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Environmental effects along the life cycle of digital technologies

Johanna Pohl, Simon Hinterholzer

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Einstein Center Digital Future
Robert Koch Forum
Wilhelmstraße 67
10117 Berlin Germany

E-Mail: info@digital-future.berlin

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Environmental effects along the life cycle of digital technologies

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Johanna Pohl, Simon Hinterholzer

Abstract

The production, operation and disposal of digital technologies consumes energy and resources causing further environmental impacts such as GHG emissions, toxicity, abiotic depletion, and water depletion. There are a large number of studies that seek to determine these impacts. However, the results of some of these studies differ considerably due to inconsistent study design and assumptions on the future development of the electricity demand of data centres and communication networks. In this report, we analyse the results of selected studies in light of the way they were modelled, and identify environmentally relevant trends. Based on our analysis, we show which policy measures are needed to address the environmental challenges of digital technologies.

About the authors

Johanna Pohl is a researcher at Technische Universität Berlin and a fellow at Zurich Knowledge Center for Sustainable Development ZKSD. She investigates the environmental effects of ICT-based services and develops basic approaches for the sustainable design of hardware and software.

Simon Hinterholzer is researcher at the Borderstep Institute and investigates the effects of ICT on sustainability, especially in relation to climate change. His main focus lies on data centres' and data networks' energy demand and how this can be reduced.

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1 INTRODUCTION

The production, operation and disposal of digital technologies consumes energy and resources, impacting the environment through greenhouse gas (GHG) emissions, toxicity, abiotic depletion, and water depletion. The environmental effects of digital technologies are particularly substantial in terms of their electricity demand and global GHG emissions (Freitag et al., 2021).

The long-standing debate on the environmental impact of digitalisation can be divided into two strands: one dealing with the potential of digitalisation and the other with the environmental impact of the ICT sector itself. The text at hand focuses on the latter, i.e., the direct environmental effects resulting from the production, operation and disposal of digital technologies. There are a large number of studies that determine the environmental effects of digital technologies. However, the results of some of these studies differ considerably. These differences can be attributed to both inconsistent study design, e.g., regarding sector definitions or the different life cycle phases of digital equipment, and assumptions made regarding how the electricity demand of data centres and communication networks will develop. As a consequence, the informative value or comparability of some studies might be limited.

In this report, we analyse the results of selected studies in light of how they were modelled and identify environmentally relevant trends. To do so, we first provide a definition of the areas of the ICT sector before providing an overview of the environmental effects of ICT for three subsectors: end user devices, data centres and communication networks, as well as for the ICT sector as a whole. Based on our analysis, we show which policy measures are needed to address the environmental challenges of ICT.

2 DEFINITION OF THE ICT SECTOR

The ICT sector is usually divided into three subsectors: end-user devices, data centres and network infrastructure (see Figure 1, Table 1).

The category of **end-user devices** includes devices that use microelectronics to collect, process, store or transmit data. These can be traditional digital devices such as desktop computers, laptops, tablets and smartphones, but also printers, audio and video devices or ICT in public spaces such as ATMs, ticket machines or security cameras. Besides the traditional network-connected devices, there is a growing number of Internet of Things (IoT) devices. The IoT comprises several technologies that create a link between physical objects and the virtual world. This allows devices, machines, interfaces and sensors to communicate with each other and creates new opportunities for digital transformation. Communication is possible in areas such as home, industry, automotive, energy or healthcare. Particularly in the case of consumer electronics equipment and television sets, the definition of the subsector of end-user devices is not consistent throughout existing studies.

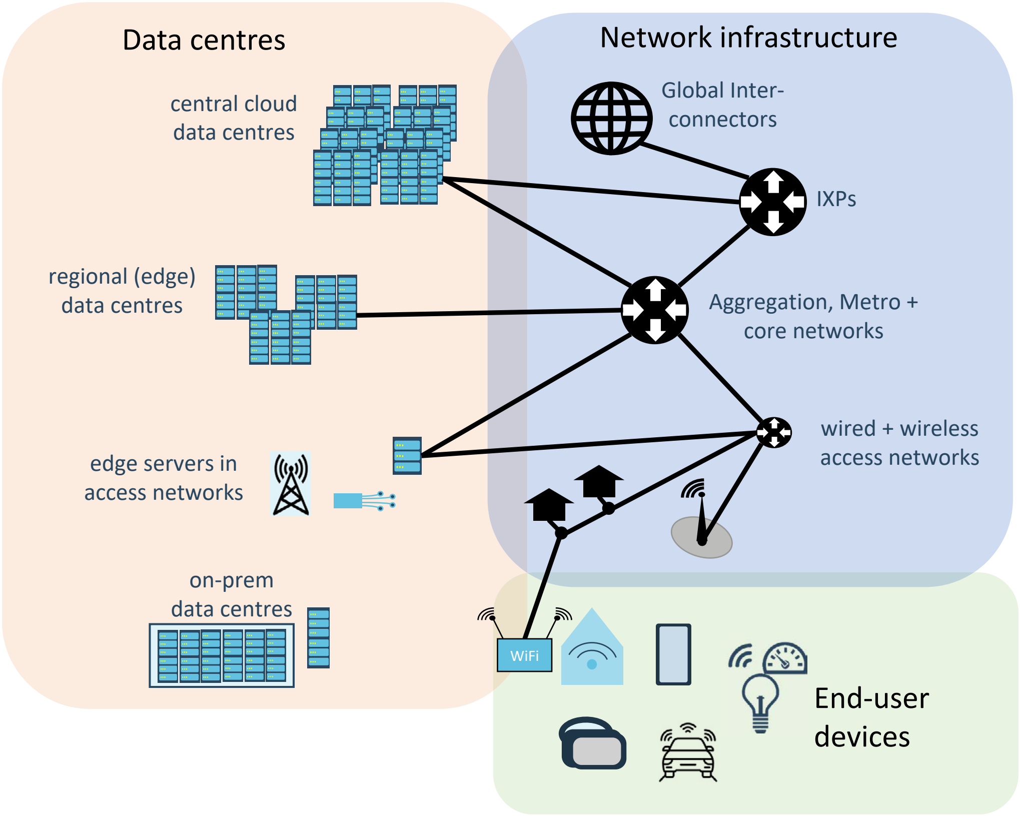

Figure 1: Schematic illustration of the three areas of the ICT sector: end-user devices, data centres and network infrastructure

Data is stored, and processed in **data centres**. Data centres consist of the building, the supply infrastructure (cooling, uninterruptible power supply, lighting, protective equipment, etc.) and, of course, the IT components (server, storage, network). Data centres can be characterised by their operator (e.g., enterprise, service provider, colocation, research/high performance computer (HPC), public sector), their deployment model (public/private/hybrid cloud, on-premises), or by their size/capacity (e.g., IT floor space, rated IT power, number of servers/racks).

Data is transmitted to and from end-user devices and data centers via **communication networks**. Access networks, sometimes in combination with customer premise equipment, connect the end-user devices with the internet and can be either mobile (e.g., 5G, LTE) or fixed (e.g., DSL or fiber, partly also in combination with WiFi). Customer premise equipment includes DSL modems, and WiFi routers. Disagreement exists as to whether the energy consumed by customer premise equipment for internet access should be counted as part of end-user devices or as part of communication networks.

