitalisation and its future development.

The project was carried out from 2020 to 2023 by a consortium of Ramboll Germany GmbH (Ramboll), the Institute of Economic Structures Research (GWS), the Fraunhofer Institute for Intelligent Analysis and Information Systems IAIS, and the German Institute for Standardization (DIN). This brochure presents the core results of the research project briefly. **The detailed results can be found in the final report (Abraham et al. 2023a) and the annex (Abraham et al. 2023b)** (see also www.umweltbundesamt.de/digitalressourcen).

2 Digitalisation and natural resources – an inventory

At the outset of the research project, current scientific works with a close connection to the intersection of digitalisation and resource conservation were researched and evaluated. Additionally, an overview of the current environmental and resource policy discussion on the topic of digitalisation was compiled.

In the **analysis of scientific works**, contributions that had already addressed the issue of resource use and digitalisation, achieving quantitative results regarding the resource question, were of particular interest. In the research project, results from nearly 100 studies at the micro and meso/macro levels were researched and evaluated.

The **micro level** in most studies is addressed through life cycle assessments (LCA) focusing on energy consumption or climate-relevant emissions. The use of life cycle assessment data is often fraught with uncertainties, as they cannot keep pace with the rapid pace of technological digitalisation. Also, due to the specific data collection methodology, data from life cycle assessments were rarely usable. Some works already examine the resource efficiency of digital products and technologies, with a focus on the potential for resource savings rather than resource intensity. Only a few current research projects specifically deal with the calculation and prediction of the resource intensity of digital transformation.

On the micro level, not only were scientific publications evaluated, but a broad spectrum of data and information sources, such as reports from federal authorities, database entries, and data from private interest groups, was utilised. The insights gained were used to make valid statements about the availability of data for certain products and elements of digitalisation. Additionally, an examination was conducted to determine which software, calculation methods, and databases are best suited for analysis at the micro level.

On the **meso and macro levels**, scientific studies were evaluated that deal with the nexus of digitalisation and resource consumption from a sectoral or macroeconomic perspective. Previous studies mostly analysed the potential for resource savings through digital technologies, such as the report by Neligan (2021). Two preliminary works relevant to the research project were identified: an analysis of past trends in the use of information and communication products in Switzerland by Cabernard (2019), and a report by the Scientific Advisory Council of the German Federal Government describing the future development of resource consumption through the use of digital applications (WBGU 2019). The analysis of available databases led to the selection of the GLORIA database ("Global Resource Input-Output Assessment", Lenzen et al. 2022) as the basis for macroeconomic calculations in this project.

Digitalisation has had high political priority in Germany for many years. The **environmental and resource policy discussion** on the topic is evident, for example, in the 2022 adopted "Digital Strategy Germany – Creating Digital Values Together," which aims for sustainable and resource-efficient digitalisation. In 2020, the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) in Germany developed the "Environmental Policy Digital Agenda," (dt. „Umweltpolitische Digitalagenda") with the goal of harnessing the opportunities of digitalisation while making it environmentally friendly. The German Resource Efficiency Program (ProgRess) contains measures for more resource efficiency along the entire value chain. The National Circular Economy Strategy (dt. "Nationale Kreislaufwirtschaftsstrategie", NKWS, forthcoming) defines goals and measures for circular economies and resource conservation. At the European and international levels, numerous political programs and action plans already exist regarding digitalisation and resources, including the European Green Deal, which sets the framework for sustainable economic development. Initiatives such as the digital product passport or the right to repair also influence the further shaping of digitalisation.

3 System boundaries of digitalisation

For the calculations conducted at the micro and macro levels in this project (see below), it was particularly important to first discuss and define the **system and observation boundaries** of the digitalisation topic. According to the project mandate, the goal was to analyse, discuss, and define precisely what digitalisation means in this project and which system and observation boundaries apply.

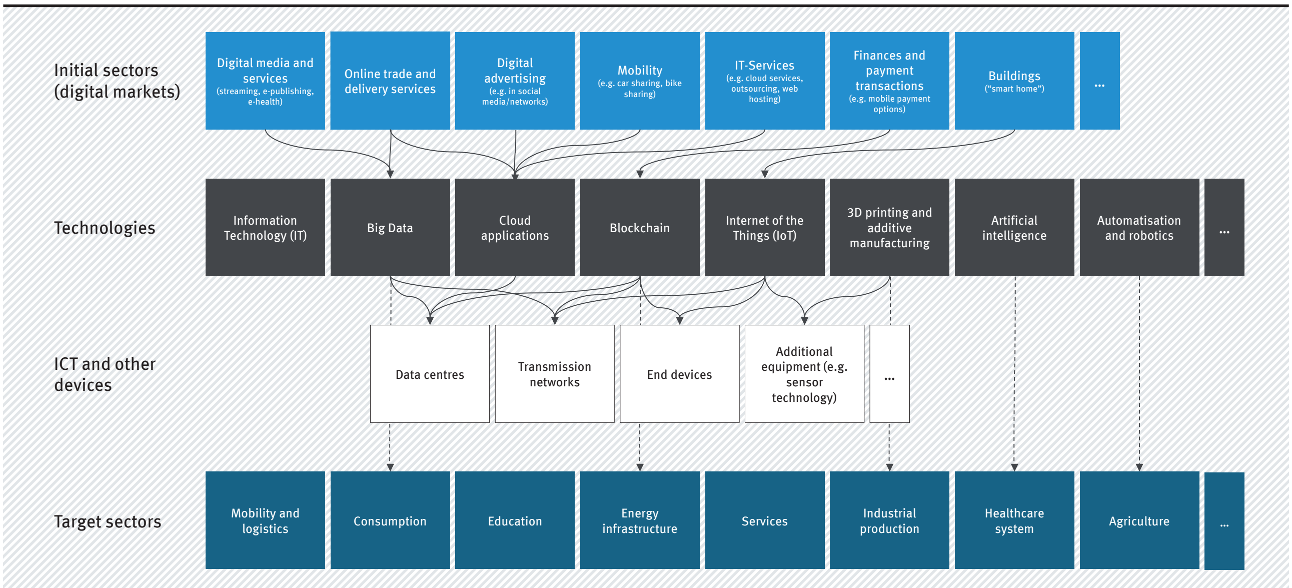
On a purely technical level, digitisation (in differentiation to digitalisation) refers to the transformation of analogue information into digital signals. Digitalisation, in the context of digital transformation, also describes a comprehensive process that includes the automation of existing industrial processes and even their obsolescence. Furthermore, digitalisation, in terms of digital change, represents profound changes in the industry and far-reaching structural impacts on society.

For the research project, a **conceptual model** was developed. It consists of various interrelated subsystems, taking into account the diversity of digital solutions and application areas, their dynamic interactions, and the complexity of the system of digitalisation (Figure 2). The initial and target sectors frame the model. Within these boundaries, the direct effects of digitalisation originate from the application of individual technologies and the associated utilisation of information and communication technology (ICT) hardware and other required products.

On the **micro level**, individual relationships within the complex system of digitalisation can only be examined in detail within a specific case study. The selected case studies (Chapter 4) were chosen to cover a broad spectrum of digitalisation (initial or target sectors). The focus was on specific digital applications that, in turn, require digital products, technologies, etc.

Figure 2

Understanding of digitalisation in the research project



Source: Own representation

Source: mh – stock.adobe.com

In the **macroeconomic Input-Output modelling**, all uses of ICT goods and services in Germany were captured as direct effects of digitalisation (Chapter 5). As the complex interplay of digitalisation should be comprehensively represented across different initial and target sectors, both, the final demand as well as the intermediate demand for ICT goods and ICT services were fully captured and evaluated for target sectors in the sense of Figure 2. For this purpose, a **functional definition** of digitalisation related expenditure flows was applied. The challenge was that the revenues of digitalisation-relevant economic sectors are usually reported in aggregate. Therefore, individual percentage values for ICT goods and ICT services were calculated in the research project.

4 The micro level: ten case studies on life cycle data of selected digital use cases

In the context of the work at the micro level of the project DigitalRessourcen, a total of ten case studies were to be exemplary examined. Thereby, the respective resource intensity (various indicators) and greenhouse gas potential (CO_2 equivalents) were to be calculated.

The **selection of case studies** was based on various criteria. The case studies should be representative and cover the breadth of the digitalisation topic. They should address relevant products and technologies that are directly used by end consumers. The availability of information and data on product manufacturing and use was another important selection criterion. For each case study, a specific use case was defined. Subsequently, the technologies, ICT hardware, and software used in the specific use case by end consumers were identified (Table 1).

The resource intensity was calculated for all case studies based on **uniformly defined indicators**. In addition, the use cases were qualitatively assessed in terms of their current and future **societal relevance** and their **theoretical potential for environmental relief**.

The **approach for calculating** resource intensity and other indicators was based on the method of environmental life cycle assessments (LCA) according to DIN EN ISO 14040/44 (DIN EN ISO 14040:2021-02). However, in this project, the focus was on the life cycle inventory level and the corresponding incoming and outgoing resources (main focus) and emissions (using the example of CO_2 equivalents). For analysing the case studies, the **software OpenLCA**[1] in combination with the **Ecoinvent database** (Version 3.8)[2] for life cycle data was used to calculate the defined resource indicators (Wernet et al. 2016).

The indicators considered in all case studies are **raw material input** (RMI)[3], **total material requirement** (TMR)[3], **cumulative energy demand** (CED), **water depletion potential** (WDP), **land occupation potential** (LOP), and additionally, **global warming potential** (GWP) (Figure 3). In the case of RMI, the specific **bulk raw materials** used in each case study were additionally discussed, such as gangue, hard coal and lignite, crude oil, and shale. Again, related to the RMI, special attention was paid to critical raw materials such as technology metals or rare earth elements. Although of minor importance with respect to used masses, these **digitalisation-relevant raw materials** are of particular strategic importance for digitalisation and are often associated with significant environmental impacts (ecological and social) (Jacob et al. 2021; Kristof und Hennicke 2010; Liu et al. 2019). To analyse the case studies, a total of 27 digitalisation-relevant raw materials were defined and calculated for each case study. These include raw materials that play a special role in the production of digital technology, such as gallium
(a component of electronic components like transistors, integrated circuits in mobile phones, or LEDs), tantalum (for the production of small capacitors like in mobile phones), and neodymium (part of permanent magnets in headphones and speakers or hard drives).

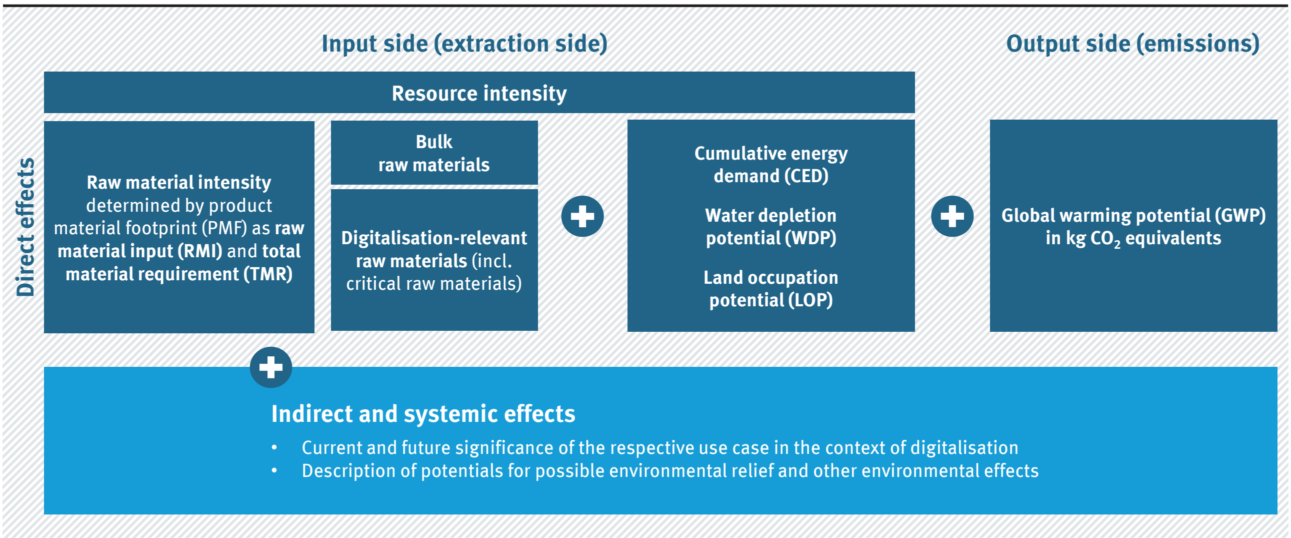
The selection of this set of indicators ensured that relevant direct environmental effects were considered in terms of a life cycle inventory analysis. Consequently, the resource intensity of the input side of the use cases was comprehensively assessed based on four resource footprints (material, fossil energy, water, land). On the output side, a particularly relevant environmental impact – global warming due to greenhouse gases – was considered. Other environmental effects were not the focus of the project or could not be determined due to a lack of data and traceability.

In addition, each case study was evaluated through a qualitative assessment of the use cases in terms of their current and future **societal relevance** and their theoretical **potential for environmental relief** (indirect and systemic effects).

1 https://www.openlca.org (Accessed: 15.12.2022)
2 https://support.ecoinvent.org/ecoinvent-version-3.8 (Accessed: 14.12.2023)
3 RMI and TMR are typically used as indicators at the macroeconomic level. In this project, they were also applied to micro-level analyses based on the methodology developed by Mostert and Bringezu (2019).

