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The trade-offs between digitalisation and climate action: Why digitalisation must be sustainable

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Digitalisation is a double-edged sword when it comes to climate action. On the one hand, digital technologies play an important role in the energy, transport and heating transition – for example in improving the integration of weather dependent renewable power into the electricity market or in leveraging energy efficiency potentials through the use of smart measuring, monitoring and control technology. On the other hand, growing digitalisation itself is causing higher energy and resource consumption and, hence, greenhouse gas (GHG) emissions. This is the key finding of a study conducted on behalf of KfW Research, in which the Öko-Institut (Institute for Applied Ecology) and the Institute for Futures Studies and Technology Assessment (IZT) analysed in detail the reciprocal effects between the two megatrends of digitalisation and climate neutrality. The research consortium estimates that 8 to 9% of total electricity consumption in Germany currently stems from the use of information and communication technologies (ICT). Greenhouse gas emissions from digitalisation in Germany are currently estimated to be at least 34 million tonnes of CO_{2e} annually. In addition to emissions from the use of ICT, these estimates also include emissions from the manufacture of digital devices and infrastructure. In purely arithmetic terms, this represents a good 4% of all current GHG emissions in Germany.

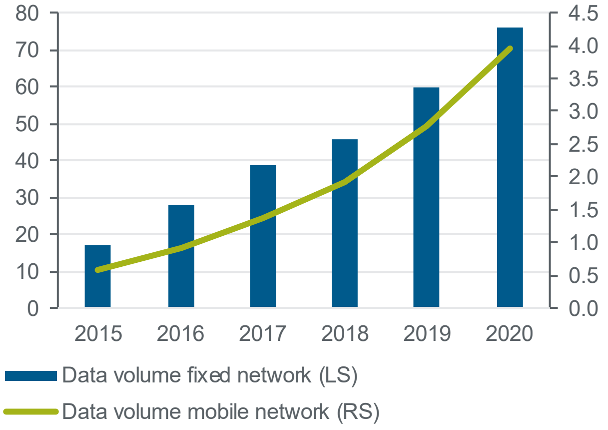
Successful digital transformation in the economy is of enormous importance for Germany's future competitiveness and for opening up new growth areas. At the same time, Germany is to become climate-neutral by 2045. The drive to digitalisation must therefore take climate change concerns into consideration right from the start. This requires policy guidelines, both for harnessing the opportunities of digitalisation for climate action and for limiting harmful environmental effects. Important approaches to lowering digital GHG emissions include making ICT devices and computer centres more energy-efficient, extending the useful life of ICT devices, pushing ahead with the circular economy in ICT, developing efficient software and using electricity from renewables to power ICT infrastructure.

The megatrend of digitalisation …

Digitalisation is making inroads into nearly all areas of life and work and it is undisputed that the importance of digital technologies and business models will only continue to grow – also with a view to securing Germany's international competitiveness. The development is characterised by growing linkage of an increasingly greater number of digital devices and users, growing data volumes, the expanding use of artificial intelligence and increasing computing and storage capacities. The digital transformation in Germany is reflected in fast-growing data transfer volumes in fixed and mobile communication networks. According to the Bundesnetzagentur (Federal Network Agency), annual data transfer through broadband connections in fixed network more than quadrupled between 2015 and 2020 and even grew sevenfold in the mobile broadband network (Figure 1). In the course of the coronavirus pandemic, digital technologies in Germany experienced an additional surge in importance. Consumers changed their usage behaviour during the pandemic, leading to a sharp increase in data volume in the year 2020 (+27% in fixed and +44% in mobile networks) – primarily driven by the streaming of movies, online computer games, home working and video-conferencing.

Figure 1: Development of data volume in fixed and mobile networks

In billions of gigabytes



Source: Federal Network Agency (annual report 2020); data for Germany

… meets the megatrend of climate neutrality

Germany aims to become climate neutral by 2045, which means that no more net greenhouse gas (GHG) emissions are to be released into the atmosphere from then on. By the year 2030 Germany's GHG emissions are to be initially reduced by at least 65% against the 1990 baseline (status in 2020: -41%). Digital technologies are regarded as very important for the climate-friendly transformation of key areas of the economy and society such as energy supply, industry, transport and housing. At the same time, however, information and communication technology (ICT) itself is responsible for a growing share of energy and resource consumption around the world. It is estimated that between 1.8 and 3.2% of global GHG emissions in 2020 can be attributed to the production, use and disposal of digital devices and infrastructures (computer centres, telecommunications networks).[1] If ICT were a state, it would be fifth on the list of the world's largest emitters, just ahead of Japan.