End-user devices	Desktop computers, laptops, tablets Smartphones Printers Audio and video devices ICT in public spaces Internet of Things (IoT) devices
Data centres	Servers, storage systems, network Transformers, cooling, uninterruptible power supplies (UPS) — Third party provider data centres Network operator data centres Enterprise data centres
Network infrastructure	Mobile base stations, gateways, routers, network monitoring/control, amplifiers Cooling, UPS — Core network Edge network Access network (fixed/mobile) Customer premise equipment

Table 1: The ICT sector in detail. Note that system boundaries of the ICT sector may differ in the various studies.

3 ENVIRONMENTAL EFFECTS OF THE ICT SECTOR

Based on available studies, we first summarise the various environmental effects of the ICT sector and their potential development over the next decade. Subsequently, we analyse the different study results for the three subsectors: end-user devices, data centres and communication networks.

As depicted in Figure 2, **electricity consumption** of digital technologies along their life cycle makes up approximately 8% to 10% of global electricity consumption. This is projected to remain steady or rise further. Similarly, the ICT sector makes up between 2.1 and 3.9% of global **GHG emissions** including embodied emissions (Freitag et al., 2021). These emissions are expected to further increase in the next few years.

Depending on the various modelling decisions and assumptions for end-user devices, data centres and communication networks, the values of the sector's future electricity demand vary by 20%, as can be seen from the min/max values in Figure 2.

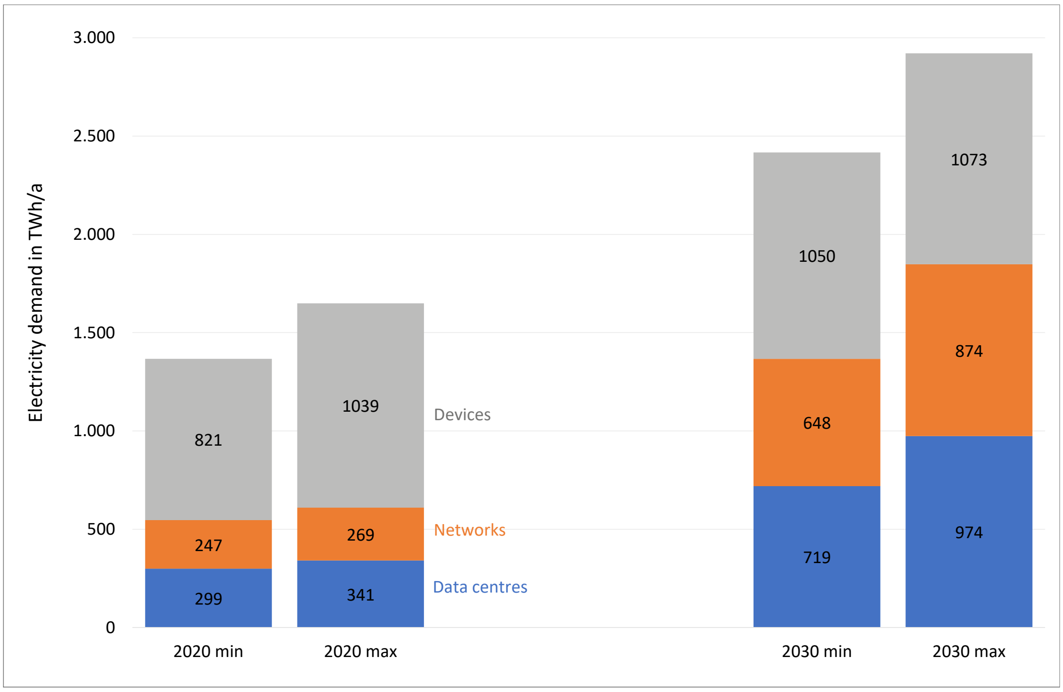

Figure 2: The ICT sector's global electricity demand, min and max based on Andrae (2020), Bieser et al. (2020), Greenpeace and Ceprei Calibrations&Testing Center (2021), Hintemann (2020), Malmodin and Lundén (2018), Masanet et al. (2020), Petit et al. (2021), The Shift Project (2019)

Various environmentally relevant trends can be clearly identified, such as a projected increase in the number of devices, subscribers and data traffic as well as in the energy efficiency of individual processes for ICT devices, data centres and network infrastructure. Whether these ultimately lead to an increase in the electricity demand of the ICT sector and the associated GHG emissions in the projections depends on five modelling assumptions:

[I] Whether increased use outbalances increased energy efficiency

[II] Modelling approach of energy intensity of data traffic per subscriber or per GB

[III] Future development of data center capacity vs. energy efficiency of IT equipment and utility infrastructure/ power usage effectiveness (PUE)

[IV] Future development of data volumes vs. transmission efficiency of communication network infrastructure

[V] Future development of electricity demand for the use of key digital technologies

Study	Reference year	Electricity consumption [TWh/year]	Share of global electricity [%]	GHG emissions [Gt CO2e/ year]	Share of global GHG emissions [%]
Malmodin & Lundén (2018)	2010 2015	800 (1,990)* 800 (1,800)*	4.3 (10.7)* 3.8 (8.5)*	 730 (1,150)*	
The Shift Project (2019)	2015 2025	3,373 6,326	11.7 22.6	1,448 3,669	2.9 7.6
Andrae (2020)	2010 2020 2030	1,942 1,988 3,218	. 8.8^ 11.5^		
Petit et al. (2021)	2020 2030	1,935 3,177	8.7 11.5°	0.955 0.899-1.201	2.8 2.6-3.4
Belkhir & Elmeligi (2018)	2010 2020 2040			0.5-0.7 1.11-1.31 5.3	 14
Freitag et al. (2021)	2020			1.2-2.2	2.1-3.9

** in brackets: electricity consumption and GHG emission of the ICT sector + media sector. This dichotomy can only be found in Malmodin and Lundén (2018), all other studies include the devices from the media sector to the ICT sector.*

^ based on numbers from Petit et al. (2021)

° Petit et al. (2021) additionally assume 8.3% losses in transmission and distribution (T&D) infrastructure globally

Table 2: Overview of available study results on the environmental effects of the ICT sector and their potential development over the next decade

As for **resource demand**, the sector's overall impact is rather low at 0.5% of total raw materials (Malmodin et al., 2018). For selected materials, however, the ICT sector represents significant demand. Raw materials such as rare earths, cobalt and niobium are also in high demand in other sectors (e.g., mobility, energy, defense), leading to growing competition in the global minerals market (Hanski et al., 2021). Crucial resources, such as Tantalum and Terbium are already reaching scarcity, while production levels of other key minerals will be insufficient some years ahead, even in best-case sustainability scenarios (Marscheider-Weidemann et al., 2021). Hence, the whole ICT sector is a very 'linear economy' – far from being circular. In addition, digital devices consist of various metals that are classified as conflict raw materials or of concern, while the mining of several crucial resources as well as hardware production usually take place under insufficient environmental standards and labour conditions (Chan, 2019; WEED e.V., 2018). Furthermore, there is considerable environmental impact through river pollution, deforestation and air pollution (Pilgrim et al., 2017).