Figure 3

Indicator set for the analysis in the case studies



Source: Own representation based on Mostert and Bringezu (2019)

Figure 3 shows the set of indicators used in this research project for the analysis within the framework of the ten case studies.

Moreover, information from additional literature (including scientific publications, relevant research and project reports, grey literature, and foresight studies) was considered during the calculations and analysis of the case studies and served as a reference for the interpretation and discussion of the calculated results. The **unit and boundaries of analysis** were individually defined for each case study. For all case studies, framework conditions for the influence of data centres, the life cycles considered, and the use of multifunctional devices were defined. The production of data centres and other network infrastructure was only approximated and included in selected case studies. The resource demands were assigned, based on the LCA methodology, to the life cycle phase they occur at. This was mainly the manufacturing or use phase, the end-of-life phase was only considered when it played a significant role. Furthermore, a usage time-based allocation was undertaken for multifunctional devices.

Results of the case studies

For each case study, information about the case study, the unit of analysis, as well as the results of the analysed indicators and a discussion, were compiled. The ten case studies and the main results are merely summarised in this brochure as an overview (Table 1). Exemplarily, the essential contents of the case study "video conference while working from home" are presented in more detail.

Table 1

Overview of the ten case studies considered

Case study	Use case	Results for the selected indicators in the DigitalRessourcen		Overview[a]
1. Video conference while working from home	Participation of an individual in a one-hour group video conference in a professional context	RMI: 116 g CED: 1.03 MJ WDP: 0.85 L	TMR: 134 g GWP: 70 g CO_2-eq. LOP: 0.0044 m^2a	M > U ↑
2. Smart-home-system	Five-year utilisation of an energy management system for buildings	RMI: 2,938.11 kg CED: 40,795 MJ WDP: 14.61 m^3	TMR: 3,699.8 kg GWP: 2,321.8 kg CO_2-eq. LOP: 123 m^2a	M < U ↔ (!)
3. Digital media	30-minute reading of messages on a digital end device	RMI: 47.1 g CED: 0.47 MJ WDP: 0.00045 m^3	TMR: 54.8 g GWP: 0.03 kg CO_2-eq. LOP: 0.0016 m^2a	M > U ↑ (!) ↺
4. E-grocery	Realisation, provision, and delivery of an online food order[c]	RMI: 5.6 – 17.2 kg CED: 82.5 – 286.3 MJ WDP: 0.02 – 0.08 m^3	TMR: 7.4 – 22.9 kg GWP: 4.2 – 15.1 kg CO_2-eq. LOP: 1.6 – 3.5 m^2a	↑ (!)
5. Car-sharing	Ride in a carsharing car for one kilometre[c]	RMI: 291.4 – 436.4 g CED: 2.67 – 3.90 MJ WDP: 0.0006 – 0.0015 m^3	TMR: 363.8 – 561.4 g GWP: 76.4 – 232.2 g CO_2-eq. LOP: 0.0062 – 0.0126 m^2a	M > U (exempl. scenario) ↑ ↺
6. Cryptocurrency[b]	Operation of the Bitcoin network for one year[d]	RMI: 38,1 Mt CED: 641 PJ WDP: 0.16 km^3	TMR: 44.8 Mt GWP: 33.7 Mt CO_2-eq. LOP: 618 km^2a	↓ (!)
7. Consumer-to-consumer-platform	Sale of a T-shirt via a C2C platform incl. dispatch or collection[c]	RMI: 0.46 – 3.91 g CED: 5.77 – 50.63 MJ WDP: 0.005 – 0.008 m^3	TMR: 0.58 – 4.64 g GWP: 0.31 – 3.33 g CO_2-eq LOP: 0.12 – 0.15 m^2a	M > U (exempl. scenario) ↑ (!) ↺
8. E-sport	One hour of gaming and streaming League of Legends (LoL)	RMI: 3.07 kg CED: 45 MJ WDP: 0.02 m^3	TMR: 3.92 kg GWP: 2.54 kg CO_2-eq LOP: 0.13 m^2a	M < U ↓ (!)
9. 3D printing	77 hours of using a 3D printer for home use	RMI: 353.74 kg CED: 2,224.6 MJ WDP: 1.06 m^3	TMR: 437.98 kg GWP: 148.09 kg CO_2-eq LOP: 9.08 m^2a	M > U ↓
10. E-health	16 hours of using a smartwatch in combination with a smartphone	RMI: 58.6 g CED: 0.95 MJ WDP: 0.0003 m^3	TMR: 77.1 g GWP: 53 g CO_2-eq LOP: 0.0025 m^2a	M < U ↓

Abbreviations: RMI = raw material input, TMR = total material requirement, CED = cumulative energy demand, GWP = global warming potential, WDP = water depletion potential, LOP = land occupation potential

[a] Symbols: M <> U shows, whether the influence of the manufacturing (M) or use (U) phase prevails regarding the environmental indicators, ↑ potential for environmental relief, ↔ low to no potential for environmental relief, ↓ potential for environmental impact, (!) the design of the use case has a significant influence, ↺ potential for rebound effect

[b] In all case studies, the manufacturing phase (M) and use phase (U) are considered. Due to a lack of data availability, the end-of-life phase could not be taken into account. However, in the cryptocurrency case study, the end-of-life phase was estimated due to its expected high relevance. It was not possible to make a statement about the relative influences of M and U in this case.

[c] In this case study, various scenarios were examined, and results for the indicators are provided as a range across the scenarios.

[d] In this case study various scenarios were considered, the results presented here originate from the "standard scenario."

Source: Own representation.

Example of the case study "video conference while working from home"

Source: Wikimedia No. P060782-6183

Background: Already prior to the COVID-19 pandemic, surveys showed that the share of working from home in Germany could continue to rise. With the outbreak of the pandemic, remote work has become more widespread and firmly established. The acceptance of remote work is expected to increase further as both employers and employees appreciate the flexibility and efficiency of working from home. Video conferences are also increasingly used in private settings as they provide an appealing way to communicate and see each other despite long distances.

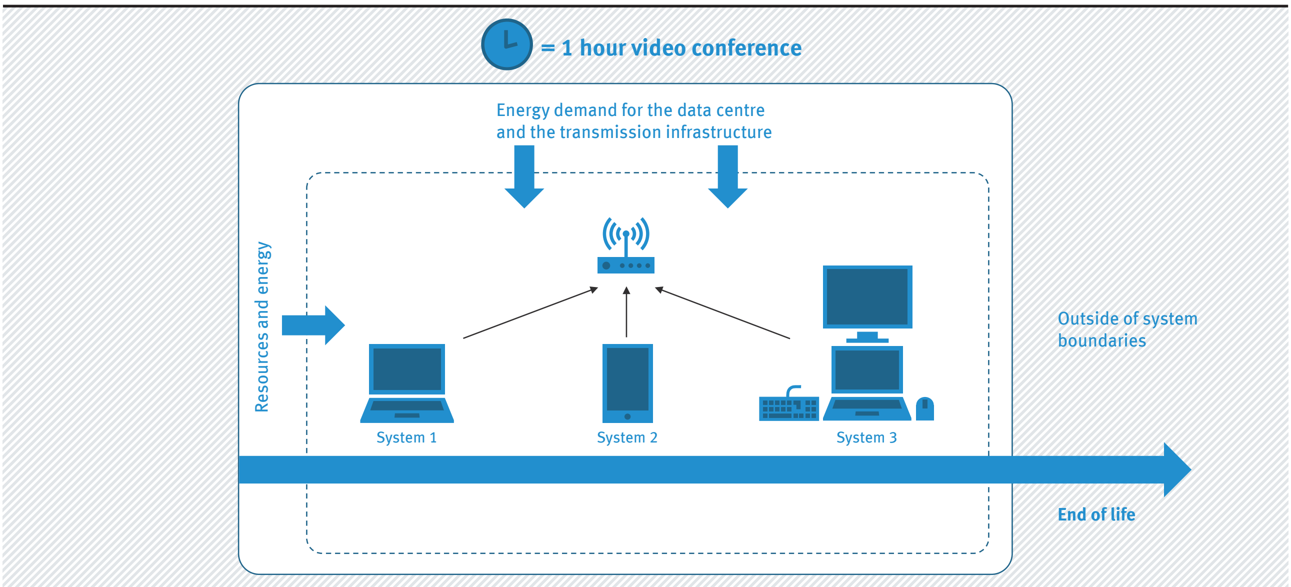
The **unit of analysis** was defined as one hour of participation in a group video conference using a mix of three common device combinations from a professional context: System 1: Laptop with integrated camera and microphone, System 2: Smartphone, System 3: Laptop with integrated camera and microphone, external monitor, external keyboard, optical PC mouse (Figure 4).

Results of the calculations: With respect to the unit of analysis "1 hour of video conference while working from home," a total **raw material input** (RMI) of **116 g/h** was calculated. For the manufacturing of the devices used in a video conference, the raw materials gangue, hard coal, biotic raw materials, and gravel are primarily used in terms of quantity. When including unused extractions in the calculations, the **total material requirement** (TMR) amounts to **134 g/h**.

The other indicators were calculated analogously to the material indicators (Figure 5). One hour of video conference results in a **water depletion potential** (WDP) of **0.85 L** and a **land occupation potential** (LOP) of **44 cm²a**. The **cumulative energy demand** (CED) is **1.03 MJ/h**, and the **global warming potential** (GWP) is **70 g CO_2-eq/h**.

Figure 4

Functional unit of the case study "video conference while working from home"

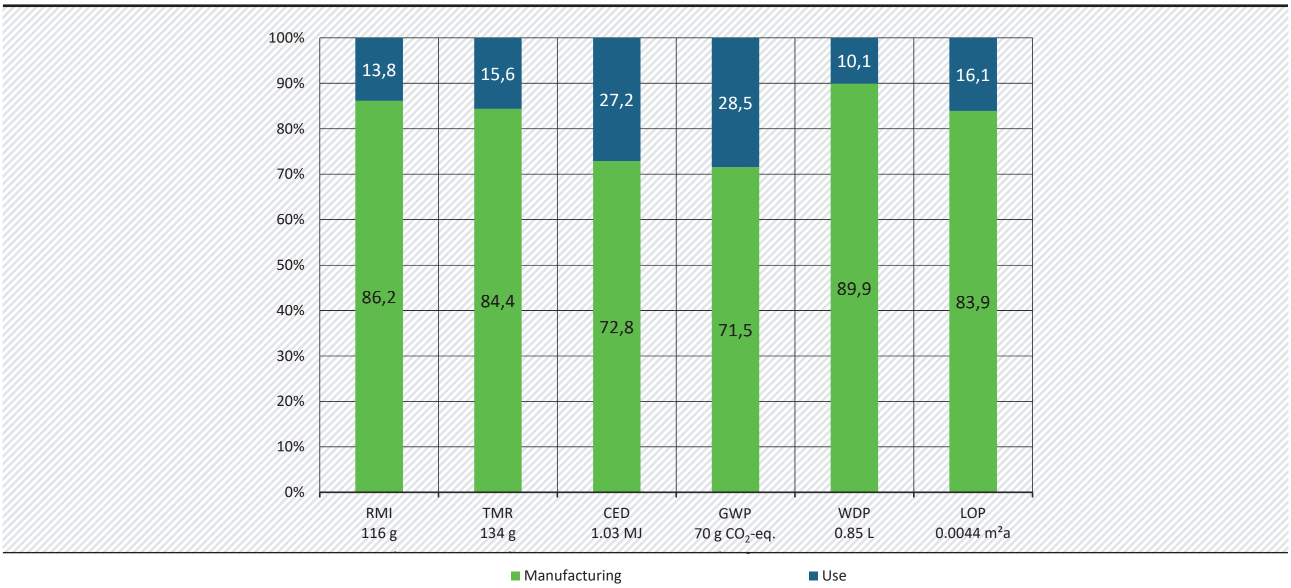


Used parameters for the calculation: Standard quality bandwidth 480 p, download/upload speed 800 Kbps / 1 Mbps, data consumption 810 MB/h (Braun 2020), energy demand for server, storage, network, and infrastructure of a data centre: 0.0041 kWh/h, energy demand for data transmission: 0.0016 kWh/GB for a VDSL connection (Gröger et al. 2021).

Source: Own representation.

Figure 5

Comparison of resource and LCA indicators between manufacturing and use phase for a one-hour video conference



Note: RMI = raw material input, TMR = total material requirement, CED = cumulative energy demand, GWP = global warming potential, WDP = water depletion potential, LOP = land occupation potential.

Source: Own calculations

The calculated absolute values of the indicators for one hour of video conference were divided into the manufacturing and use phases. For all examined indicators, **the manufacturing phase dominates**, but with varying proportions. For example, the manufacturing phase of the devices accounts for 86 % of the **RMI**. The TMR behaves similarly. In the case of WDP and LOP, the use phase accounts for almost 30 %, while it accounts for less than 20 % of CED and GWP.

Discussion of the results and insights from the case studies

When discussing the results of the case studies and drawing conclusions, the chosen boundaries of the system and the analyses, as well as the selected unit of analysis, should be considered. The results show **diverse pictures** depending on the case study regarding the main drivers of resource demand and greenhouse gas potential. For some cases studies, the majority of resource consumption occurs during the

Digitalisation-relevant raw materials

Allocated to the use case, these raw materials play a negligible role in terms of quantity, with approximately **0.26 g/h** in the **Video Conference** case study. However, they are of great strategic and political importance due to their geological rarity and the partially limited capacity of countries like Germany to purchase (import) them. In the case study "video conference while working from home", copper accounts for the largest quantity of digitalisation-relevant raw materials, at approximately **0.13 g/h**. Other digitalisation-relevant raw materials include tin and silver. When looking at the distribution of digitalisation-relevant raw materials across individual components of the video conference system, it can be observed that more than 95 % of the lithium demand is attributed to the laptop and more than 80 % of the tantalum demand is attributed to the monitor.

manufacturing phase (e.g., Video Conference and 3D Printing). For other case studies, resource consumption is mainly attributed to the use phase (e.g., Smart Home and E-Sports).