Against this background, KfW Research commissioned a study with the Öko-Institut (Institute for Applied Ecology) and the Institute for Futures Studies and Technology Assessment (IZT) to analyse in detail the reciprocal effects between the two megatrends of digitalisation and climate neutrality. The study focuses on both the opportunities of digitalisation for achieving ambitious climate targets in Germany and the risks arising from the additional ICT-induced greenhouse gas emissions. It also examines possible ways in which GHG reduction potentials can be harnessed in information and communications technology. The key findings of this study are summarised in the following and complemented by KfW Research's own analyses.[2]

Digital technologies are an important building block in the energy, transport and heating transition

The study describes specific examples of the application of digital technologies for the energy, transport, building and manufacturing sectors that can have great potential for reducing GHG emissions. Virtual power plants, videoconferencing in work situations, the serial modernisation of buildings using digital technologies and measures for the automated flexibilisation of industrial electricity demand as a function of grid load are some of the examples analysed in greater detail (see info box).

Info box: Examples of digital applications with expected positive climate effects[3]

Virtual power plants (VP)

A virtual power plant is a pool of decentralised units in the electricity network that are coordinated using a common control system. The decentralised units can be electricity producers – such as biogas, wind power or photovoltaic systems –, electricity consumers or electricity storage units. The purpose of a VP is the combined sale of electricity and flexibility from the swarm of the aggregated units. This enables them to make an important contribution to integrating weather dependent renewable power into the electricity market and stabilising the electricity network. They also promote the integration of small decentralised units, allowing them to actively operate in the market. Germany already has providers of virtual power plants that link third-party units based on the Renewable Energy Sources Act and sell their electricity directly.

Videoconferencing in work situations

Videoconferencing can substitute long business trips and considerably help reduce GHG emissions. A sample calculation shows that replacing four (face-to-face) expert meetings per year with virtual conferences reduces the individual carbon footprint of conference participation by approx. 94% (from 88.6 to 5.6 kg CO_{2e}). The assumption was that participant drove 10 km by car to a railway station and travelled 300 km by train to attend the face-to-face events (one-way travel). The GHG reduction potentials would be even greater if a domestic flight were taken to attend the event instead of a train. The flight alone would emit a good half tonne of CO_{2e} per year.

Serial modernisation of buildings

Serial modernisation is a strategy in which energy systems in buildings are modernised by uniform planning, production and implementation processes and through the use of modern digital technologies. The modernisation is planned on the basis of a 3D scan of the building. The building elements – facade, roof and technical equipment – are then individually prefabricated using modular building industry techniques. Serial modernisation is expected to hold great cost-reduction potential, thereby making an important contribution to increasing the rate and depth of modernisation. The idea of serial modernisation was developed in the Netherlands, where it has already been carried out on some 5,000 buildings. In Germany a first pilot project was completed in Hameln in early 2021 as part of the energy modernisation of an apartment block.

Flexibilisation of industrial electricity demand (load management, demand side management)

Transitioning the electricity market to renewable energy requires not only a change in the supply of energy but also more flexible use that can respond within a certain range to the weather dependent supply of renewable energy in the market. The industrial sector is a relevant factor here. The chemical industry, for example, can make an important contribution to flexibility with appropriate grid-side incentives through targeted adjustment and control of electricity demand using digital technologies. Flexibility options that prove promising here are the hybridisation of heat generation (shift between electricity-based and natural gas-based heat generation), electrically heated thermal storage and the production/use of electricity-based synthetic fuel gases (such as green hydrogen). However, economic incentives have so far been too low for load management to be given greater significance in Germany.

The GHG reduction potential from digitalisation has not yet been comprehensively and consistently quantified. The range of potentials ascertained in the literature is broad owing to different assumptions and approach methods. Challenges and pitfalls include the definition of suitable reference scenarios and expectations of market penetration of the respective digital applications. Furthermore, studies rarely take into account rebound effects (additional consumption resulting from cost and time savings enabled by ICT) and induction effects (additional consumption resulting from increased options provided by digital technologies) that may reduce savings.[4] In addition, most case studies systematically select applications with positive GHG reduction potential and neglect those that have the potential to increase GHG emissions. These include digital applications with a focus on entertainment and comfort enhancement, for example.