The recycling potential for e-waste (i.e., the waste stream of disposed electrical and electronic equipment) is currently largely untapped; only 20% of the e-waste generated in Europe is recycled at all. The majority either ends up in residual waste, where it is later incinerated, or is exported illegally, mostly to countries in the Global South (Forti et al., 2020). The production process is also characterised by a lack of transparency and it is often impossible to determine which components were produced or disposed of where and under what conditions.

The associated impact of the ICT sector with regards to **other environmental indicators** such as water demand, land use or biodiversity loss has been barely studied. However, for a robust environmental assessment of the ICT sector, it is essential to address other impact categories in addition to indicators for energy and GHG emissions. This allows for the identification of shifts in environmental impacts due to the application of ICT-based services, of supply chain risks (see e.g. Hanski et al., 2021; UNCTAD, 2020), or of (local) shortages of certain resources (e.g. Moss, 2021; Tenuta, 2019 on water scarcity).

3.1 End-user devices

The subsector **end-user devices** is characterised by the following environmentally relevant trends:

- Billions of networked end-user devices at present (see Figure 3), with ever shorter recycling cycles of these devices (Cisco, 2020; Malmodin & Lundén, 2018). The category of IoT devices in particular is increasing rapidly, and this is projected to accelerate into the future.
- Production of electronic components is energy-intensive and often takes place at locations with a high proportion of coal in the electricity mix (Manhart et al., 2016). For laptops, tablets and smartphones, for example, 50-75% of the cumulative energy demand and GHG emissions occur in the production phase (Hischier et al., 2015).
- Devices are getting bigger and better in absolute terms, thus requiring more energy in the production an operation phases due to increased functionalities and computing power (Prakash et al., 2017; Proske et al., 2020).
- Significant efficiency improvements for all device types, both when it comes to digital performance (computations per time, network bandwidth, storage capability) per environmental resource use (e.g., energy consumption) and in terms of device types (i.e., there is a shift away from desktop computers toward smaller, more energy-efficient end-user devices).

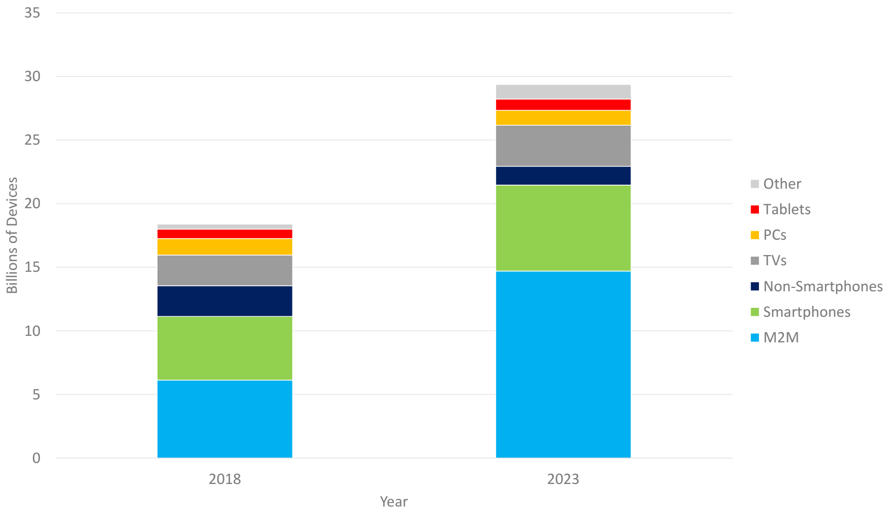

Figure 3: Global device and connection growth (based on Cisco, 2020)

For end-user devices (see Figure 4), the electricity demand during use (operational electricity demand) was between 800 and 1000 TWh in 2020, and is expected to reach around 1.000 TWh in 2030 (Andrae, 2020; Petit et al., 2021).

The previous development of the operational global energy demand of end-user devices has different scenarios depending on the modelling approaches: Andrae (2020) calculates a roughly stable energy demand for end-user devices since in 2015. Petit et al. (2021) estimate a slight increase (3%) in annual electricity demand to 2030. In its estimated scenario, the Shift Project (2019) projects a doubling of electricity consumption from 2015 to 2025. This is due to the fact that, compared to the studies by Andrae (2020) and Petit et al. (2021), the Shift authors assume a significantly lower electricity consumption in 2015, as can be seen in Figure 4. About one sixth of the global operational energy demand is accounted for by the EU-27 (Kemna et al., 2020).

In addition, energy demand due to hardware manufacturing is estimated between 300 and 500 TWh per year in 2020 (Andrae, 2020; Malmodin & Lundén, 2018; Petit et al., 2021). Petit et al. (2021) expect an increase in electricity demand from hardware manufacturing to 759 TWh in 2030. The Shift Project (2019) does not show the electricity demand for the production of digital technologies separately for end-user devices.

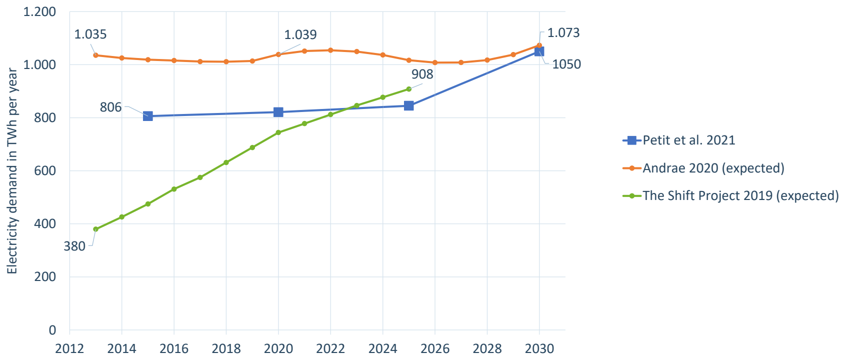

Figure 4: Different results on global electricity demand of end-user devices in the use-phase

Estimates on GHG emissions from the operational phase for end-user devices such as desktop PCs, laptops and consumer electronics vary between 0.5 Gt CO2e (Petit et al., 2021) and 1.4 Gt CO2e in 2020 (Freitag et al., 2021). Petit et al. (2021) expect a slight decrease in GHG emissions from the operation of end-user devices to a maximum of 0.4 Gt CO2 by 2030. Embodied emissions from hardware production is estimated between 0.26 (Petit et al., 2021) and 0.8 Gt CO2e in 2020 (Freitag et al., 2021).

Differences in estimations for electricity consumption and GHG emissions are due to varying modelling approaches and assumptions:

- Developments in electricity demand due to the increasing number of devices and the devices' increasing energy efficiency offset each other vs. a slowdown in efficiency improvements in the coming years
- Saturation in terms of the number of ICT devices worldwide
- Different system boundaries, with regards to IoT devices or consumer electronics. The increasing number of devices that were previously not associated with ICT, such as refrigerators, washing machines and lamps, are now increasingly being equipped with computing chips and interfaces, making it more difficult to distinguish the environmental effects of ICT from non-ICT effects.