The **use phase** in all case studies is characterised by the electricity demand of the application. Depending on the case study, the **electricity demand** of end devices used by users or the data transmission (including data centres) dominates. The resource demand in the **manufacturing phase** is primarily influenced by the **materials** used and the associated procurement and manufacturing processes in the supply chains. Depending on the product or system being considered, resource demands are reflected in different life cycle phases. For example, the resource demands for various end devices are clearly influenced by the phases from raw material extraction to manufacturing. In the case of data centres, on the other hand, the use phase or operation significantly contributes to the abiotic resource demand. These findings are consistent with previous analyses (Köhn et al. 2020).

Looking at the distribution of resource demand among different groups of raw materials, **metal ores** dominate as raw material inputs in the manufacturing phase in all case studies. When considering the use phase exclusively or in addition, **fossil energy carriers** generally prevail. This is due to the electricity mixes being often dominated by fossil energy. Among bulk raw materials, **gangue** is the most extracted material in most case studies. Gangue occurs as a mandatory by-product of ore mining. Thus, its presence in large quantities compared to, e.g., energy carriers is not surprising. Other raw materials that are among the **most important materials** in terms of mass in the case studies include – in different order and weight – hard coal, lignite, gravel, shale, sand, and crude oil.

Among the digitalisation-relevant raw materials, **gallium, tantalum, gold, silver, tin, nickel**, and sometimes **lithium** and **scandium** stand out in almost all case studies. In terms of EU classification, gallium, tantalum, and lithium are considered critical (European Commission 2020; the updated list of critical raw materials in March 2023 could not be considered in this project). However, gold, silver, nickel, and tin are also essential for the production of various ICT components. The main drivers of demand for digitalisation-relevant raw materials are often specific devices or components of the examined product system. Examples include (gaming) computers in the E-Sports case study or the power supply unit in the 3D Printer. Individual raw material demands are almost exclusively attributed to specific end devices or components. An example is the lithium demand for the production of the laptop battery in the Video Conference case study.

All case studies analyse the same six indicators (Figure 3). It is noteworthy that in each case study, all indicators show the same trend when dividing between the manufacturing and use phases. In other words, within all examined use cases, the **main drivers** of the individual indicators can be found in the same life cycle phases.

Uncertainties in the analysis of the case studies mainly arise from **data availability**. For example, the timeliness of data sets from the LCA database often cannot keep up with the rapid technological development of digital end devices.

Finally, the case studies should also examine whether the respective digital application has the potential for **environmental relief** (Table 1). In some case studies, this can be affirmed (e.g., Video Conference case study). In other case studies, the examined use case only serves to **increase comfort** (for example the Smart Home case study in most scenarios) or to promote additional consumption behaviour (for example the 3D Printing as a home application). In these cases, the digital application likely does not have any advantages with respect to resource demand and environmental effects or may even have a negative impact. In such cases, sustainable and environmentally friendly design is particularly important.

5 The macro level: resource intensity and CO_2 emissions of the digital transformation from 2000 to 2020

In order to calculate the environmental impacts of production and consumption at the meso and macro level, two different approaches are conceivable: "**Bottom-up**" analyses are based on a – as comprehensive as possible – list of goods and services that are relevant for the overall system being analysed. For all selected goods and services, their respective environmental impacts are then recorded in great detail. Based on this individual recording, an extrapolation is then carried out at the macro or meso level. "**Top-down**" approaches, on the other hand, do not rely on a detailed investigation of individual goods and services. Instead, an exclusive analysis is carried out at the macro or meso level. This involves a systematic examination of macroeconomic supply chains and demand structures for the analysed production sectors and their aggregated supplies of goods and services.

Sectoral analyses, as conducted in the "case studies on life cycle data of digital use cases" (Chapter 4), are typical examples of "bottom-up" analyses. They are characterized by a high level of detail. However, they require an extremely large amount of information. For this reason, "bottom-up" analyses were only carried out for the goods, services, or digital applications selected for individual case studies. For economy-wide assessments of current as well as prospective environmental and economic impacts of the digital transformation, macroeconomic calculations and simulations were conducted as independent "top-down" analyses (Chapter 5 and 6).

Methodology for analysis at the macro level

The macroeconomic boundaries of the "system of digitalisation" were defined as follows for the "top-down" evaluations in the research project: Any use of ICT (Information and Communication Technologies) goods and services in Germany was considered a direct effect of digitalisation. This approach follows the systemic understanding introduced in Chapter 3, "system boundaries of digitalisation". In the terminology of national accounting systems (**national accounts**, dt. "Volkswirtschaftliche Gesamtrechnungen", VGR), this means that direct demand effects stem from a) the demand of all economic sectors for ICT goods and services as intermediate inputs to their respective production processes, b) total domestic final demand for ICT goods and services in Germany and c) total foreign demand for exports of ICT goods and services from Germany.

The national accounts capture aggregated **payment flows** between conceptually defined economic sectors and different types of final demand (gross investment, government consumption expenditure, consumption expenditure of private households and non-profit institutions, export demand from abroad) in a standardised manner. However, the national accounts do not explicitly report on a correspondingly defined digitalisation sector or on the demand for goods and services provided by this sector. Therefore, based on the "Guide for Measuring the Information Society" (OECD 2011), the sectors that can be directly attributed to the ICT sector were defined at the level of individual groups of official economic statistics. This selection allows for an evaluation of the ICT service industry, ICT trade, the ICT repair industry, and the ICT manufacturing industry in the macroeconomic analyses (Table 2).

For all macroeconomic assessments in the DigitalRessourcen research project, the global **Multi-Regional Input-Output (MRIO) database GLORIA** ("Global Resource Input-Output Assessment") version "Release 055" from March 2022 was used (Lenzen et al. 2017; 2022). Commissioned by an international institution (International Resource Panel by the United Nations), this database was developed in parallel during the term of the research project with the aim of creating a freely accessible statistical reference for environmental-economic assessments.

The GLORIA database also applies the official economic classifications of the national accounts. It reports in a standardised manner not only on the aforementioned monetary expenditure flows between source and target sectors, but also on corresponding **pressures on the biosphere** (such as raw material extractions or CO_2 emissions). The database has a spatial reporting scope of 160 countries and 4 "Rest of World" regions, covers the period 1990 to 2020, is divided into 120 economic sectors and contains various

Table 2

Definition of the digitalisation sector in the macroeconomic assessments

WZ 2008 Code*	Departments analysed and related groups*
26.1	Manufacture of computers, electronic and optical products: Manufacture of electronic components and printed circuit boards
26.2	Manufacture of computers, electronic and optical products: Manufacture of data processing equipment and peripheral equipment
26.3	Manufacture of computers, electronic and optical products: Manufacture of telecommunications equipment and equipment
26.4	Manufacture of computers, electronic and optical products: Manufacture of consumer electronics equipment
26.8	Manufacture of computers, electronic and optical products: Manufacture of magnetic and optical data carriers
46.5	Wholesale trade (excluding trade in motor vehicles): Wholesale of information and communication technology equipment
58.2	Publishing: Publishing software
61	Telecommunication
62	Provision of information technology services
63.1	Information services: Data processing, hosting, and related activities; Web portals
95.1	Repair of data processing equipment and consumer goods: Repair of data processing and telecommunications equipment

* Groups of the Classification of Economic Activities (Statistisches Bundesamt 2008) that have been assigned to the ICT sector in the macroeconomic assessments.

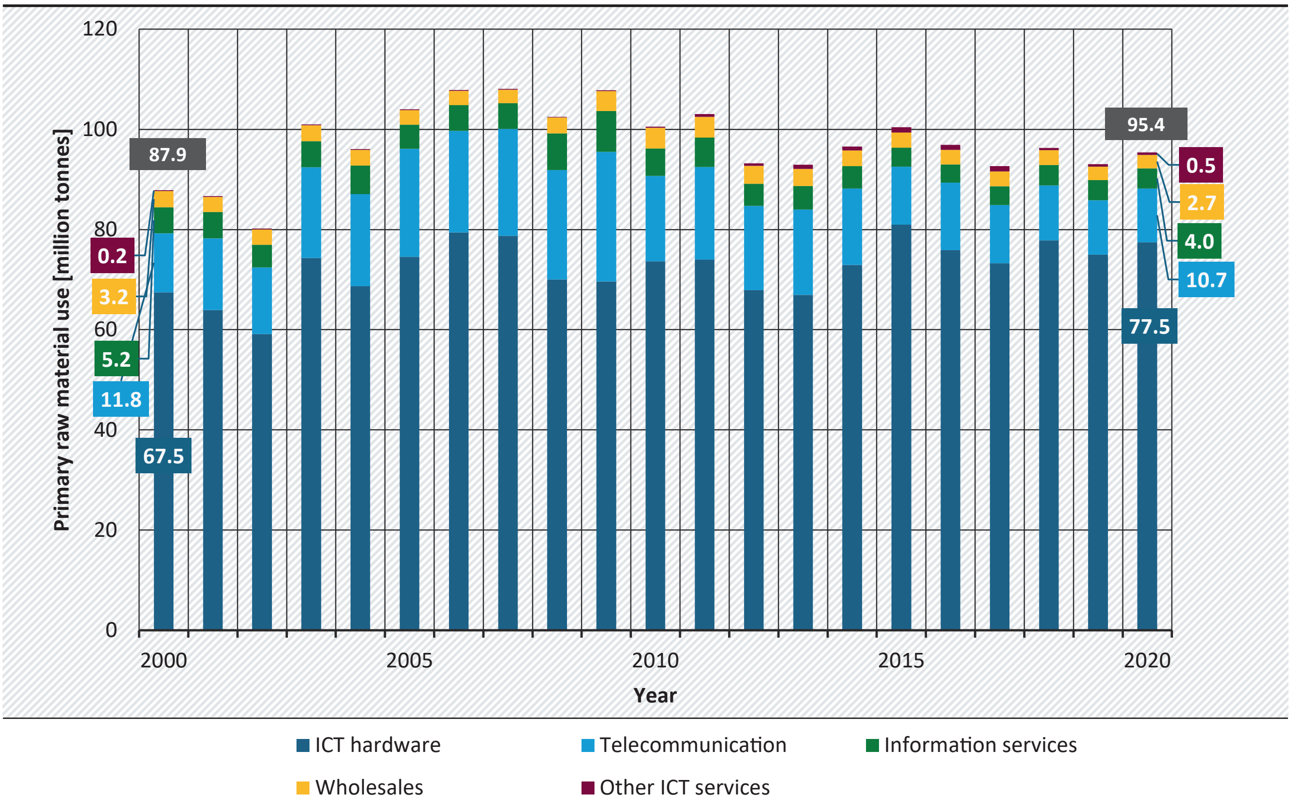
Source: Own illustration based on OECD (2011)

environmental factors such as CO_2 emissions and a total of 62 material categories. The latter include, for example, fossil energy carriers, ores, non-metallic minerals, biomass, etc. (Lenzen et al. 2017; 2022). Consequently, the GLORIA database was the first choice for all macroeconomic assessments in this research project.

Based on the GLORIA database, the following indicators were analysed for the German digitalisation sector (Table 2) for the years 2000 to 2020: **raw material consumption** ($RMC_{Dig.}$), raw material input ($RMI_{Dig.}$) and the **carbon footprint of digitalisation** ($CO_{2,\ Dig.}$). In general, the RMC represents the global use of primary raw materials required for the provision of all goods and services that are finally consumed or invested in an analysed country. The reporting object is the total mass of these primary raw materials. To calculate this mass, the weight of all raw materials directly extracted from nature domestically must be added to the weight of primary raw materials used through imports, and the weight of primary raw materials for exports must be subtracted from this sum. To determine the total amount of raw material masses utilised in the economy via imports and exports, the research project calculated so-called **raw material equivalents** using detailed information from the GLORIA database. Raw material equivalents capture **all primary raw material uses during the production phase along global supply chains**. Although there are currently no binding political targets for the long-term development of the RMC, this indicator has become a well-established reporting element for international comparisons of economy wide material consumption in the context of the 2030 Agenda for Sustainable Development (Lenzen et al. 2022). By definition, the global sum of all national RMC values corresponds to the sum of all globally used raw material extractions.

Figure 6

Analysis of the raw material consumption ($RMC_{Dig.}$) of digitalisation in Germany



$RMC_{Dig.}$: Global use of primary raw materials for the production of ICT goods and services for domestic consumption, investment, and production activities.

Source: Own calculations

The raw material input (RMI) corresponds to the raw material consumption (RMC) **plus** all global uses of primary raw materials that are used to provide goods and services exported from the domestic market to other world regions. Analogous to the RMC, the carbon footprint accounts for all CO_2 emissions that arise globally during the production of goods and services subsequently used domestically.

The results of the macroeconomic analysis for the years 2000-2020

As explained in Chapter 3, the following results are based on a system approach that fully captures both the macroeconomic final demand and the total intermediate demand for ICT goods and services. This broader perspective allows for the analysis of more comprehensive material flows. In the interests of better readability, the names of the conceptually expanded indicators are kept in the following: Raw Material Consumption ($RMC_{Dig.}$), Raw Material Input ($RMI_{Dig.}$) and Carbon Footprint ($CO_{2,\ Dig.}$) of digitalisation.