Despite all methodological uncertainties, the existing potential studies make an important contribution to identifying digital technologies that are likely to play a major role in the transition to climate neutrality. A recently published study conducted on behalf of the digital association Bitkom identified the largest net GHG reduction potentials for Germany in the following digital applications based on the GHG footprint of the digital technologies used:[5]

- **Energy**: Crucial technologies in the energy sector include smart grids – intelligent electricity networks in which electricity generators, network operators, electricity consumers and storage components are interlinked using ICT, enabling them to share information about their current operational status, energy consumption and energy demand in real-time. This enables electricity grids to be managed and utilised more efficiently. It also enables decentralised renewable energy sources to be better integrated into the network. In addition, the digital monitoring of renewable energy systems such as wind farms is expected to provide major savings potential, which enables breakdowns to be prevented through anticipatory maintenance and capacity utilisation to be increased.

- **Transport**: Intelligent systems for optimising traffic flows and smart logistics systems that optimise freight routes and avoid empty trips using ICT are important levers for reducing GHG emissions in transport. Digital areas of application, such as sharing mobility, mobile working, the substitution of business trips with videoconferences and telemedicine, could make a critical contribution to reducing traffic load and thus fuel consumption.

- **Buildings**: In the area of smart home systems, the use of digital technologies for the automatic, demand-oriented control of heating technologies provides energy savings potential that can be harnessed in the short term. Digital solutions can also be applied in large office and commercial buildings to automatically control heating, ventilation, air conditioning and lighting in accordance with weather conditions, user behaviour or number of persons present.

- **Industry**: A promising technology in the industrial sector is production automation, in which facilities, machines, parts and their components are interconnected and processes are controlled independently (Industry 4.0, smart manufacturing). The more efficient management of production processes allows energy and material losses to be reduced. Furthermore, the use of digital twins holds significant potential for GHG reduction. A digital twin is a data-based virtual model of an existing physical industrial operation. It enables companies to test optimisation processes in advance in the digital space before they are introduced to the actual operation – thus saving energy and resources.

- **Agriculture**: The use of intelligent fertiliser spreaders with variable dosing quantity and precise preliminary analysis of soil characteristics, for example, could significantly reduce the use of energy-intensive fertilisers on fields.

Net GHG balances of digital technologies are not always clear: the example of home-based work

GHG emissions caused by commuting currently account for some 25% of total transport emissions in Germany.[6] Private motor vehicles continue to heavily dominate daily commutes. The change in occupational mobility is therefore a key building block of a successful transport and energy transition. In this context, mobile and home working is a subject of intense debate. The possibility of shifting work to the home using ICT can reduce daily commutes and cut transport-specific greenhouse gas emissions. However, in order to estimate the reduction potentials holistically, reductions in transport emissions enabled by mobile working must also be compared with opposite effects such as energy consumption from the use of ICT, heating and lighting at the home workplace.

Against this background, the Institute for Applied Ecology and the Institute for Futures Studies and Technology Assessment calculated the individual carbon footprint of two specific home working variants in order to draw conclusions on additional environmentally relevant expenses and possible leakage effects. The underlying assumptions for the calculations are summarised in Figure 2. In order to map the possible range of GHG emissions, the study assumed a minimal variant of ICT equipment at the home workplace (use of an existing laptop from the office plus additional monitor) and a fully equipped home workplace (additional desktop PC with monitor plus additional printer plus dedicated office room). The assumption for both variants is that the worker regularly exchanges data with the employer's computer centre or server room or uses other cloud services.

The annual carbon footprint of the fully equipped home workplace is four times higher than the variant with minimum ICT equipment without a dedicated office room. For the fully equipped home workplace the production of the digital devices as well as additional heating for the office room are the primary sources of additional GHG emissions. The comparison with the GHG emissions avoided by not driving to the workplace – assuming a distance of 10 km to the regular workplace – shows that mobile working is not a priori good for the climate. Whether and to what extent it actually causes lower GHG emissions than working at the regular workplace depends heavily on the ICT equipment used at the home workplace, the office room used and the means of transport being substituted. The more car trips to the regular workplace can be avoided in the long term, the higher the GHG reduction potential. However, if home working primarily substitutes short commutes undertaken with climate-friendly means of transport, working from home does not lead to a reduction in carbon emissions due to the additional energy consumption at the home workplace (rebound effect). The calculations are based on the assumption that no significant GHG reduction effects are to be expected at the regular workplace as office areas will continue to exist and be occupied in the short and medium term even when a high proportion of workers are at home. If parallel workplace infrastructures are eliminated, however, further GHG reduction potential can be realised in the long term.