3.2 Data centres

The subsector data centres can be characterised by the following environmentally relevant trends:

- The rapidly increasing demand for capacity in data centres for processing, storing and transmitting data
- The continuous increase in IT equipment performance per energy unit consumed (FLOPS per Watt, TB per Watt, etc.)
- The trend toward larger data centres with increasing capacity deployed in multi-tenant cloud infrastructure
- A slight increase in energy efficiency in utility infrastructures such as cooling and power supply
- Increasing power density in data centres, especially in GPU-accelerated compute servers for HPC or AI applications

The enormous growth in data volumes, computing power and data transmission is expected to lead to a net growth in electricity consumption, from 200-400 TWh in 2020 to 700-1.000 TWh in 2030 (Hintemann et al., 2022). Similarly for EU-27, an increase in electricity demand is expected due to ongoing digitalisation and strong growth in data centre capacity, which significantly exceeds the efficiency gains achieved at all levels. About 10% of the operational energy demand is accounted for by the EU-27 in 2025 (Montevecchi et al., 2020).

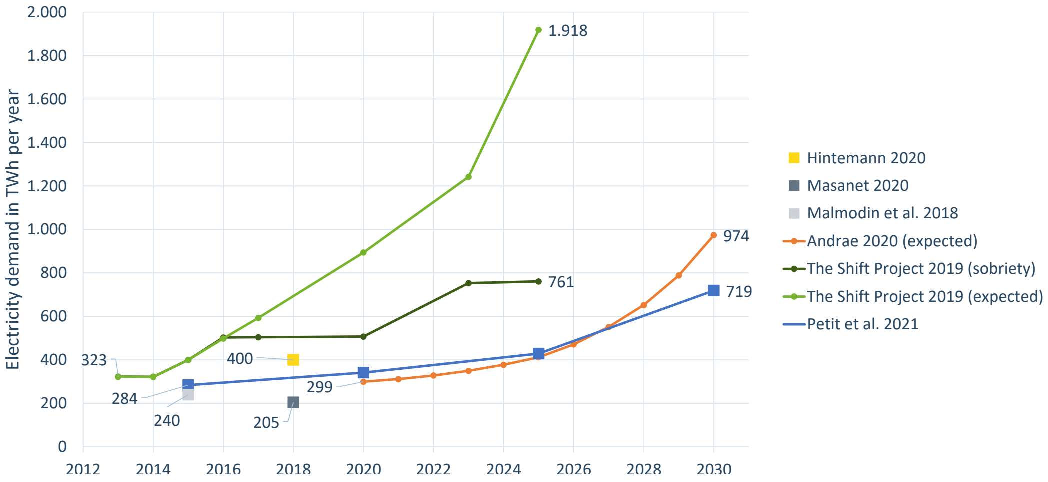

Figure 5: Different results on global electricity demand of data centres in the use-phase

However, studies on the operational electricity consumption of data centres show great heterogeneity regarding the sector's future development of operational electricity consumption and corresponding GHG emissions (see Figure 5). Differences in estimations can be traced back to varying modelling approaches with regard to the assumed development of data traffic, the structure of the worldwide data centre market and system boundaries.

Andrae (2020) assumes an annual increase in energy demand of between 6% in his best scenario and 13% in his expected scenario until 2030. The scenarios differ mainly in terms of the growth of the workload (in terms of data traffic) and the annual increase in data centre efficiency. The limits of miniaturisation (the end of Moore's Law or Koomey's Law) are a strong influence on his future forecasts. Similarly, due to significantly increased server workloads, Petit et al. (2021) estimate an annual increase in electricity demand of 21%. Based on a previous study of Andrae and Edler (2015), the Shift Project (2019) predicts a five-fold increase in electricity demand between 2015 and 2025 in their expected scenario, assuming strong growth and relatively weak efficiency gains. In contrast, Masanet et al. (2020) estimate a comparatively moderate 6% increase in energy consumption between 2010 and 2018, despite significantly rising data traffic, data centre workloads and compute instances due to impressively increased energy efficiencies. Malmodin and Lundén (2018) estimate an approximately 15% higher electricity consumption than Masanet et al. (2020). The authors attribute the differences to variations in the number of servers and the inclusion of enterprise networks in offices into their sector definition (Malmodin & Lundén, 2018).

According to Belkhir and Elmeligi (2018), GHG emissions from global data centre operational energy consumption more than tripled between 2010 and 2020, from 159.3 MteCO2-e to 494.9 MteCO2-e. Malmodin and Lundén (2018) on the other hand, assume, for both data centre electricity demand and manufacturing, GHG emissions of 160 Mt CO2e for 2015. They do not expect any future increase in GHG emissions due to an assumed constant data centre electricity demand. Similarly, Petit et al. (2021) expect almost no change in GHG emissions between 2020 and 2030. In their decarbonized scenario, they expect a slight decrease in emissions.

There are hardly any estimates of the ratio of energy consumption and GHG emissions from production vs. use of data centres. Gröger et al. (2021), using the KPI4DCE tool, model the distribution of environmental impacts of four different data centres (see Figure 6) between the manufacturing phase (green) and the use phase (blue) for Abiotic Depletion Potential (ADP), Global Warming Potential (GWP) and Cumulative Energy Demand (CED). When interpreting the data, however, it is important to notice, that in the KPI4DCE tool, the figures were calculated with a GWP or carbon intensity of 635 g/kWh. This is comparatively high (global carbon intensity was 442 g/kWh in 2021, see Carbon intensity of electricity (2021)) and leads to very high share of GWP in the use phase. For other countries or more updated calculations in Germany, the production phase could be much more significant.

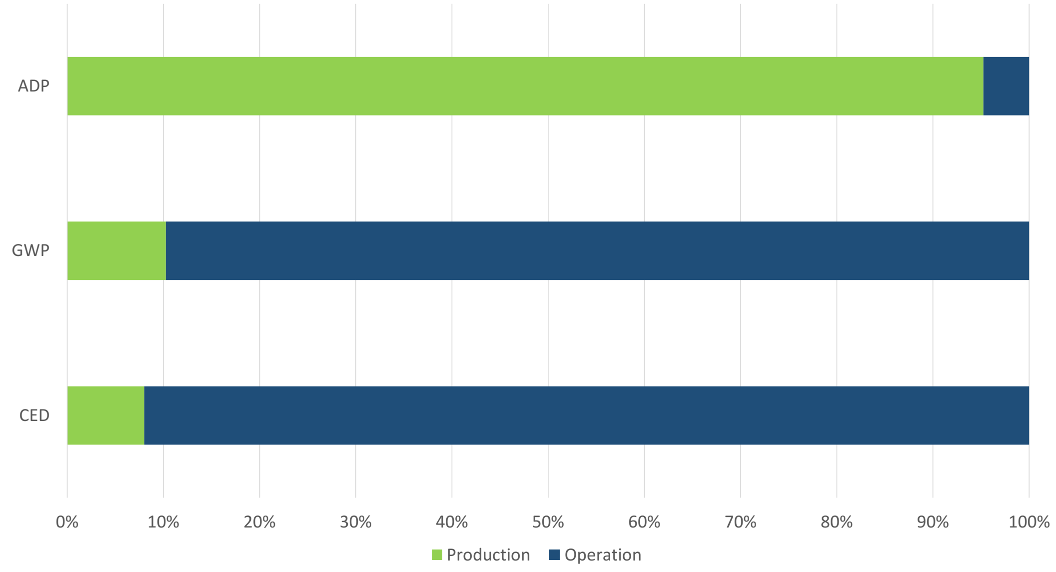

Figure 6: Distribution of Abiotic Depletion Potential (ADP), Global Warming Potential (GWP) and Cumulative Energy Demand (CED) of data centres by the life cycle phases production and operation using the KPI4DCE tool, based on Gröger et al. (2021)