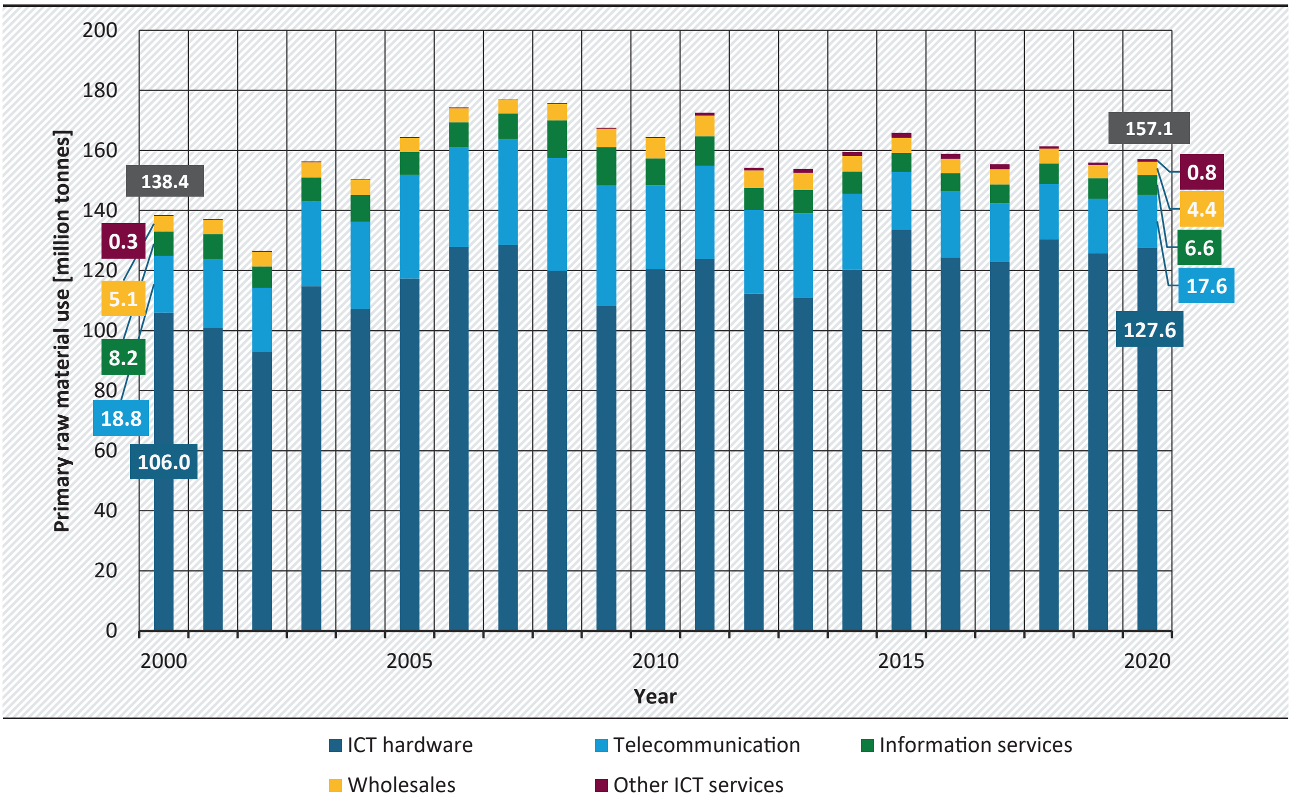
The **raw material consumption** of digitalisation in Germany ($RMC_{Dig.}$) reached **95.4 million tonnes** in 2020 (Figure 6). This represents an **increase of approximately 8.5 %** compared to just under 88 million tonnes in 2000.

Throughout the entire period, the development of $RMC_{Dig.}$ has been significantly influenced by the demand for **ICT hardware**. In 2020, this demand accounted for more than 80 % of the raw material consumption of digitalisation. ICT services show significantly lower values. Telecommunications services accounted for the largest remaining share (approximately 11 % in 2020). Information services, as well as wholesale and retail trade, also contribute noticeably to $RMC_{Dig.}$, but to a much lesser extent (shares in 2020: information services 4.2 %, wholesale trade 2.8 %).

Further calculations of our own show that digitalisation in Germany has also increased its share in relation to the total RMC: In 2000, $RMC_{Dig.}$ accounted for approximately 4.3 % of Germany's total RMC. By

Figure 7

Analysis of the raw material input ($RMI_{Dig.}$) of digitalisation in Germany



$RMI_{Dig.}$: Global use of primary raw materials for the production of ICT goods and services for domestic consumption, investment, and production activities, as well as the export of goods and services.

Source: Own calculations

2020, this **share had increased to 5.6 %** (total German RMC 2020: approximately 1,701 million tonnes).

If the total **raw material input** of the German economy for ICT goods and services ($RMI_{Dig.}$) is considered - i.e. all primary raw material requirements for export demand from abroad in addition to the primary raw material requirements for domestic final demand - the total value for 2020 amounts to **157.1 million tonnes**. From 2000 to 2020, $RMI_{Dig.}$ **increased** by nearly **13.5 %** (Figure 7). While the share of ICT services in raw material input declined slightly in the long term, $RMI_{Dig.}$ increased by over 21 million tonnes between 2000 and 2020 due to ICT hardware. In 2000, approximately 76 % of $RMI_{Dig.}$ was related to ICT hardware. In 2020, it was already over 81 %.

$RMI_{Dig.}$ has also gained importance in relation to the overall raw material input over the years: It accounted for 4.7 % of the total RMI in 2000, reaching a share of 4.9 % in 2020 (German RMI 2020: 3,179 million tonnes).

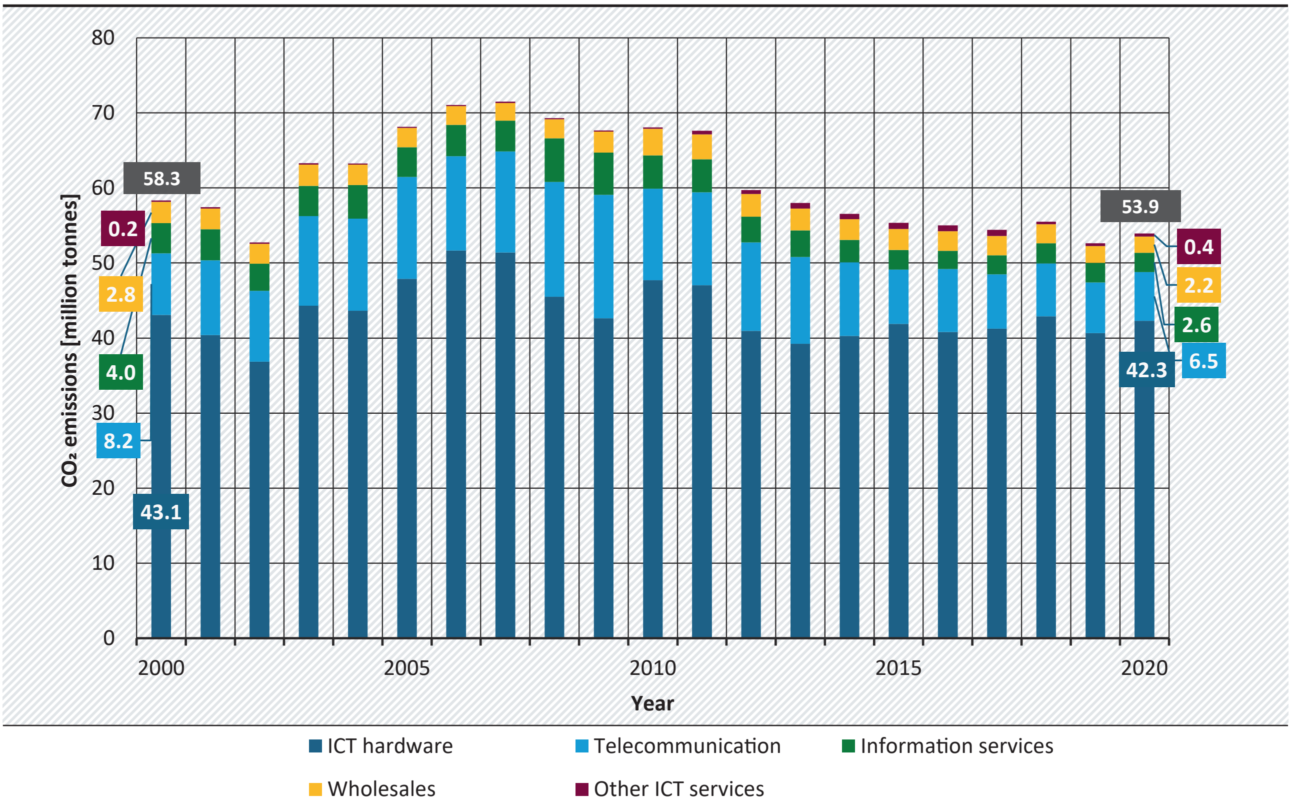
Similarly to the digitalisation-related consumption and use of raw materials, the **carbon footprint** of digitalisation ($CO_{2,\ Dig.}$) was calculated in this project also using the GLORIA model. In 2020, the CO_2 emissions associated with the production of ICT goods and services for domestic consumption, investment, and production activities totalled just over **53.9 million tonnes** (Figure 8). Between 2000 and 2020, the carbon footprint of digitalisation in Germany decreased by **7.6 %.** At the same time, there has been a long-term increase in the **share of digitalisation** in Germany's total carbon footprint: from 5.1 % in 2000 to **5.7 % in 2020**. In 2020, the shares of the $CO_{2,\ Dig.}$ footprint and the previously described raw material consumption ($RMC_{Dig.}$) show a high degree of **consistency.**

Analysis by raw material groups, geographical origin, and uses

In the analysis of the research project, the indicators previously presented were also broken down according to the following aspects: shares of

Figure 8

Demand-based analysis of the $CO_{2, Dig.}$ footprint of digitalisation in Germany



Source: Own calculations

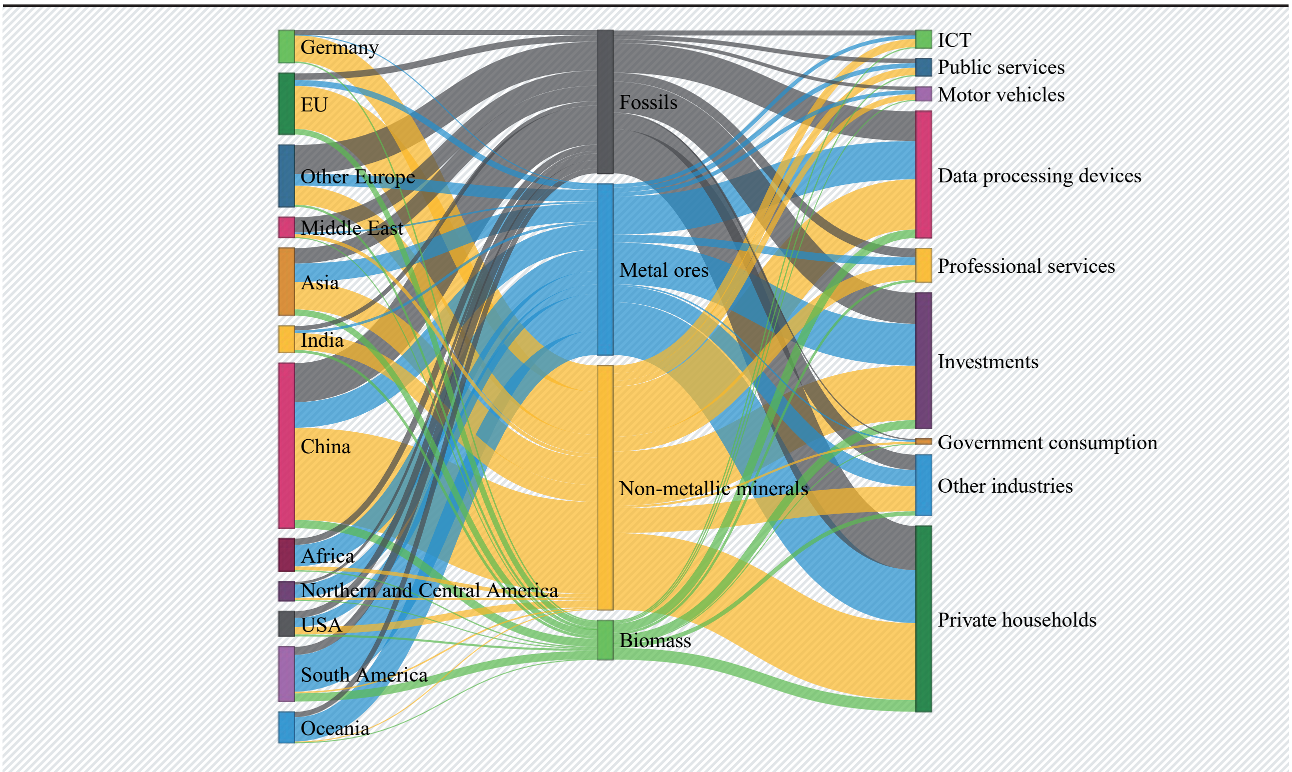
individual target sectors, materials used (non-metallic minerals, metal ores, fossil energy carriers, biomass), as well as countries of origin of goods and services or upstream products. This is described below using the example of raw material consumption ($RMC_{Dig.}$). At the same time, Figure 9 illustrates how complex the calculations of the indicators were in this research project.