Growing digitalisation itself leads to higher energy consumption …

Even if the use of digital technologies at first glance appears to be clean because it does not cause any visible emissions, it is by no means climate-neutral. Both the manufacturing and the use of digital devices, computer centres and data transmission networks consume energy and resources. There are no comprehensive analyses on the environmental impact of digitalisation in Germany in this area either. On the basis of a 2015 study which forecast the electricity demand of information and communication technology in Germany[7] and a Bitkom study (2020) on the global GHG emissions of digital technologies[8], the Institute for Applied Ecology and the Institute for Futures Studies and Technology Assessment estimated the current electricity consumption and GHG emissions caused by digitalisation in Germany. They estimated the annual electricity demand from the use of digital technologies in Germany to be approx. 45 to 50 TWh. That is a share of around 8 to 9% of total electricity consumption in Germany in the year 2019, the last year before the coronavirus pandemic, when it was 577 TWh[9]. This calculation includes not just electricity consumption from the use of digital devices in private households (including TV sets), at the workplace, in building supply and in public infrastructure but also consumption from the operation of computer centres and data transfer networks. A statistic recently published by the German Association of Energy and Water Industries shows that information and communication technology now accounts for a very high 27.3% of average electricity consumption of private households, well ahead of washing and drying, which accounts for a good 13%, and lighting, which consumes just under 13%.[10]

ICT-related electricity demand is expected to rise further over the coming decades as a result of a further increase in digital devices in private households and businesses as well as rising energy demand for computer centres and data transfer.[11] The primary drivers of growing electricity demand of computer centres and telecommunication networks are more intensive internet use from, among other things, the streaming of high-definition video, increasing use of artificial intelligence and the Internet of Things[12]. The interconnection of machines, vehicles, electrical appliances and building services systems significantly increases the number of network-capable objects, such as sensors, control elements and display systems, and network requirements increase merely through the connection of these objects, as the signalling needs in ICT infrastructure systems lead to data transfer relatively independently from specific usage.[13]

… and increasing GHG emissions

According to estimates by the Institute for Applied Ecology and the Institute for Futures Studies and Technology Assessment, annual GHG emissions from digitalisation in Germany currently stand at around 34 million tonnes of CO_{2e}. In addition to emissions from the use of ICT, these estimates also include emissions from the manufacture of digital devices and infrastructure.[14] In purely arithmetic terms, this corresponds to a good 4% of Germany's total GHG emissions in the year 2019. At the same time, much of the GHG emissions from the manufacture of ICT devices and ICT infrastructure is generated outside Germany. When interpreting this estimate it must also be taken into consideration that the literature data underlying the forecast electricity demand from the year 2015 is now deemed outdated given the dynamic development of the ICT sector, so that the estimate is more likely to underrepresent than overrepresent actual GHG emissions.

Figure 2: Home workplace – estimate of individual annual carbon footprint for two scenarios

Assumption	Scenario 1: Minimal ICT equipment	Scenario 2: Fully equipped home workplace
ICT set-up	Use of available laptop from work, use of router, additional monitor	Additional desktop PC with monitor, use of router, additional printer
ICT use	220 working days per year, 8 hours per working day, 4 GB data use per working day	
Lighting and heating of workplace	Not applicable (shared use of rooms, which are heated and lit anyway will)	Office with 12 m^2 space, lighting: 50 watt for 8 hours, heating requirements: 105 kWh_{th}/m^2a) – half of office use taken into account
Total GHG emissions (in kg CO_{2e} per year)	95.0	443.0
of which:		
production digital appliances	17.6	111.2
use digital appliances	52.7	138.1
use internet / data	24.7	24.7
lighting homeoffice	0.0	41.2
heating homeoffice	0.0	127.9

Comparison:

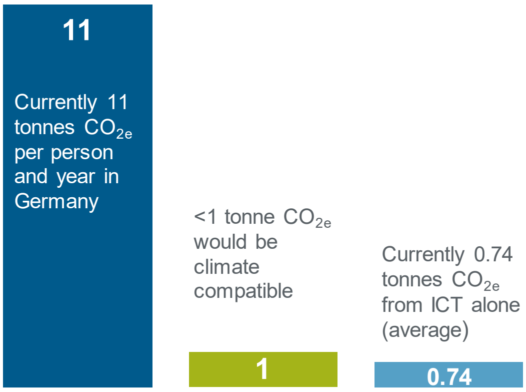
Avoided traffic-induced GHG emissions (10 km journey to workplace):

- Use car (single occupation): 647 kg CO_{2e}/a
- Use public transport: 304 kg CO_{2e}/a
- Use bicycle: 0 kg CO_{2e}/a

Source: Gensch et al. (2021): Deutschland auf dem Weg zur Klimaneutralität: Welche Chancen und Risiken ergeben sich durch die Digitalisierung? (*Germany on the way to climate neutrality: what opportunities and risks arise from digitalisation?* – our title translation, in German)

Another way to map the environmental impact of digital applications is to calculate the individual digital carbon footprint. For an assumed average private use of digital devices and services, current findings show a footprint of around 740 kg of CO_{2e} per person per year, which rises to around 1,050 kg of CO_{2e} per year with intensive use.[15] The scope of the study comprises both the manufacture and the use of digital devices and services (such as video or music streaming). In both usage profiles it is evident that the GHG emissions released in the manufacture of ICT devices are anything but negligible. They amount to between 50 and 60% of the digital carbon footprint. If we apply the results of the digital carbon footprint to the annual per-capita carbon emissions of currently around 11 tonnes of CO_{2e} in Germany, the shares range from 6.7 to 9.5%. With a view to the ambitious climate targets, these shares are problematic as they will tend to increase further as ICT devices become more widespread and their use intensifies. For comparison: In order to maintain global warming well below two degrees in accordance with the Paris Climate Agreement, it is estimated that each inhabitant of Germany will have to reduce their total annual GHG emissions to less than one tonne by 2050 (Figure 3).[16]

Figure 3: Carbon footprint of each German inhabitant



Source: Rendition by KfW Research on the basis of data from the Federal Environment Agency and the Institute for Applied Ecology

GHG reduction potentials in the digital sector must be systematically leveraged

Even if the calculated figures are only an estimate, their magnitude alone shows that significant efforts must still be undertaken both for digital devices and in data networks and computer centres in order to reduce greenhouse gas emissions. There is growing urgency to act. In order to be able to meet national and international climate targets, the digital sector – like all other economic areas – must be largely climate neutral by the middle of this century. Important approaches to harnessing GHG reduction potentials include:

- **Continued improvements to the energy efficiency of ICT devices, computer centres and telecommunication networks:** In digital devices, further energy reduction potentials can be leveraged, for example through technical optimisations and by making more intensive use of energy-efficient mobile devices such as notebooks, tablets and smart phones instead of desktop PCs. In the modernisation of existing and the construction of new computer centres, refrigeration, air conditioning, ventilation and waste heat utilisation are areas that hold great greenhouse gas reduction potentials. Furthermore, many computer centres are oversized and their capacity is therefore underutilised.[17] More demand-based planning and the use of modular components that can be added or expanded can make the operation of computer centres more efficient. With respect to telecommunication networks, fibreglass networks in broadband expansion provide greater energy efficiency than other transmission technologies. In mobile telecommunication, data transmission using modern 5G infrastructures is 20 times more efficient than in old 3G networks (UMTS) and three times more efficient than the current 4G mobile communication network (LTE).[18]

- **Extending the useful life of ICT devices:** The manufacture of ICT devices is very energy- and resource-intensive and pollutes the environment. The production phase of a notebook, for example, can create between 56 and 75% of its total greenhouse gas emissions. It is therefore a sound idea to use notebooks as long as possible and repair or upgrade them instead of purchasing new notebooks in short intervals. That means new and possibly more energy-efficient computer generations would go into operation at a later stage but the resulting additional GHG emissions would be more than offset by using the hardware for a longer period.[19]

- **Advancing the circular economy in the field of ICT:** Energy and resource savings can also be achieved through a resource-efficient and recycling-friendly design of ICT hardware. Many digital devices contain a high amount of valuable and scarce resources such as platinum group metals, rare earths and precious metals. The extraction and processing of these materials is often associated with significant energy and resource consumption and environmental contamination. [20] At the same time, securing adequate supplies of these technology metals, which are very important for many technologies of the future, is fraught with risks because existing deposits are concentrated in individual countries or companies. The circular management of such resources could make Germany more independent from imports while protecting the environment. In order to be able to harness this resource potential more effectively, however, greater incentives for recycling and innovative recycling processes will be necessary.