3.3 Communication networks

The subsector communication networks, which roughly consist of core, edge and access networks, can be characterised by the following environmentally relevant trends:

- Increases in energy-efficiency of data transmission technologies, with fixed broadband networks (VDSL, FTTH) being the most energy-efficient (see Figure 7)
- A shift from fixed to mobile access networks use, rollout of new more energy-efficient mobile data transmission technologies (5G) and replacement of older technologies (LTE, 2G, 3G), enabling the provision of new data-intensive mobile services
- More diverse frequency bands in new mobile networks (5G), extending into the mm wave range. This also means different cell types, including small cells and femtocells in addition to classic macrocells, since mm-wave does not penetrate building walls

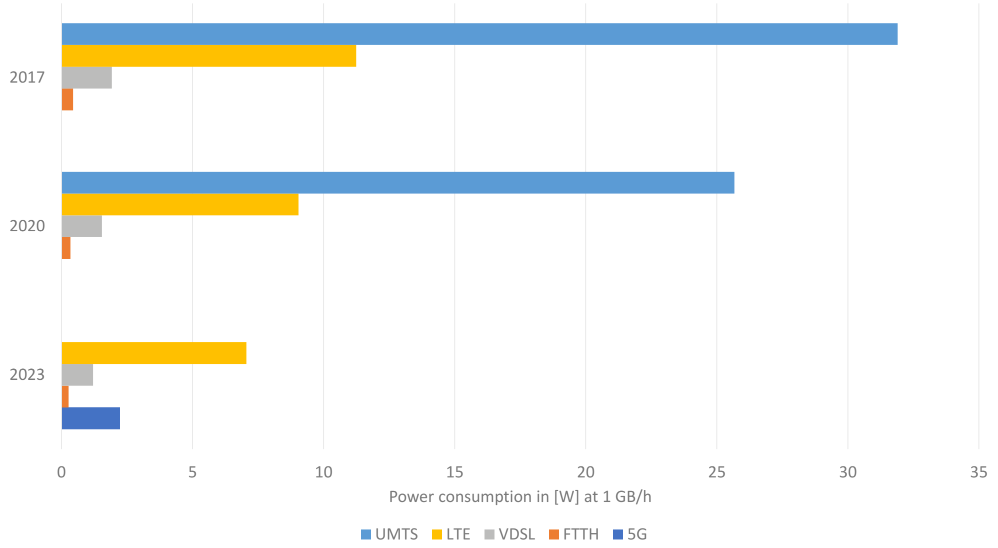

Figure 7: Power consumption in the communications network at 1 GB/h up to the data center depending on the technology generation, based on Gröger et al. (2021)

The enormous growth in data volumes, in particular of mobile data, is expected to lead to net growth in electricity consumption, from 200 – 450 TWh in 2015 to 650-900 TWh in 2030 (see Figure 8).

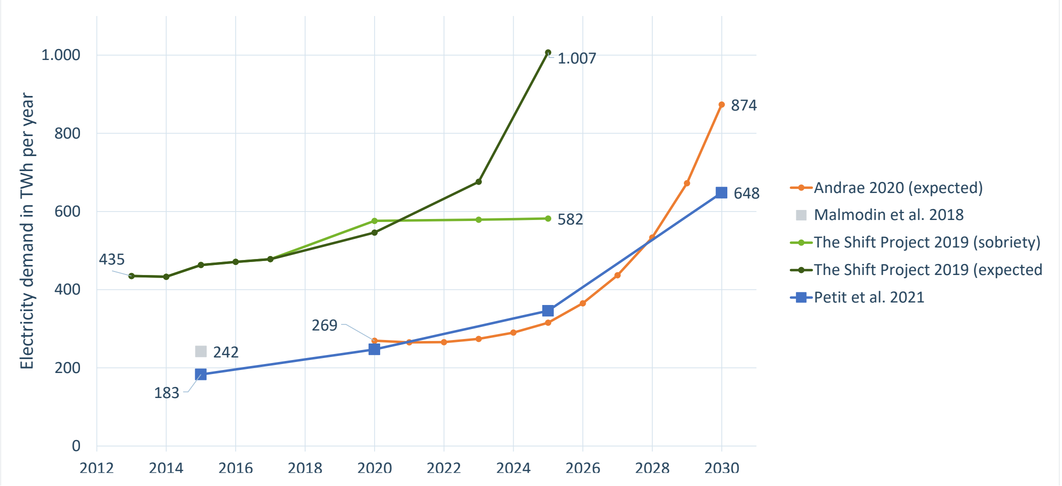

Figure 8: Global energy demand of communication networks in the use-phase

Available studies show great heterogeneity, especially with regard to the future development of electricity consumption until 2030.

Petit et al. (2021) expect electricity demand to almost triple between 2020 and 2030 as fast growing data traffic outpaces the networks' improving energy efficiency. Andrae (2020) expects network electricity consumption to more than triple between 2020 and 2030. The Shift Project (2019) assumes a doubling of the communication networks' electricity demand between 2015 and 2025 and thus expects significantly higher electricity consumption than in the other studies by Andrae (2020), Malmodin & Lundén (2018) and Petit et al. (2021).

Based on primary data from European telecom networking operators, Lundén et al. (2022)

estimate a slight decline in electricity consumption of communication networks in Europe between 2018 and 2020. However, the authors choose a different modelling approach and extrapolate the energy consumption for Europe per subscription, based on primary data from operators representing about 36% of subscriptions in Europe. However, the representativeness of the sample is unclear because of country-specific differences in communication network structures.

4 ICT TRENDS IMPACTING THE SECTOR'S FUTURE ELECTRICITY CONSUMPTION

Recent developments in key digital technologies might influence the future electricity consumption of end-user devices, networks and data centres (see Figure 9). Based on analyses by Montevecchi et al. (2020), we describe current developments and trends for smart sensors/IoT, 5G, cryptocurrencies, and AI.

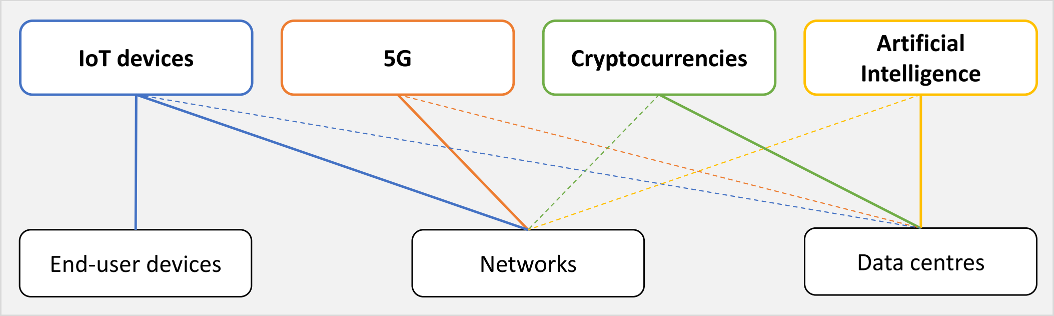

Figure 9: Impact of ICT trends on environmental effects of end-user devices, networks and data centres. Thick lines depict dominant links, dotted lines depict secondary links. Own work, adapted from Freitag et al. (2021)

Internet of Things

Various publications forecast a rapid growth for the IoT, such as Cisco (2020), Grijpink et al. (2020) and Transformer Insights (2021). Cisco (2020) expect that by 2023 half of all connected devices (14.7 billion) may be attributed to the IoT. This has implications for the anticipated amount of data traffic, which is expected to increase more rapidly than the number of M2M connections, as in the future there will be more and more applications that include video transmission. This will impact energy demand due to data generation, analysis and transmission, in particular for IoT devices that transmit video data, or track large amounts of data, such as connected cars.