Geographical origin: As described previously (Figure 6), the raw material consumption of digitalisation in Germany is mainly driven by the demand for ICT hardware. Since ICT hardware is mostly imported from **Far Eastern regions of the world**, German digitalisation leads to the extraction of raw materials, particularly in China and the rest of Asia. For all ICT goods and services used in Germany in 2020 (intermediate demand together with final demand), China alone extracted around 26.3 million tonnes of raw materials. This corresponds to slightly over a quarter of the total German $RMC_{Dig.}$ (Figure 9). For comparison: In 2020, Germany itself extracted only 5.2 million tons of raw materials due to digitalisation.

Main raw material groups: Non-metallic minerals are the most important material category in the consumption of raw materials for of digitalisation. In 2020, nearly 39 million tons of non-metallic minerals (mostly sand and gravel) were needed. This represents a share of approximately 40.9 % of the recorded primary raw materials. **Metal ores** amounted to 27.3 million tonnes, exceeding the quantity of fossil energy carriers. The latter were used in an amount of 22.8 million tonnes. Their share of $RMC_{Dig.}$ (around 24 %) is thus significantly higher than the share of biotic raw materials (6.6 %). Fossil energy carriers were primarily used in China, in European regions outside the EU, in the Middle East, and in the rest of Asia. This is primarily due to the energy systems underlying the production of ICT goods in the mentioned world regions. The metal ores used for digitalisation in Germany mainly come from China, Africa, South America, Oceania, and North and Central America. Non-metallic minerals

Figure 9

Raw material consumption of the digital transformation in Germany in the year 2020 ($RMC_{Dig.}$) by raw material groups, geographical origin und uses



Source: Own calculations

are also extracted to a large extent in Germany and other European regions.

Uses: The domestic final demand for digitalisation-relevant goods and services[4] in 2020 resulted in a total raw material consumption of more than 52.1 million tonnes. This corresponds to a share of approximately 55 % of the total $RMC_{Dig.}$ and a share of 3.1 % of the total economic RMC in 2020. The share of total intermediate demand[5] in German $RMC_{Dig.}$ amounted to around 43.3 million tonnes in 2020. With 20 million tonnes, the share of intermediate demand for the production of data processing equipment was almost equal to that of investment demand (21.7 million tonnes).

Putting the results of the macroeconomic analysis into context

The meso- and macro-level analyses of the DigitalRessourcen research project enabled **the first comprehensive global assessment** of the material and CO_2 intensity of the digital transformation in Germany. Previously, there were hardly any similar studies or calculations on this topic.

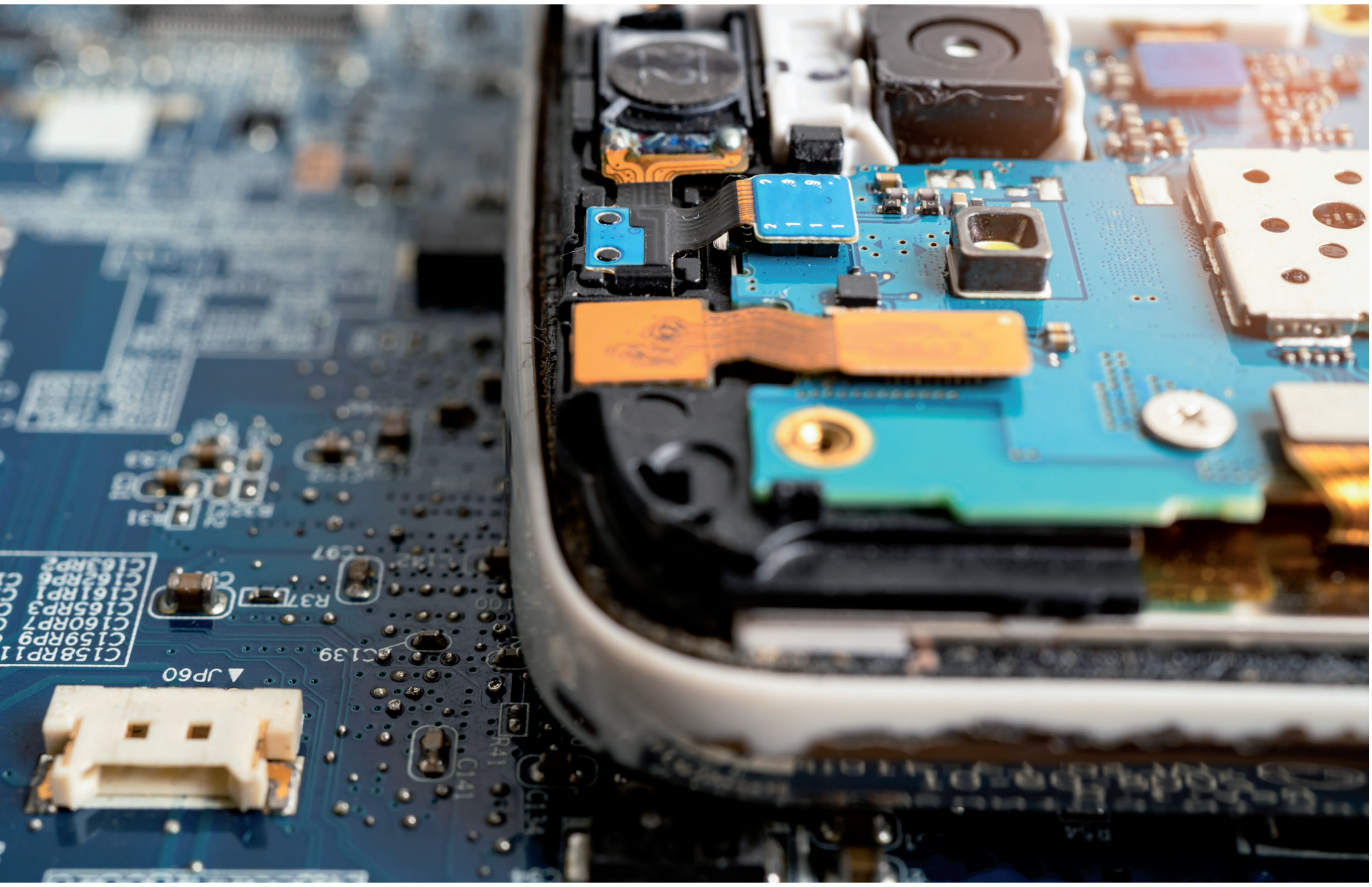
The **UBA Resources Report** 2022 (Lutter et al. 2022) estimated the raw material consumption of German digitalisation (consumption of raw materials for ICT-related commodity groups and services). However, the work in the present DigitalRessourcen project uses a much broader conceptual understanding of the system of digitalisation and utilizes a different empirical method. Therefore, a direct comparison of the results is not possible. This applies to both the absolute values of the macroeconomic indicators RMC and RMI, as well as the results of the sub-indicators $RMC_{Dig.}$ and $RMI_{Dig.}$ However, it is interesting to note that Lutter et al. (2022) estimated the relative share of domestic ICT final demand in the total German RMC to be 3 % for the year 2019. These initial estimates are **almost**

4 In Figure 9 further subdivided into government consumption, investments, and private household consumption.
5 Figure 9 further subdivides the target sectors of information and communication services, public services, vehicle manufacturing, production of data processing equipment, business-related services, and other economic sectors.

identical to our own calculations for the RMC share of domestic ICT final demand (approximately 3.1 % in 2020).

The results from this research project show that the digital transformation in Germany between 2000 and 2020 contributed to increasing shares to macroeconomic environmental impacts. The **raw material consumption** of digitalisation in Germany increased **by about 8.5 %** during this period. While $RMC_{Dig.}$ accounted for approximately 4.3 % of the total German RMC in 2000, this share increased to 5.6 % by 2020. The **raw material input** of the German economy for ICT goods and services ($RMI_{Dig.}$) increased by **almost 13.5 %** from 2000 to 2020. In 2000, $RMI_{Dig.}$ still accounted for 4.7 % of the total German RMI; by 2020, it had increased to 4.9 %.

The **carbon footprint** of digitalisation in Germany showed a decline in absolute numbers between 2000 and 2020. However, the overall carbon footprint of the economy decreased more significantly during the same period. This results in a **long-term increase** in the share of digitalisation in Germany's total carbon footprint to **5.7 % in 2020**.



Source: amazing studio – stock.adobe.com

6 Resource intensity and CO_2 emissions: Modelling the digital transformation up to the year 2050

Computer-based modelling of potential future scenarios is an important part of applied sustainability research. Likewise, the global multi-regional input-output assessment approach developed in the research project can simulate the **raw material consumption and greenhouse gas emissions** of German digitalisation over future decades. For this purpose, the **GRAMOD model** was developed in the research project, which dynamically updates the data structures of the **GLORIA database** (Chapter 5).

According to the project assignment, possible future development paths (scenarios) of the defined "system of digitalisation" were to be quantitatively modelled and corresponding simulations were to be developed under the requirement of a resource-efficient and resource-intensive development.

The trend scenario until 2050

The assumptions regarding economic growth and population numbers in the world regions represented by GRAMOD were centrally specified in the trend scenario.

The trend scenario simulates significant progress in national climate policy with an extensive extrapolation of other historical development trends (development of aggregated final demand components compared to predetermined gross domestic product (GDP) growth rates, structural changes in final demand in individual thematic areas, future globalisation trends, and resulting macroeconomic changes in resource productivity). The assumed development of country-specific price-adjusted **GDP** per capita was taken from current long-term projections by the OECD (OECD.Stat, 2021).

The **population projections** are based on the World Population Prospects 2022 by the United Nations (United Nations Department of Economic and Social Affairs 2022). The UN projection assumes that the global population will increase to a total of 9.7 billion people by 2050. For Germany, a slight population decline is expected in the long term (around -5.1 % by 2050 compared to today). Despite this declining population projection, stable economic growth is expected for Germany in the long term.

The projected annual **growth rate** of gross domestic product (GDP) in the trend scenario for Germany averages approximately 0.8 %. However, this GDP growth is relatively low compared to the global GDP growth rates (which are slightly above 2.1% on average per year).

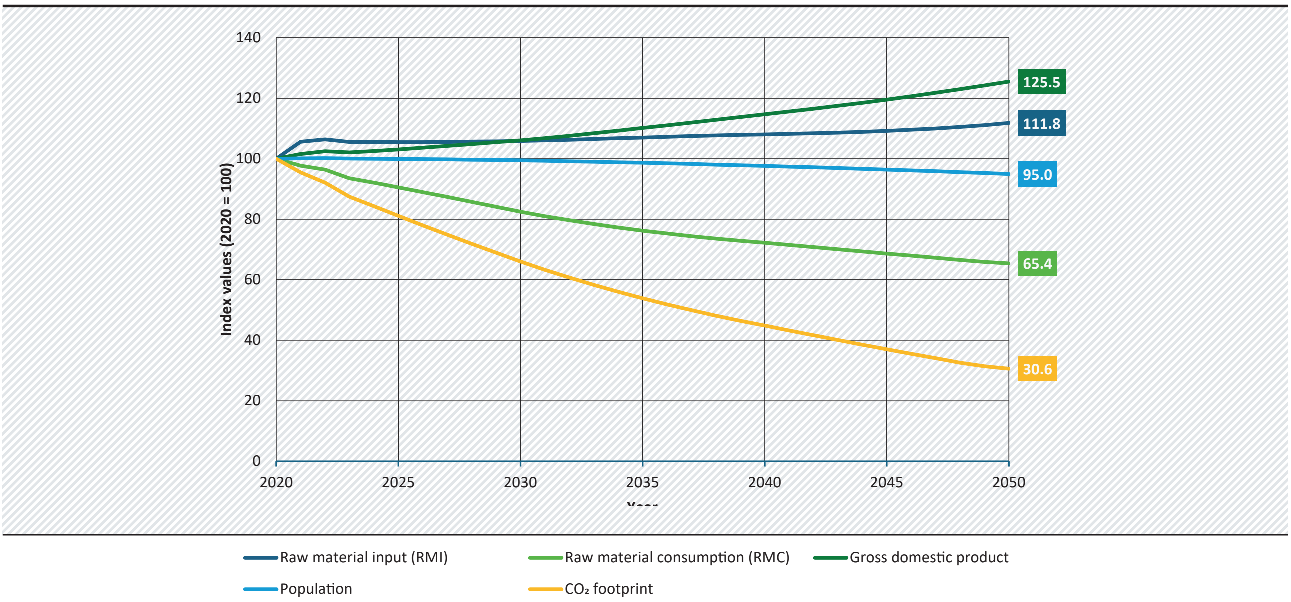
In addition, future environmental developments in other areas can be calculated by altering **pre-specified scenario parameters**. For the projected energy and climate policies the following assumptions were included: In the trend scenario for Germany, there is already a **comprehensive substitution** of fossil energy carriers by renewable energies in electricity generation, significant reduction in energy intensity in production, and an extensive decarbonisation of production (excluding electricity generation). Similarly, the global trend scenario also assumes long-term decarbonization trends. However, it is assumed that **other world regions**, compared to Germany, will need **longer periods** of time to achieve corresponding transformation progress. Therefore, global industrial CO_2 emissions are projected to continue rising until the mid-2030s.

Nevertheless, according to the calculations of the research project, the German **carbon footprint** is steadily declining in the trend scenario (Figure 10). Over the entire period from 2020 to 2050, there is an approximate **reduction of 70 %**.

The overall German **raw material consumption** (RMC) is also projected to decline in the long term. However, the decline between 2020 and 2030 is only one third of the original level (Figure 10). Thus, the raw material consumption (RMC) achieves an **absolute decoupling** from economic growth, similar to the **carbon footprint**. In contrast, the **raw material input** of the German economy (RMI = RMC + export demand) is only **relatively decoupled** from economic development in the long term. Between 2020 and 2050, the raw material input (RMI) increases by approximately 12 % (Figure 10).