- **Development of efficient software:** To be sure, software products are immaterial goods but their use can trigger significant material and energy flows. Only in the past few years has the recognition grown that software characteristics decide what hardware capacity is required and how much electrical energy devices, networks and computer centres consume. In many cases, software design is also responsible for early replacement of supposedly low-performance hardware.[21]

- **Supplying ICT infrastructure with electricity generated from renewable energy:** The carbon footprint of digitalisation can also be reduced by using electricity from renewables. It must be taken into account that electrification will play a key role in decarbonising the transport, heating and manufacturing sectors and that electricity demand will therefore rise sharply in the coming decades. In order to be able to achieve a high share of renewables, existing limitations to land areas that can be used for their expansion make reductions in energy consumption and improvements in energy efficiency indispensable in all areas of the economy – also for cost reasons. Climate action strategies in the digital sector that are aimed exclusively at using renewables are therefore not sufficient.

Conclusion: we need policy guidelines for a sustainable orientation of the digital sector

With a view to the goal of climate neutrality, digitalisation is currently showing an ambivalent development. To be sure, digital technologies provide opportunities for achieving ambitious climate action targets in many sectors. But these opportunities also come with risks from growing energy and resource consumption and associated greenhouse gas emissions. These risks arise from the energy and resource requirements for the increasing production and use of ICT devices and ICT infrastructure but also from indirect effects resulting from rebound and induction effects. This applies in particular to digital applications that do not replace existing offerings but enable new consumption options that generate additional GHG emissions.

Successful digital transformation in the economy is of enormous importance for Germany's future competitiveness and for opening up new growth areas. At the same time, Germany is to become climate-neutral by 2045. The drive to digitalisation must therefore take climate change concerns into consideration right from the start. This requires effective and coherent policy guidelines, both for harnessing the opportunities of digitalisation for climate action and for limiting harmful environmental effects. Policy guidelines are necessary as market incentives have so far been limited. In order to provide a better basis for policy decisions, continuous monitoring of the environmental impacts of digitalisation and a comprehensive analysis of the greenhouse gas reduction potentials of digital technologies are to be welcomed.

In particular, existing tools for promoting green IT should be further developed and adapted to the innovative momentum of digital technologies in order to harness energy efficiency potentials in ICT. For example, it should be assessed whether the EU Eco Design Directive, which sets out minimum requirements for the environmentally sound design of energy-relevant products, could be expanded to further ICT applications and supplemented by resource efficiency aspects. Binding EU-wide regulations on the provision of software updates and repairability of devices would also be desirable in order to prolong the lifespan of ICT devices. In addition, accelerating the expansion of renewable energy is crucial for digitalisation in order to be able to cover the remaining electricity demand in ICT infrastructure in the long term in a climate-neutral manner. Along with targeted promotional measures, an effective carbon price can help to accelerate the market penetration of sustainable digital business models.

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[1] Cf. Bieser, J.; Hintemann, R.; Beucker, S. et al. (2020): Klimaschutz durch digitale Technologien – Chancen und Risiken (*Climate action through digital technologies – opportunities and risks* – our title translation, in German). Short study on behalf of Bitkom e. V.

[2] For the full study see: Gensch, C.; Degel, M.; Fritzsche, K. et al. (2021): Deutschland auf dem Weg zur Klimaneutralität: Welche Chancen und Risiken ergeben sich durch die Digitalisierung? (*Germany on the way to climate neutrality: what opportunities and risks arise from digitalisation* – our title translation, in German only), Institute for Applied Ecology and Institute for Futures Studies and Technology Assessment, on behalf of KfW.

[3] Cf. Gensch, C.; Degel, M.; Fritzsche, K. et al. (2021): loc. cit.