Furthermore, the evolution of energy consumption in the operational phase of the IoT is significant for both standby and active network status, as a study commissioned by the IEA 4E (2019) shows. The increase in electricity consumption in standby mode can be traced to the rapidly increasing number of IoT devices/connections, while the increase in electricity consumption in active mode is mainly driven by the electricity demand of local transmission networks. Theoretically, energy consumption can be greatly reduced in the case of no or low use, e.g., through energy-saving functions for network, memory and computing; this is referred to as energy-proportional computing. These energy-saving functions are already used extensively on battery-powered devices to optimize battery life. For mains-powered devices, however, energy consumption is not such an important feature for usability, which is why these devices still often lack energy-proportional computing.

Artificial Intelligence

The application of artificial intelligence (AI) is ubiquitous in many economic sectors, e.g., voice or facial recognition, social bots, medical diagnostics, predictive maintenance and autonomous driving (Rohde et al., 2021). AI is also considered an impactful tool for reducing GHG emissions (Rolnick et al., 2022). However, the discussion about AI's own energy demand and related carbon emissions is only just beginning (van Wynsberghe, 2021). In particular, the training periods needed by the subsymbolic machine learning models that are typical for today's AI (also known as 'Artificial Neuronal Networks') can have a rather high energy demand. The need for computational capacity for AI will increase more than efficiency gains from new chips will allow in the next few years, so energy demand is expected to increase (Desislavov et al., 2021). There is an urgent need for sustainability indicators that address not only ethical issues such as transparency and traceability, but also environmental aspects such as AI's energy and resource consumption (Rohde et al., 2021).

Cryptocurrencies

Cryptocurrencies are among the most discussed applications of blockchain technology. Blockchain is a distributed ledger technology that makes transactions possible without central authorities. The ledger is maintained, shared and validated on a distributed network of computers running specific blockchain software. To ensure security against manipulation, some cryptocurrencies use a consensus mechanism, e.g., Proof of Work (PoW), which utilises computers on the network ('miners') (Kamiya, 2019; Rauchs et al., 2018). Using Bitcoin as an example, it was shown that the energy required for storage and network transmission is virtually negligible, and that the computing power required for the cryptographic tasks of the PoW mechanism alone determines the high energy requirement (Coroamă, 2021). The computational effort – the so-called difficulty of cryptographic tasks – is not fixed, but adapts proportionally to the performance of the network, which is why more powerful hardware does not lead to energy savings.

IEA estimates energy used for cryptocurrency mining at 100 TWh in 2020 (Kamiya, 2021). Rauchs et al. (2018) estimate that the top-6 cryptoassets consume between 52 and 111 TWh of energy a year. For Bitcoin, Digiconomist (2022) estimates an energy demand of 204 TWh per year. The high range of the result is due to the lack of reliable data on mining equipment, energy sources and the energy efficiencies of data centres. Data on the resulting GHG emissions are also subject to great uncertainty, as they depend on the local electricity mixes of the miners.

According to Rauchs et al. (2018), mining facilities cover on average 28% of their energy demand from renewable sources. This is roughly equivalent to the global share of renewables in the electricity mix (IEA, 2021). One potential approach to regulating the energy consumption of cryptocurrencies is choosing a more sustainable consensus mechanism. For example, Proof of Stake, which Etheurum has been trying to switch to, is much less energy intensive than PoW.

5G

5G, the fifth and latest generation of mobile networks, is characterised by high download speeds, low latency and high connection densities. New application areas are mainly in the fields of virtual reality, autonomous vehicles and IoT (Williams et al., 2022). Mobile data traffic is expected to increase significantly with the introduction of 5G (Cisco, 2020). According to several industry-oriented studies, the energy consumption of mobile networks will decrease (Ericsson, 2021; Laidler, 2019). However, these estimates do not take into account the embodied energy from the production of 5G base-stations (Williams et al., 2022). This omission is particularly relevant regarding energy effects, as the 5G rollout requires the construction of entirely new base stations. Moreover, 5G transmission technology uses higher Ghz frequency ranges (millimeter wave), requiring a much closer proximity of the antenna to the end device, or at least a direct line of sight, resulting in the need for numerous additional antennas. Hence, when considering embodied energy, the energy efficiency of the base station is expected to decrease (Humar et al., 2011). Additionally, if data volumes increase more than the efficiency gains from 5G deployment due to new application cases, the overall energy consumption will increase (Williams et al., 2022).

5 POLICY MEASURES ADDRESSING THE ICT SECTOR’S ENVIRONMENTAL FOOTPRINT

To achieve sustainable digitalisation, our analysis shows that further improvements in the energy efficiencies of devices, communication networks, data centres and service provision are important, but will not suffice. It is vital to reduce the environmental impacts of end-user devices, data centres and network components. ICT sector regulations must also include policies and measures that serve circularity and sufficiency. In the following section, we propose policy measures for the sustainable design of end-user devices, services and ICT infrastructure.

5.1 End-user devices

Measures which ensure the efficiency of digital technology must be accompanied by consistency and sufficiency strategies encompassing all areas of the product life cycle.

The **modularisation** and standardisation of hardware enables and improves repairability, prolongs service life, helps to reduce electronic waste and preserves resources. At the EU level, this can be achieved by means of mandatory specifications for the **standardisation** of electronic accessories and electronic components. For example, the amended Radio Equipment Directive 2014/53/EU mandates USB-C as the single charger solution for all devices.

Furthermore, the **repair and update capability** of hardware and software must be ensured. For example, the publication of all information relevant to a device's repair while maintaining the user's rights of use and warranty should be mandatory, even if the repair is carried out by an independent, certified repair company and/or alternative software or operating systems are used. Equipment must also be designed in such a way that it can be repaired (Design for Repair & Upgrade). With the revision of the Ecodesign Directive and the implementation of a Digital Product Passport (Proposal repealing Directive 2009/125/EC [COM(2022)142 final], 2022), the European Union is already improving durability, repairability and upgradability. However, a broad civil society alliance argues that the regulatory requirements for right to repair could be strengthened, and demands that non-discriminatory and permanent access for all (commercial) repairers and end-users to all means and tools relevant to the repair, and access to information on repair and maintenance information and to spare parts should be guaranteed.

Another requirement is a **functioning recycling system** that exploits its potential through a) efficient collection (e.g., a deposit system for equipment or a low-threshold return system in shops) and the further development of recycling technologies so that valuable digital components can be reused, b) better preparation and reuse of electronic waste, and c) separation quotas for plastics, capacitors and batteries, and recycling quotas for plastics and critical minerals (see Handke et al., 2019 for details).