Figure 10

Development of selected macroeconomic key indicators for Germany in the trend scenario from 2020 to 2050



Note: Key indicators are presented as index time series with the base year 2020 for better comparability.

Source: Own calculations

The different dynamics of the macroeconomic indicators RMI and RMC in the trend scenario can be explained by the differing socio-economic developments in Germany and the rest of the world. Since other world regions show stronger average economic growth compared to Germany, the simulation shows that export demand increases more dynamically than domestic final demand in Germany.

In terms of their composition, both macroeconomic material indicators show **qualitative consistency in the long term**: the share of fossil resources decreases significantly in the trend scenario by 2050 (the RMC of fossil raw materials by 64 %, the RMI of fossil raw materials by 39 % compared to 2020). The use of biotic materials also declines in the long term in the trend scenario (RMC: -46 %, RMI: -23 %). The primary raw material utilisation of metal ores and non-metallic minerals also decreases in the long term according to the RMC concept in the trend scenario (metal ores: -26 %, non-metallic minerals: -11 %). However, these main resource categories are the main drivers of the observed increase in the macroeconomic indicator RMI (metal ores: +31 %, non-metallic minerals: +48 %).

It should be noted that the trend projection does **not represent an economic forecast**. It is rather a plausible future development scenario that serves as a basis for assessing alternative development scenarios.

Six alternative future scenarios until 2050

The six alternative scenarios aim to depict the effects of key factors influencing the future development of digitalisation in Germany. In the simulations, several factors were varied as "key impact parameters" for an illustration of the impacts of alternative efficiency improvements in **production** as well as for alternative developments in **private households** consumption patterns.

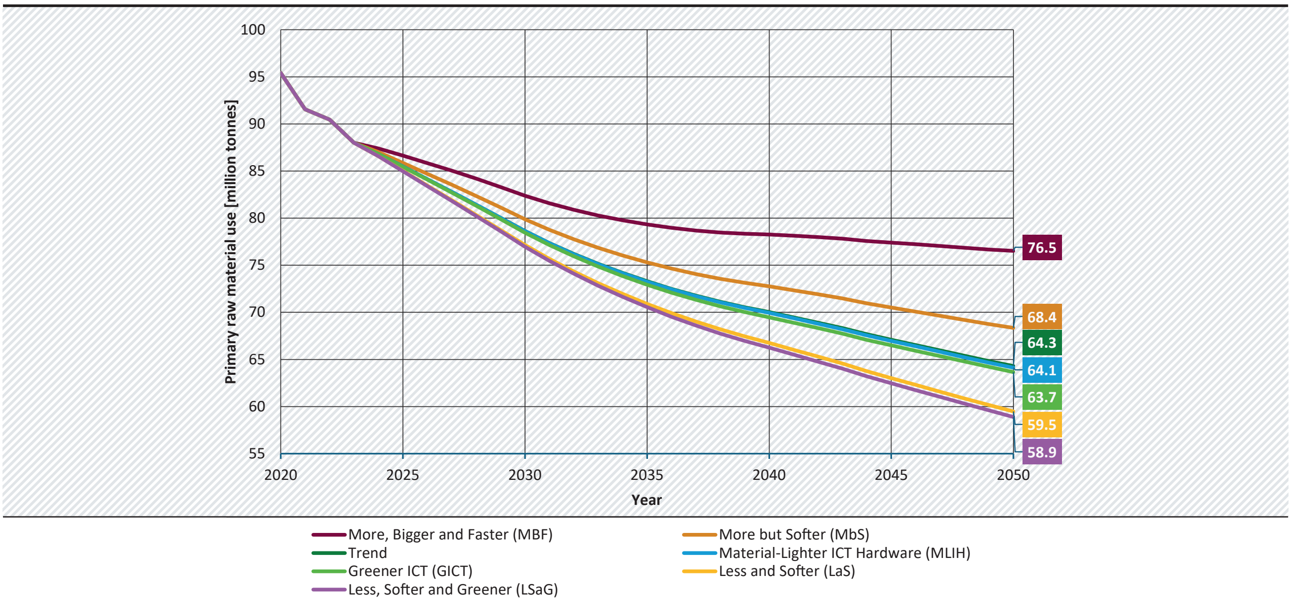
As a result, the research project developed **the following six alternative scenarios**:

1. **More, Bigger and Faster (MBF)**: Private households in Germany increase their demand for goods and services relevant to digitalisation by 50 % by 2050 compared to the trend scenario. Consumption focuses on the demand for ICT hardware. The share of ICT goods in total consumer demand for ICT goods and services will double by 2050 compared to the trend scenario.

2. **More but Softer (MbS)**: In this scenario, private households in Germany also increase their

Figure 11

Development of raw material consumption ($RMC_{Dig.}$) of digitalisation in Germany for different ambitious scenarios in the period 2020 to 2050



Source: Own calculations

demand for digitalisation-related goods and services by 50% compared to the trend scenario until 2050. However, this development is driven by the demand for ICT services: their share in the total consumption demand for ICT goods and services doubles compared to the trend scenario by 2050.

3. **Less and Softer (LaS)**: In this scenario, private households in Germany reduce their demand for goods and services relevant to digitalisation by 20 % by 2050 compared to the trend scenario. As in the "More but Softer" scenario, structural changes in demand towards a less resource-intensive demand are assumed. The share of ICT services in total consumer demand for ICT goods and services doubles by 2050 compared to the trend scenario.

4. **Material-Lighter ICT Hardware (MLIH)**: This scenario is used to illustrate the effects of efficiency improvements in the domestic production of ICT goods. It is assumed that domestic producers of ICT goods will be able to reduce their material inputs by 7.5 % by 2050 compared to the trend projection.

5. **Greener ICT (GICT)**: This scenario also serves to illustrate the effects of efficiency improvements in domestic production. However, this time it is assumed that domestic producers of ICT goods and services will be able to reduce their material inputs by 7.5 % by 2050 compared to the trend projection. In addition, it is assumed that the producers of ICT goods and services in Germany can also realize additional energy saving potential by 2050. Compared to the trend projection, a 15 % reduction in producers' energy demand is assumed by 2050.

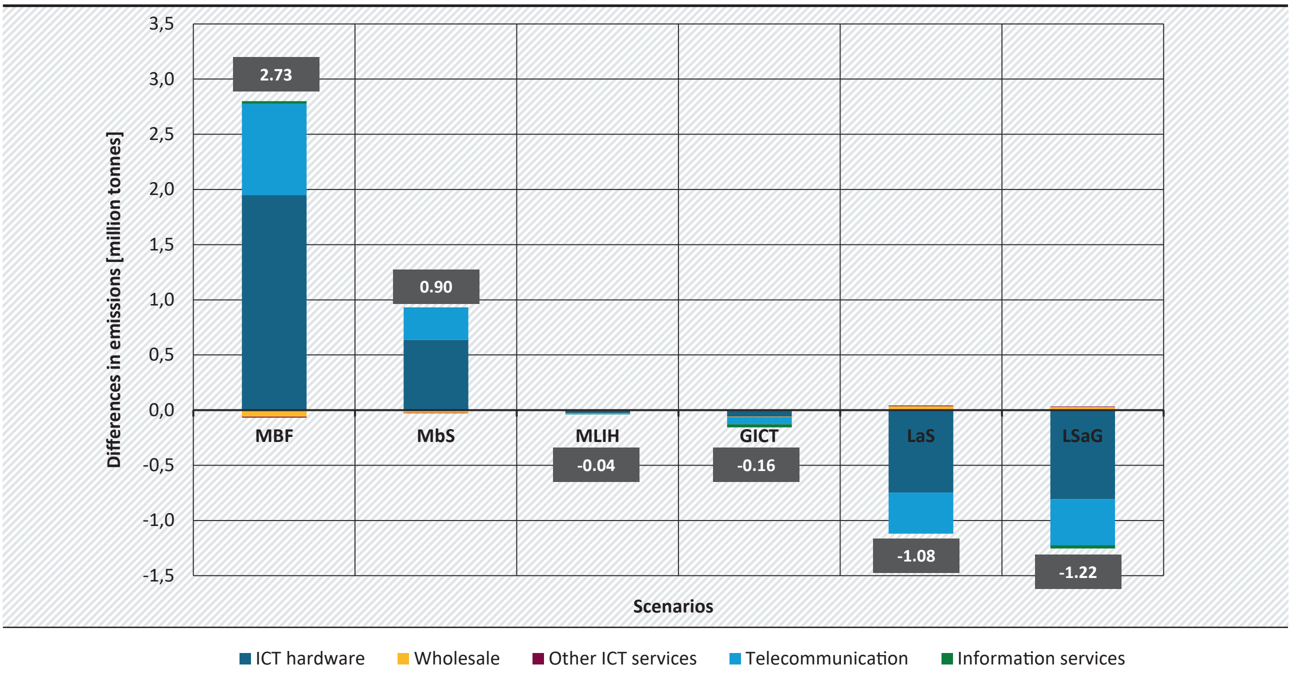
6. **Less, Softer and Greener (LSaG)**: This scenario considers the combined effects of efficiency improvements in production and demand and consumption developments of private households. For this purpose, the scenario settings for "3. Less and Softer" are combined with those of the scenario "5. Greener ICT".

The **raw material consumption** ($RMC_{Dig.}$) of digitalisation in Germany develops in parallel in all considered scenarios until 2024 (Figure 11).

From 2024 onwards, they develop separately, while the scenarios "Trend", "Material-Lighter ICT Hardware", and "Greener ICT" develop very similarly,

Figure 12

$CO_{2, Dig.}$ footprint of digitalisation in Germany, differences in scenario results compared to the trend scenario for the year 2050



MBF (More, Bigger and Faster). MbS (More but Softer). MLIH (Material-Lighter ICT Hardware). GICT (Greener ICT). LaS (Less and Softer). LSaG (Less, Softer and Greener).

Source: Own calculations

likewise the scenarios “Less and Softer” and “Less, Softer and Greener”.

The use of primary raw materials decreases over the entire period shown, starting from around 95 million tonnes. In the “Less, Softer and Greener” scenario with the strongest decrease, it is less than 59 million tonnes by 2050. The “More, Bigger and Faster” scenario is characterised by the highest usage of primary raw materials. The difference between this scenario and the “Less, Softer and Greener” scenario amounts to approximately 17.6 million tonnes in 2050. This corresponds to an increase of about 30 %. The two “More” scenarios are above the trend from 2024 onwards, and the two “Less” scenarios are below. The development of the raw material consumption of digitalisation ($RMC_{Dig.}$) in Germany in the “Material-Lighter ICT Hardware” scenario is not visibly different from the development projected in the trend scenario. In the “Greener ICT” scenario, the raw material consumption of digitization in Germany is marginally reduced compared to the trend scenario. In 2050, this is 1% less than the reference value of the trend scenario.

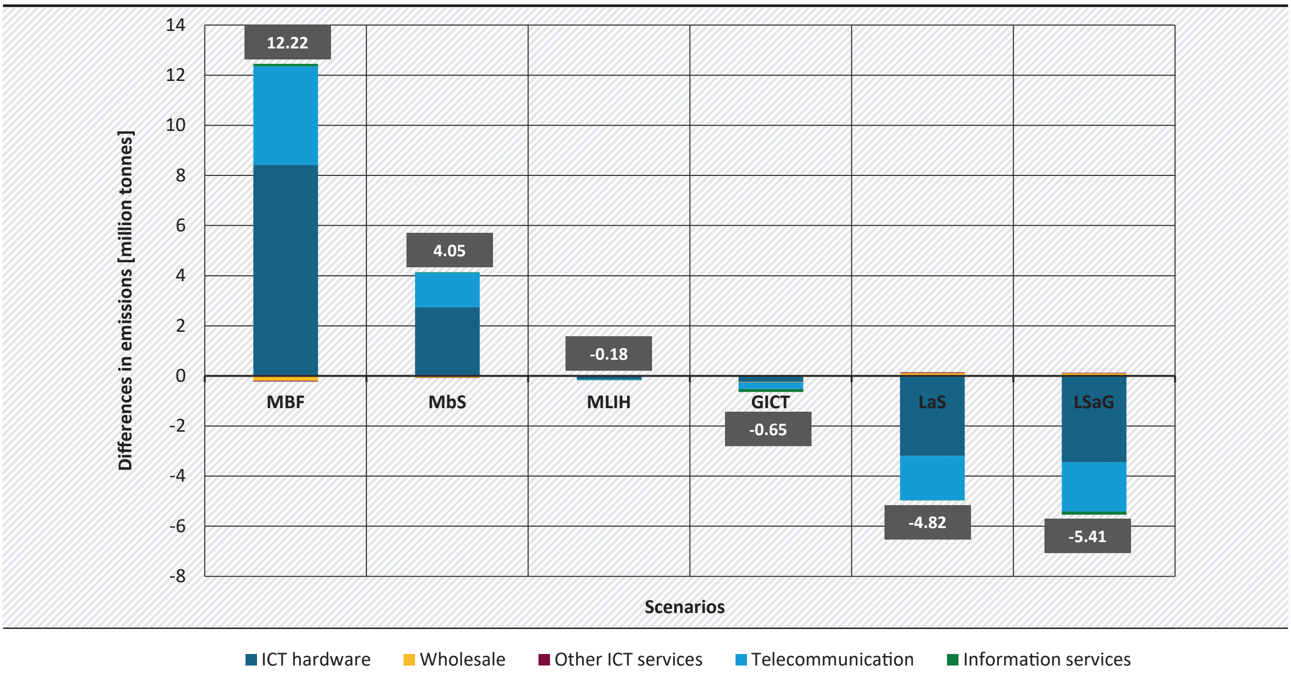
Concerning the **$RMI_{Dig.}$** (not shown in Figure 11, for details see (Abraham et al. 2023a)), all scenarios also develop almost identically up to 2024. From 2024 onwards, they continue to develop separately. Over the entire period shown, the usage of primary raw materials increases. It starts at about 157 million tonnes in 2020 and increases to around 170 million tonnes by 2050 in the “More, Bigger and Faster” scenario with the strongest increase.”