[4] The rebound effect means that savings achieved through efficiency improvements are partly or fully offset by additional consumption elsewhere. Example: More efficient engine management reduces the cost of kilometre travelled. As a result, many consumers use their car more often or purchase a larger one because of the lower fuel costs. The induction effect causes digital technologies to generate demand for things that would not exist without them. Example: E-commerce enables households to avoid shopping trips while inducing additional transport demand for distribution of goods from warehouses to households.

[5] Cf. accenture (2021): Klimaeffekte der Digitalisierung. (*Climate effects of digitalisation* – our title translation, in German only), study commissioned by Bitkom to assess the contribution of digital technologies to climate action.

[6] Schelewski, M.; Follmer, R.; Dickmann, C. (2020): CO2-Fußabdrücke im Alltagsverkehr. (*Carbon footprints in day-to-day transport* – our title translation, in German only), data evaluation on the basis of the study on mobility in Germany. Study on behalf of the Federal Environment Agency (texts 224/2020).

[7] Cf. Stobbe, L.; Hintemann, R.; Clausen, J. et al. (2015): Entwicklung des IKT-bedingten Strombedarfs in Deutschland. (*Development of ICT-related electricity demand in Germany* – our title translation, in German only), study commissioned by the Federal Ministry for Economic Affairs and Energy.

[8] Cf. Bieser, J.; Hintemann, R.; Beucker, S. et al. (2020): loc. cit.

[9] Cf. AG Energiebilanzen (2021): Energieverbrauch in Deutschland im Jahr 2020 (*Energy consumption in Germany in the year 2020*).

[10] Cf. German Association of Energy and Water Industries (2021): Konjunktur und Energieverbrauch (*Business cycle and energy consumption* – our title translation, in German only). Issue 04/2021.

[11] Cf. Sensfuß, F.; Lux, B.; Bernath, C. et al. (2021): Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. Kurzbericht: 3 Hauptszenarien (*Long-term scenarios for the transformation of the energy system in Germany 3. Short report: 3 main scenarios* – our title translation, in German only). Study on behalf of the Federal Ministry for Economic Affairs and Energy.

[12] The Internet of Things (IoT) connects physical objects with the virtual world. Intelligent devices and machines are connected with each other and with the internet (examples: smart home applications, self-driving vehicles).

[13] Cf. Stobbe, L.; Hintemann, R.; Clausen, J. et al. (2015): loc. cit.

[14] GHG emissions from manufacture are extrapolated to a year by dividing total emissions by the number of years of usage of the digital devices or infrastructure. In addition, the estimated emissions from manufacture include not just GHG emissions from energy consumption during manufacture itself but also those emissions associated with upstream resource extraction and material production.

[15] Cf. Gröger, J. (2020): Digitaler CO2-Fußabdruck. Datensammlung zur Abschätzung von Herstellungsaufwand, Energieverbrauch und Nutzung digitaler Endgeräte und Dienste (*Digital carbon footprint. Data collection for estimating manufacturing cost, energy consumption and use of digital devices and services* – our title translation, in German only). Study by the Institute for Applied Ecology on behalf of the Bund für Umwelt und Naturschutz e.V. (BUND).

[16] Cf. CO_2 calculator of the Federal Environment Agency. Available online at https://uba.co2-rechner.de/de_DE/.

[17] Cf. German Federal Environment Agency (2020): Energie- und Ressourceneffizienz digitaler Infrastrukturen. Ergebnisse des Forschungsprojekts "Green Cloud-Computing" (*Energy and resource efficiency of digital infrastructures. Findings of the research project 'Green Cloud Computing'* – our title translation, in German only).

[18] Cf. German Federal Environment Agency (2020): ibid.

[19] Cf. Prakash, S.; Liu, R.; Schischke, K. et al. (2011): Zeitlich optimierter Einsatz eines Notebooks unter ökologischen Gesichtspunkten (*Optimising the useful life of a notebook from an ecological perspective* – our title translation, in German only). Study on behalf of the Federal Environment Agency.

[20] Cf. Köhler, A. R.; Gröger, J.; Liu, R. (2018): Energie- und Ressourcenverbräuche der Digitalisierung (*Energy and resource consumption of digitalisation* – our title translation, in German only). Short report on behalf of the German Advisory Council on Global Change (WBGU).

[21] Cf. Gensch, C.; Degel, M.; Fritzsche, K. et al. (2021): loc. cit.