Free licensing of hardware and software, at least after the end of production, also contributes to the longest possible service life. For hardware, this means that the rights of use or ownership for building instructions and spare parts after the end of production are made available to the general public under a free licence. Thus, users and workshops can reproduce spare parts themselves. Regarding software, once a software or electrical device is no longer supported, publication of the source code under a free licence (Upcycling of software) should be mandatory. This, together with the right to install alternative software and operating systems, protects against planned software obsolescence.

In order to promote public and sustainable digital infrastructures, it should be a legal obligation to publish hardware and software developed with public money under an open source licence (Public Money Public Code or Public Money Public Hardware), i.e., developments paid for by the public should be available to the public. It is crucial to create long-term structures, such as a European Open Technology Fund, which promote the development of open, sustainable hardware and software, and contribute to digital sovereignty. The Open Technology Fund (USA) and the Sovereign Tech Fund (Germany) can serve as models here.

5.2 Services

Mandatory requirements to design software in a way that **minimises electricity and resource consumption during the utilisation phase** must be further introduced. The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety has already initiated this with the Blue Angel for software (BMU, 2020). Furthermore, compulsory info-labels for resource-saving products and applications can help consumers make informed choices. In the case of digital services such as video streaming, platform operators should ensure that the standard resolution of videos is always adapted to the size of the terminal equipment and that automatic playback is deactivated (sufficiency by default).

In addition, **mandatory opt-in strategies** should be introduced to reduce data traffic when surfing the web (e.g., regarding privacy settings, tracking, online advertisements) and collect only the personal data needed for a certain service (see Santarius et al., 2022 for details).

5.3 ICT infrastructure

Regarding communications networks, clear guidance is essential to avoid too many systems in parallel. For instance, the introduction of 5G mobile networks has been politically supported without a clear purpose or mandated conditions – simply by following the faster-is-better paradigm. Future decision-making must ensure resource-intensive **digital infrastructures do not become obsolete** prematurely and prescribe joint use of base stations by different network service providers. Perhaps the most important but also the most challenging aspect is to prevent network efficiency improvements from being countervailed by rebound effects due to ever more interconnected devices in the Internet of Things and the exponential growth of data.

Regarding data centres, political efforts currently aim to establish inventories of energy demand levels and efficiencies. However, more ambitious steps are urgently needed, such as mainstreaming the German 'Blue Angel' label for **energy-efficient data centre** operation (BMU, 2019). Moreover, this label could be extended to include criteria that assess the environmentally sound planning, operation and disposal of data centres, as well as the utilisation of their waste heat. Especially for new data centres, minimum standards on energy efficiency should be implemented, such as maximum PUE and minimum inlet air temperatures for data centres that are cooled by compression chillers. At the same time, however, the current challenges of feeding waste heat into district heating networks or heat users must be resolved.

It is extremely important that **technological standards at the European level give high priority to environmental protection.** This could be achieved, for example, by mandatory prospective environmental impact studies as part of the approval procedure of new ICT infrastructure, and by the mandatory implementation of an energy-efficiency label for new data centres. Data centres should also be required to run on 100% renewable electricity, either through direct power generation on or next to the data centres, or through power purchase agreements.

A paradigm shift towards free and open source software is particularly important in the area of **critical infrastructure.** At the EU level, for example, it is necessary to derive and implement concrete measures from the EU Commission's open source strategy.

6 REFERENCES

Andrae, A. S. G. (2020). New perspectives on internet electricity use in 2030. Engineering and Applied Science Letters, 3(2), 14.

Andrae, A. S. G., & Edler, T. (2015). On Global Electricity Usage of Communication Technology: Trends to 2030. Challenges, 6(1), 117–157. https://doi.org/10.3390/challe6010117

Belkhir, L., & Elmeligi, A. (2018). Assessing ICT global emissions footprint: Trends to 2040 & recommendations. Journal of Cleaner Production, 177, 448–463. https://doi.org/10.1016/j.jclepro.2017.12.239

Bieser, J., Hintemann, R., Beucker, S., Schramm, S., Hilty, L., & Kühn, M. (2020). Klimaschutz durch digitale Technologien – Chancen und Risiken.

BMU. (2019). Blauer Engel—Das Umweltzeichen: Energieeffizienter Rechenzentrumsbetrieb. DE-UZ 161.

BMU. (2020). Blauer Engel—Das Umweltzeichen: Ressourcen-und energieeffiziente Softwareprodukte. DE-UZ 215.

Carbon intensity of electricity. (2021). Our World in Data. https://ourworldindata.org/grapher/carbon-intensity-electricity

Chan, J. (2019). Biss in den sauren Apfel: Zu den Arbeitsbedingungen vom Apple-Lieferanten Foxconn in China. In A. Höfner & V. Frick (Hrsg.), Was Bits und Bäume verbindet: Digitalisierung nachhaltig gestalten (S. 19–22). oekom.

Cisco. (2020). Cisco Annual Internet Report (2018–2023) (Cisco White Paper). https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

Coroamă, V. (2021). Blockchain energy consumption An exploratory study. ETH Zürich. https://www.aramis.admin.ch/Default?DocumentID=68053

Desislavov, R., Martínez-Plumed, F., & Hernández-Orallo, J. (2021). Compute and Energy Consumption Trends in Deep Learning Inference. https://arxiv.org/pdf/2109.05472

Digiconomist. (2022). Bitcoin Energy Consumption Index. https://digiconomist.net/bitcoin-energy-consumption

Ericsson. (2021). Breaking the energy curve. An innovative approach to reducing mobile network energy use (S. 12).

Proposal repealing Directive 2009/125/EC [COM(2022)142 final], (2022) (testimony of European Commission).

Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The Global E-waste Monitor 2020: Quantities, flows, and the circular economy potential. United Nations University (UNU)/ United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste

Association (ISWA).

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G. S., & Friday, A. (2021). The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. Patterns, 2(9), 100340. https://doi.org/10.1016/j.patter.2021.100340

Greenpeace & Ceprei Calibrations&Testing Center. (2021). China 5G and Data Center Carbon Emissions Outlook 2035.

Grijpink, F., Kutcher, E., Ménard, A., Ramaswamy, S., Schiavotto, D., Manyika, J., Chui, M., Hamill, R., & Okan, E. (2020). Connected world: An evolution in connectivity beyond the 5G revolution. McKinsey & Company. https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/connected-world-an-evolution-in-connectivity-beyond-the-5g-revolution

Gröger, J., Liu, R., Stobbe, D. L., Druschke, J., & Richter, N. (2021). Green Cloud Computing: Lebenszyklusbasierte Datenerhebung zu Umweltwirkungen des Cloud Computing (TEXTE 94/2021, S. 202). Umweltbundesamt.

Handke, V., Hross, M., Bliklen, R., Jepsen, D., & Rödig, L. (2019). Recycling im Zeitalter der Digitalisierung: Spezifische Recyclingziele für Metalle und Kunststoffe aus Elektrokleingeräten im ElektroG: Regulatorische Ansätze. NABU - Naturschutzbund Deutschland.

Hanski, Horn, Judl, Karhu, P Kivikytö-Reponen, P Lintinen, B Långbacka, Eilu, P., & Eerola, T. T. (2021). Digitalization and natural resources. https://doi.org/10.13140/RG.2.2.26366.72004

Hintemann, R. (2020). Data centers 2018. Efficiency gains are not enough: Data center energy consumption continues to rise significantly. Borderstep Institut.