According to the research project, the **carbon footprint** of German digitalisation shows a **decrease** in all scenarios over the entire period presented (until 2050). It amounts to just under 43 million tonnes in 2025 and decreases to around 14 million tonnes in 2050 in the “Less, Softer and Greener” scenario with the strongest decrease.

The “More, Bigger and Faster” scenario is characterised by the highest $CO_{2, Dig.}$ emissions overall (Figure 12). The difference between this scenario and “Less, Softer and Greener” amounts to around 4 million tonnes in 2050. Here, the ICT hardware product group causes the most deviations from the trend scenario in 2050. This is followed by the telecommunications product group, while the other

Figure 13

Raw material consumption ($RMC_{Dig.}$) of digitalisation in Germany - differences of scenarios compared to the trend scenario by product groups



MBF (More, Bigger and Faster). MbS (More but Softer). MLIH (Material-Lighter ICT Hardware). GICT (Greener ICT). LaS (Less and Softer). LSaG (Less, Softer and Greener).

Source: Own calculations

groups are of minor importance. At the same time, it can be seen that the changes in wholesale and other ICT services slightly weaken the overall effect for scenarios with significantly higher as well as lower CO_2 emissions.

A comparison of the raw material consumption ($RMC_{Dig.}$) of German digitalisation by the **five** product groups across all scenarios shows an **increase** in the differences during the simulation period. The **ICT hardware** group is particularly significant: among all product groups, it differs the most from the trend scenario (Figure 13). However, **telecommunication services** also show significant deviations. The highest deviations occur in the “More, Bigger and Faster” scenario, and the lowest deviations occur in the “Material-Lighter ICT Hardware” scenario. The two “More” scenarios are in the positive range, while the others are in the negative range. In the case of the ICT hardware group, the **difference** is over 7.5 million tonnes in 2050. Negligibly smaller differences are simulated for the other product groups.

The efficiency improvements in Germany simulated in the scenarios “Material-Lighter ICT Hardware” and “Greener ICT” only slightly reduce the resource intensity and the $CO_{2,\ Dig.}$ emissions. This is in contrast to the other scenarios that simulate the consequences of alternative demand and consumption trends of private households. This is due to the fact that ICT hardware, which is particularly resource- and CO_2-intensive, is **mostly imported from abroad**.

Summary - modelling digital change up to the year 2050

Using the GRAMOD model developed in this project, future macroeconomic development paths of the system of digitalisation in Germany were modelled.

The basis for these assessments is a **trend scenario**. This scenario, based on the assumptions of global population growth and global economic growth, concludes that the production level of ICT goods and services will double worldwide from 2020 to 2050. For Germany, this results in weak but stable long-term economic growth with a simultaneous **absolute decoupling** from global CO_2 emissions and global raw material consumption (RMC). The trend scenario is characterised by ambitious advancements in national climate policy. The overall economic carbon footprint decreases by almost 70 % over the considered period, and the overall raw material consumption (RMC) decreases by **about one-third**. In the trend scenario for Germany, the $CO_{2, Dig.}$ footprint and the raw material consumption $RMC_{Dig.}$ also **decline in the long term**. In contrast, the raw material input $RMI_{Dig.}$ in the German economy increases slightly by 1.25 % between 2020 and 2050 in the trend scenario.

In addition to the trend scenario, **six alternative future scenarios** were examined. These scenarios varied two **key scenario parameters**: efficiency improvements in the production of ICT goods and the development of demand and consumer behaviour of private households. These alternative future scenarios show the range of possible global resource consumption due to digitalisation in Germany.

The “More, Bigger and Faster” scenario assumes a more dynamic private demand, particularly focusing on ICT hardware. Compared to the trend development, this scenario projects an **increase** in raw material consumption ($RMC_{Dig.}$) of about 19 % by 2050. It simulates deviations of 15 to 20 percent for the individual main raw material groups compared to the trend scenario. Due to the assumed increases in final domestic demand, this scenario also leads to an increase in raw material input ($RMI_{Dig.}$) in comparison to the trend scenario. In 2050, the $RMI_{Dig.}$ in the “More, Bigger and Faster” scenario exceeds the reference value of the trend scenario by 7.8 %.

On the other hand, the “Less, Softer and Greener” scenario assumes a **declining** final domestic demand for goods and services relevant for digitalisation and a more efficient production of these goods and services in Germany. In this scenario, both raw material consumption ($RMC_{Dig.}$) and raw material input ($RMI_{Dig.}$) in Germany **decrease** compared to the trend scenario: Raw material consumption ($RMC_{Dig.}$) deviates by -8.4 % from the trend scenario in 2050, and raw material input ($RMI_{Dig.}$) deviates by -3.7 %.

The carbon footprint of digitalisation varies in orders of magnitude comparable to those of raw material consumption ($RMC_{Dig.}$) (+18.2 % in the “More, Bigger and Faster” scenario, 8.1 % in the “Less, Softer and Greener” scenario; both compared to the 2050 reference).

Both alternative scenarios mentioned above assume significant variations in private demand (+50 % in the “More, Bigger and Faster” scenario, -20 % in the “Less, Softer and Greener” scenario; both compared to the 2050 reference). At the same time, the results **clearly indicate** that the analysed footprint indicators will be driven particularly by the **demand for intermediate goods** of the German economic sectors in the future. In Chapter 5, it was shown with regard to the past development of raw material consumption that the influence of intermediate demand has already changed much more dynamically in the past compared to the effects of domestic final demand.

As the DigitalRessourcen project **did not develop any specific scenarios** for future production-side demand for goods and services for digitalisation, corresponding research activities remain reserved for **future projects**. Ideally, anticipated production structures should be derived for selected production areas (such as agriculture, the automotive industry or healthcare services) and then parameterised in detail in the input-output structures of the GRAMOD model.

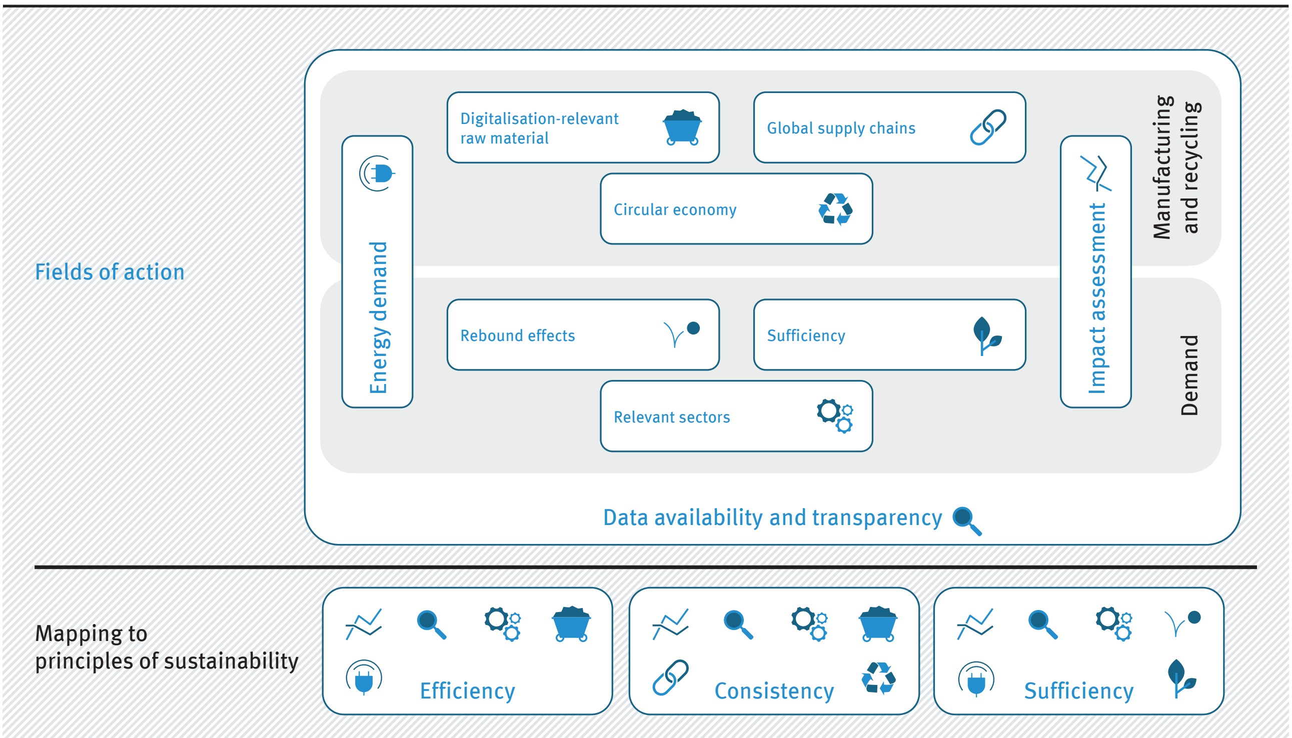
7 Fields of action for more sustainable digitalisation

Digitalisation is a complex system in which various subsystems (involved sectors, technologies, used devices, ...) are interconnected and influencing each other (Chapter 3). The investigations in the present research project DigitalRessourcen on the resource intensity of digitalisation at the micro-level (Chapter 4) and macro-level (Chapters 5–6) show: The complex system of digitalisation is associated with high resource requirements and a high level of greenhouse gas emissions in many areas, both now and in the future.

The research project aimed to identify options for a sustainable design of digitalisation. For this purpose, nine overarching fields of actions were derived and described, offering potential for reducing resource demands and environmental impacts (Figure 14). These fields of action refer to the entire life cycle of ICT goods and services. This includes their manufacturing, demand, use, and recycling. The "data availability and transparency" field of action serves as a cross-sectional field, as it influences all other fields of action. The fields of action address the implementation of **sustainability principles**, i.e., increasing efficiency, consistency, and sufficiency. For a sustainable design of digitalisation, a comprehensive transformation is required. Moreover, support from various stakeholders in politics, business, society, and science is necessary. The research project identified exemplary measures for policymakers, businesses, consumers, and researchers for each field of action. For instance, users can indirectly influence the efficiency of devices by preferring energy-efficient ones. Consistency can be improved by using renewable energy throughout the life cycle of products. Sufficiency impacts the demand for devices and services and can be directly influenced by critically questioning the need. Measures of one field of action can also impact other fields of action. For example, circular economy measures can influence supply chains. The following provides an overview of the **nine fields of action**.

Figure 14

Overview of potential fields of action for a sustainable digitalisation



Source: Own representation

The “**circular economy**” field of action aims to reduce consumption of raw materials and to use and recycle products and materials for a longer period of time. There is a high demand for ICT devices which in turn leads to an increased demand for raw materials. The short lifespan of ICT devices further intensifies the demand. Low collection and recycling rates stand in the way of circular use. A stringent implementation of principles of circular economy can contribute to a more sustainable design of digitalisation.

The production of ICT devices requires the use of **digitalisation-relevant raw materials**, which are globally available in limited quantities. Their extraction often occurs under inadequate social and ecological conditions, especially in countries such as the Congo, Rwanda, Brazil, and Nigeria. Within the research project, 27 resources particularly important for ICT device production were identified. Life cycle analyses highlighted Gallium, Tantalum, Gold, Silver, Tin, Nickel, Scandium, and Lithium as particularly relevant resources. The macroeconomic perspective identified precious metals, including Gold and Silver, as the most significant group within metal ores. Careful use of these digitalisation-relevant raw materials is necessary for the sustainable development of digitalisation.

Raw materials for the production of ICT devices are largely mined abroad. ICT devices are also produced abroad and ultimately reach consumers via long transport routes. The macroeconomic analysis in DigitalResourcen made it clear that digitalisation in Germany is heavily dependent on production processes in Asia that use significant amounts of fossil energy carriers. As part of the life cycle assessments in digital resources, the electricity mix used was identified as a crucial factor influencing the greenhouse gas emissions from digital services. An example of this is cryptocurrencies, where emission levels are highly dependent on the specific supply chain and operating locations. Transparency and international cooperation are needed to identify and reduce the environmental footprint along **supply chains**. This requires more environmentally friendly technologies and processes to make raw material extraction, manufacturing and provision of products and services more sustainable worldwide.

Increased design efficiency of digital devices and services can theoretically reduce the use of resources due to digitalisation and limit negative environmental impacts. However, efficiency gains often lead to increased consumption, potentially maintaining

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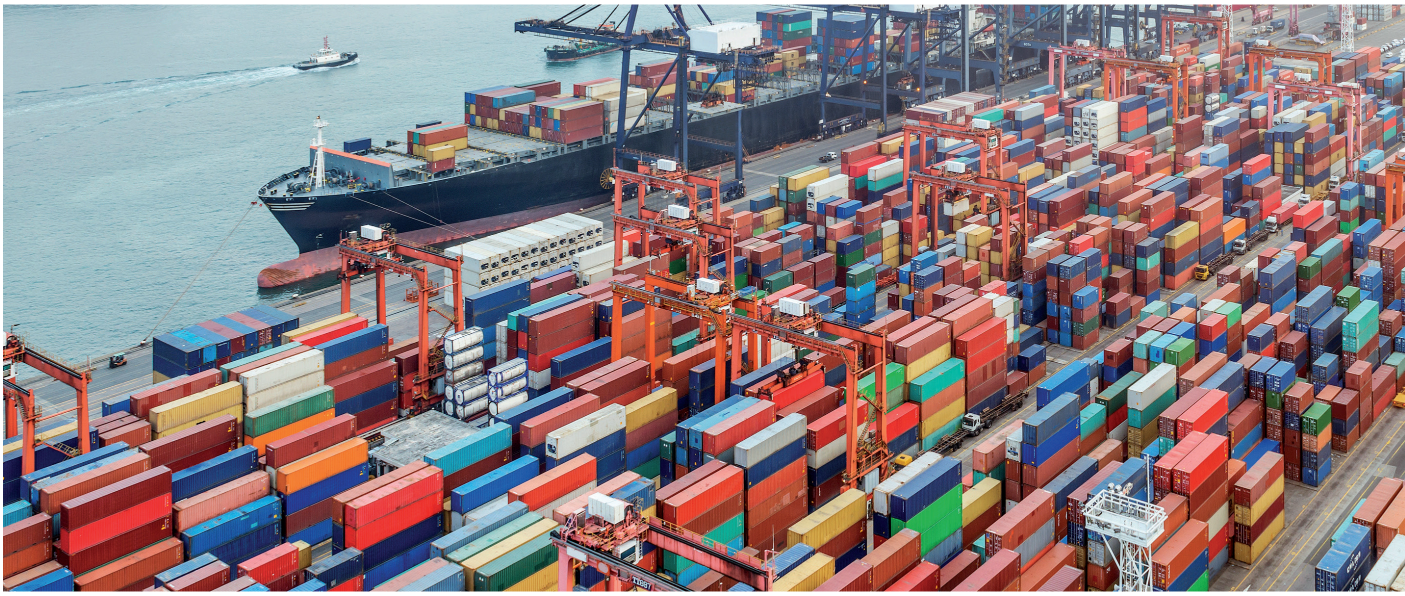

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or even increasing resource use (e.g., due to behavioural changes). Indeed, the case studies considered in DigitalRessourcen point to possible so-called rebound effects. For example, consumer-to-consumer platforms enable the purchase of second-hand goods in a more resource-efficient way, but there can be a concurrent increase in consumption due to the simple and cost-effective product access. The aim is to minimise **rebound effects** as much as possible and to create conditions for digital applications to yield real efficiency and sustainability effects.

Digitalisation has the potential to improve energy efficiency in various sectors of the economy ("Industry 4.0"). However, it in turn causes an increasing demand for energy. Particularly, ICT devices, data centres, and data transfer processes are the drivers of **energy demand**. The results of the life cycle analyses show that the predominant share of energy demand arises from the use of ICT devices and the operation of data centres. In a case study, it was shown that greenhouse gas emissions and the sustainability of a use case are strongly determined by the electricity mix used. The macroeconomic calculations showed that digitalisation is responsible for about 5.7 % of Germany's total greenhouse gas footprint. In order to make digitalisation more sustainable in the future, the energy requirements of devices and services and the accompanying infrastructure must be reduced on the one hand, and the share of renewable energies in the electricity mix must be increased on the other.

The "**relevant sectors**" field of action primarily draws on the results of macroeconomic analysis in this research project. Among the different product groups of the macroeconomic analysis, the product group "ICT hardware" has by far the largest resource requirements and carbon footprint. However, the term "ICT hardware" refers to very diverse economic activities, such as the construction of circuit boards or irradiation devices. This product group should be further analysed in additional analyses in order to identify relevant sub-areas and stakeholders. Looking at the demand side at the macroeconomic level, private households, exports, and economic investments as a whole account for almost half of the total demand. To identify relevant stakeholders from the economy, a further development of the calculation approach with the aim of a finer resolution of the demanding areas would be helpful.

ICT devices and digital services are currently in high demand and extensively used in our society. Digital technologies have a high degree of penetration. ICT devices usually have short useful lives and are replaced in short cycles. The research on the case studies in DigitalRessourcen showed useful lives of only two to four years for the ICT devices under consideration. More sustainable consumption and purchasing behaviour in terms of **sufficiency** could reduce the demand for raw materials and energy and associated greenhouse gas emissions. For example, the "private sufficiency scenario" calculated in DigitalRessourcen showed a decrease in the use of raw materials and a corresponding potential for saving resources.

Understanding the extent and impacts of the resource intensity of digitalisation is challenging: Information and environmental data for ICT devices and services are uncertain, inconsistent, or non-existent. However, only if the extent and effects are known and measurable, can the corresponding products and applications be designed more sustainably, and consumers can be supported in their purchasing and usage decisions. The cross-sectional field "**data availability and transparency**" calls for a standardization of calculation and evaluation methods as well as the improvement of the data situation and the publication and provision of this information. The field of action is considered a cross-sectional field because it affects all areas of digitalisation and all identified fields of action, and they would benefit from it.

Digital trends are often advertised as sustainable, but they themselves have a high environmental footprint. In order to understand the environmental impact of digital applications and to take measures to reduce the ecological footprint, more **comprehensive impact assessments** are needed in all areas of digitalisation. Systematic monitoring by various stakeholders would help to keep track of the progress and effects of digitalisation and to identify options for a more sustainable design.

Addressing the topics picked up in the fields of action requires **collaboration among many stakeholders** from politics, business, research, and civil society. A simple example from the "energy demand" design field will serve to illustrate this: In order to improve the energy efficiency of data centres, policymakers could set framework conditions under which energy-efficient data centres are promoted, and companies could provide data on the energy needs of data centres. Research could support the development of standards and solutions for energy-efficient data centres and data provision. These options and information would enable consumers to incorporate the sustainability criterion of "energy efficiency" into their decisions by preferring services that use energy-efficient data centres.

The next step should be a prioritization of the fields of action and a joint development of concrete solutions for a more sustainable design of digitalisation by all relevant stakeholders.

Source: vegefox.com – stock.adobe.com

8 Further research needs

Based on the analyses and work in the research department described above, overarching research needs for a sustainable design of digitalisation were identified.

Resource efficiency and circular economy approaches: A key research need is the development of resource-efficient ICT device components and the identification of alternatives for critical raw materials. This requires interdisciplinary collaboration among engineers, material scientists, and environmental experts. Research projects should focus on developing sustainable materials and manufacturing techniques to reduce resource consumption in the production of ICT devices. Additionally, promoting technologies for longer device lifespans is crucial, achievable through reparability, modular designs, and upgrade options. Circular use of digital devices and services is a key factor for resource savings. To make significant progress, research activities in this area should also concentrate on efficient resource use and recycling of digital devices. Specialised studies for different product groups, sectors, and recycling possibilities would be particularly meaningful. A digital product passport that transparently records the environmental impact of the devices can be an important driver in this regard.

Identification of recycling potentials: In order to holistically evaluate possibilities for substituting primary raw materials with secondary raw materials, an estimation of the maximum amounts of secondary raw materials that can be used through recycling must be carried out. In the present project, corresponding estimates were not available.

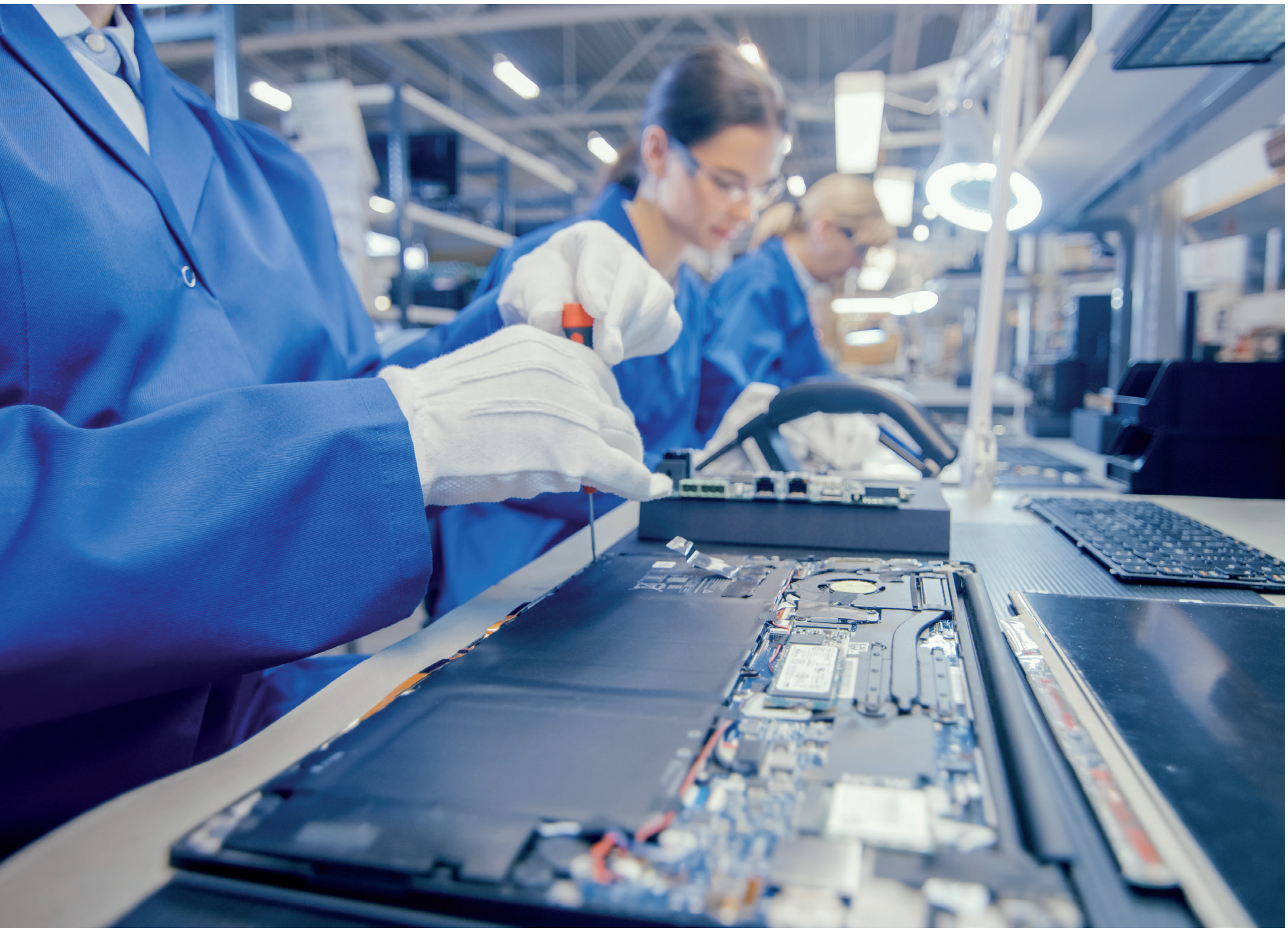
Energy efficiency and renewable energies: This research project clearly demonstrates that digitalisation is a key driver of global energy consumption. It is necessary to approach this issue consciously and to explore innovative technologies and strategies to minimize the energy consumption of ICT products. These include efficient data centres, intelligent energy management systems, and the integration of renewable energy sources into digital operations. Research in this area can help to significantly reduce the environmental footprint of digital infrastructure.

Sustainable supply chains and procurement: Establishing sustainable supply chains for digital devices and services requires further research efforts to optimize transportation and logistics solutions. This can help reduce the carbon footprint of digitalisation. In addition, sustainability criteria should be integrated into procurement processes to ensure that ICT products are manufactured and distributed in an environmentally friendly manner. In this context, research into barriers and incentives for sustainable procurement as well as the analysis of social impacts are important aspects that have not yet been sufficiently examined.

Education, awareness, and rebound effects: The potential of understanding and sensitisation of possible environmental impacts of digitalisation should not be underestimated. Accordingly, research should not solely focus on technological aspects. Instead, it must also develop educational programs to educate people about the importance of resource efficiency and sustainable use of digital technologies. This could help promote behavioural change at the individual and organisational levels. This also includes the analysis of rebound effects, where the use of resource efficiency technologies can lead to a paradoxical increase in consumption. Understanding user behaviour towards digital offerings is essential to minimise undesirable effects, such as an increased energy consumption. This necessitates interdisciplinary studies that combine behavioural economics, social sciences, and technology integration.

Foresight approaches: The integration of foresight approaches to anticipate future developments should be used more frequently but should also be supported by research efforts. This enables a forward-looking perspective that can be integrated into the planning of activities in order to actively shape change and prepare for future challenges. As a result, long-term studies are required, e.g. to monitor the resource consumption of digital technologies, in order to uncover or validate trends and developments in a meaningful way.

Independent scenario processes: With the GRAMOD model, an independent evaluation approach was developed in the project, which enables a simulation of



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alternative future developments in various transformation areas. So far, this approach has not yet been used to parameterize detailed sectoral development scenarios (e.g., future use of products relevant for digitalisation by company-related service providers, in vehicle manufacturing, or in other economic sectors). Corresponding parameterizations should therefore be derived in the future in joint scenario processes in exchange with sectoral stakeholders.

The research needs described extend across **various disciplines**, from engineering and social sciences to economics and environmental protection. Therefore, promoting interdisciplinary research and forming partnerships play a crucial role. A key instrument in this regard could be stakeholder dialogue, bringing together various stakeholders from politics, business, science, industry, environmental protection, and standardisation to define common goals, develop solutions, and create framework conditions. Such a dialogue could form the basis for a common understanding of the need for action and options for action. Involving stakeholders with a wide range of expertise would enable well-founded and innovative solution approaches. Such a **stakeholder dialogue** could help to identify different priorities and concerns among the involved parties and to address possible conflicts at an early stage.

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