Hintemann, R., Beucker, S., Hinterholzer, S., Grothey, S., Niebel, T., Axenbeck, J., & Sack, R. (2022). Dena Analyse: Neue Energiebedarfe digitaler Technologien—Untersuchung von Schlüsseltechnologien für die zukünftige Entwicklung des IKT-bedingten Energiebedarfs. Borderstep Institut, Leibniz-Zentrum für Europäische Wirtschaftsforschung, Deutsche Energieagentur.

Hischier, R., Coroama, V. C., Schien, D., & Ahmadi Achachlouei, M. (2015). Grey Energy and Environmental Impacts of ICT Hardware. In L. M. Hilty & B. Aebischer (Hrsg.), ICT Innovations for Sustainability (Bd. 310, S. 171–189). Springer International Publishing.

Humar, I., Ge, X., Xiang, L., Jo, M., Chen, M., & Zhang, J. (2011). Rethinking energy efficiency models of cellular networks with embodied energy. IEEE Network, 25(2), 40–49. https://doi.org/10.1109/MNET.2011.5730527

IEA. (2021). Global Energy Review 2021 (S. 36).

IEA 4E. (2019). Total Energy Model for Connected Devices. Report Prepared for IEA 4E EDNA.

Kamiya, G. (2019). Bitcoin energy use—Mined the gap. IEA. https://www.iea.org/commentaries/bitcoin-energy-use-mined-the-gap

Kamiya, G. (2021). Data Centres and Data Transmission Networks. IEA. https://www.iea.

org/reports/data-centres-and-data-transmission-networks

Kemna, R., Wierda, L., Li, W., van den Boorn, R., van Elburg, M., Viegand, J., & Wu, A. (2020). ICT impact study. European Commission.

Laidler, P. (2019). Curtailing carbon emissions – can 5G help? (S. 36). STL Partners.

Lundén, D., Malmodin, J., Bergmark, P., & Lövehagen, N. (2022). Electricity Consumption and Operational Carbon Emissions of European Telecom Network Operators. Sustainability, 14(5), 2637. https://doi.org/10.3390/su14052637

Malmodin, J., Bergmark, P., & Matinfar, S. (2018). A high-level estimate of the material footprints of the ICT and the E&M sector. Proceedings of ICT4S2018, 52, 168–148. https://doi.org/10.29007/q5fw

Malmodin, J., & Lundén, D. (2018). The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015. Sustainability, 10(9), 3027. https://doi.org/10.3390/su10093027

Manhart, A., Blepp, M., Fischer, C., Graulich, K., Prakash, S., Priess, R., Schleicher, T., & Tür, M. (2016). Resource Efficiency in the ICT Sector [Final Report]. Greenpeace.

Marscheider-Weidemann, F., Langkau, S., Eberling, E., Erdmann, L., Haendel, M., Krail, M., Loibl, A., Neef, C., Neuwirth, M., & Rostek, L. (2021). Rohstoffe für Zukunftstechnologien 2021 (Nr. 50; DERA Rohstoffinformationen). Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50.pdf?__blob=publicationFile&v=4

Masanet, E., Shehabi, A., Lei, N., Smith, S., & Koomey, J. (2020). Recalibrating global data center energy-use estimates. Science, 367(6481), 984–986. https://doi.org/10.1126/science.aba3758

Montevecchi, F., Stickler, T., Hintemann, R., & Hinterholzer, S. (2020). Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market. Final Study Report. European Union. https://data.europa.eu/doi/10.2759/3320

Moss, S. (2021). Data center water usage remains hidden. https://www.datacenterdynamics.com/en/analysis/data-center-water-usage-remains-hidden/

Petit, V., Carlini, S., & Avelar, V. (2021). Digital economy and climate impact: A bottom-up forecast of the IT sector energy consumption and carbon footprint to 2030. Schneider Electric. https://www.se.com/ww/en/insights/tl/electricity-4-0/digital-economy-and-climate-impact

Pilgrim, H., Groneweg, M., & Reckordt, M. (2017). The Dark Side of Digitalization: Will Industry 4.0 Create New Raw Materials Demands? PowerShift.

Prakash, S., Gröger, J., Hipp, T., Rodem, I., Borgstedt, S., Schlösser, A., Stobbe, L., Proske, M., Riedel, H., Chancerel, P., & Scheiber, S. (2017). Ermittlung und Erschließung des Energie- und Ressourceneffizienzpotenzials von Geräten der Unterhaltungselektronik. Umweltbundesamt.

Proske, M., Poppe, E., & Jaeger-Erben, M. (2020). The smartphone evolution—An analysis of the design evolution and environmental impact of smartphones. 8.

Rauchs, M., Blandin, A., Klein, K., Pieters, G. C., Recanatini, M., & Zhang, B. Z. (2018). 2nd Global Cryptoasset Benchmarking Study. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3306125

Rohde, F., Gossen, M., Wagner, J., & Santarius, T. (2021). Sustainability challenges of Artificial Intelligence and Policy Implications. Ökologisches Wirtschaften, 36(O1), 36–40. https://doi.org/10.14512/OEWO360136

Rolnick, D., Donti, P. L., Kaack, L. H., Kochanski, K., Lacoste, A., Sankaran, K., Ross, A. S., Milojevic-Dupont, N., Jaques, N., Waldman-Brown, A., Luccioni, A. S., Maharaj, T., Sherwin, E. D., Mukkavilli, S. K., Kording, K. P., Gomes, C. P., Ng, A. Y., Hassabis, D., Platt, J. C., … Bengio, Y. (2022). Tackling Climate Change with Machine Learning. ACM Computing Surveys (CSUR), 55(2), 1–96. https://doi.org/10.1145/3485128

Santarius, T., Bieser, J. C. T., Frick, V., Höjer, M., Gossen, M., Hilty, L. M., Kern, E., Pohl, J., Rohde, F., & Lange, S. (2022). Digital Sufficiency: Conceptual Considerations for ICTs on a Finite Planet. Annals of Telecommunications. https://doi.org/10.1007/s12243-022-00914-x

Tenuta, E. (2019). Water Scarcity Could Put Your Data Center at Risk. 8.

The Shift Project. (2019). Lean ICT: Towards digital sobriety. https://theshiftproject.org/wp-content/uploads/2019/03/Lean-ICT-Report_The-Shift-Project_2019.pdf

Transformer Insights. (2021). Global IoT Forecast Report, 2020-2030.

UNCTAD. (2020). Digital economy growth and mineral resources: Implications for developing countries (Nr. 16; UNCTAD Technical Notes on ICT for Development, S. 44).

van Wynsberghe, A. (2021). Sustainable AI: AI for sustainability and the sustainability of AI. AI and Ethics, 1(3), 213–218. https://doi.org/10.1007/s43681-021-00043-6

WEED e.V. (2018). At the other side of the supply chain. ICT brands' approaches to responsible minerals sourcing. WEED e.V.

Williams, L., Sovacool, B. K., & Foxon, T. J. (2022). The energy use implications of 5G: Reviewing whole network operational energy, embodied energy, and indirect effects. Renewable and Sustainable Energy Reviews, 157, 112033. https://doi.org/10.1016/j.rser.2021.112033

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Technische Universität Berlin
Einstein Center Digital Future

Coordination: Samira Franzel, Friedrich Schmidgall (ECDF)

info@digital-future.berlin
www.digital-future.berlin