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Sustainability & Materiality of the Internet

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Introduction

The internet and information and communication technologies generally enjoy a clean image in Western societies: the virtual world is perceived as "liberating, friendly, not-polluting," even as an alternative to mobility and tools for overcoming ecological crises, described as "tools in the service of the environment" or "green technologies" (Carré 2018, 107ff). We associate the internet with democracy movements, freedom, emancipation, exchange, productivity, and much more (Carré 2018, 111). However, does "Hyperconnectivity" (Carré 2018) and the infinite regress of speed (Carruth 2014, 358) not have ecological consequences?

The desire for escapism – the longing to escape from the body and materiality – is manifested through traditional ontology in the separation between mind and body, culture and nature, subject and object, individual and society. The metaphor of the cloud for the internet suggests a transcendence beyond space and time, beyond material and ecological problems. Carruth interrupts the bias and notion of an invisible and entirely immaterial cloud with the image of storm clouds or the mushroom cloud of an atomic bomb (Carruth 2014, 342). "If the internet were a country, it would have the world's third-highest electricity consumption," calculated Gröger and Herterich (Höfner 2019, 25). Mills claims, "the Cloud begins with Coal" (Mills 2013). The cloud as an emission cloud. Is the metaphor of the "Cloud" actually greenwashing because it appears invisible in environmental discourse (Carruth 2014)? The virtual ecosystem requires rematerialization (Carré 2018).

Within the theme of Materiality, this thesis explores the bias of the immaterial internet, questioning what ecological sustainability means in the context of information and communication technologies. After explaining the Rebound Effect, I examine the components of the three material pillars of the internet for global interconnectivity and conclude with three ecological sustainability factors. The goal of the work is to advance the rematerialization of the internet.

Rebound Effect

The so-called Rebound Effect, also known as Jevons Paradox, is the correlative relationship that increasing energy efficiency, as a result of technological progress, leads to an overall increased consumption of the resource (Carré 2018, 110). The namesake of this phenomenon, William Stanley Jevons, observed during the industrial revolution that the higher efficiency of James Watt's steam engine ultimately led to an increase in coal consumption, not least because it found new applications (Deutscher Naturschutzring 2024).

The Rebound Effect can also be observed in the development of Information and Communication Technologies (ICT): There is a tendency to potentially reduce overall resource consumption through digitization by overcoming the distance and availability of service offerings through ICT. However, Langkau and Hilbig see no effective decoupling of economic growth and resource consumption (Höfner 2019, 14-17). For example, the ecological footprint of consuming audiovisual content on streaming platforms is much lower than driving to a video rental store; however, the overall consumption of content and thus the energy demand increases due to the accessibility and simplicity of digital services for more consumers (Shehabi, Walker, and Masanet 2014).

Advantages of ICT include reducing commuting traffic through telecommuting, efficiency improvements in production processes by outsourcing computationally intensive tasks, or integrating geographically marginalized societal groups (Baisch et al. 2022). Digitization is not only an energy-efficient alternative to overcome distances but also creates other qualitative offerings and new needs. Comparing a carrier pigeon with a WhatsApp message, the resource consumption of information transmission has not only decreased but also increased the transmission speed, reliability, and functionality. Nevertheless, ICT and its contribution to interconnectivity, along with its services, have become an integral part of the cultural lifestyle, encouraging increased energy consumption due to constant accessibility and usage of ICT. Although two information transmission tools, such as a pigeon and a messenger service, are comparable in retrospect in terms of energy efficiency, technological innovations cannot always be traced back to the cause of using resources more sparingly.

To mitigate the Rebound Effect, Lange, Santarius, and Zahrnt propose the concept of digital sufficiency, which promotes a meaningful number of digital devices in households and moderate consumption without sacrificing the benefits of ICT (Höfner 2019, 112-114). Sufficiency is mentioned briefly here. Although sufficiency shares common ground with sustainability, the first concept aims at a normative approach to dealing with ICT that contradicts a realistic prognosis. In this thesis, the increase in digital consumption is the starting point for the challenge of identifying factors of ecological sustainability.

The Three Material Pillars of the Internet

For this chapter, I incorporate various quantitative data, particularly from reports by the Office for Technology Assessment at the German Bundestag (Grünwald and Caviezel 2022) and Kamiya (Kamiya 2020), who, in turn, utilizes data from the International Energy Agency (IEA) reports of 2019 and 2020. Due to dynamic developments, current sources are crucial for analysing complex matters such as data circulation (data volume per time), energy consumption, efficiency, and CO2 emissions, taking into account the local power mix.

In 2013, the digital ecosystem consumed 10% of the total electricity worldwide, equivalent to 1,500 TWh/year (Mills 2013). The estimate of the electricity demand of the internet at 10% (Renzenbrink 2013) is used as a consensual benchmark (cf. Höfner 2019, 14). The digital world rests on three material pillars. To enable the internet, the material prerequisites consist of (1) Information and Communication Technologies (ICT), (2) ICT infrastructure, and (3) data centers. The internet comprises a variety of services such as cloud services, streaming platforms, social media, etc. (1) ICT includes all end-user devices, such as smartphones, computers, TVs, etc., providing access to the internet. (2) Under ICT infrastructure, I refer to all network technologies, including access networks (mobile/fixed) connecting ICT to the internet, such as fixed networks, mobile networks, TV cable networks, etc., and the core network connecting specific servers, such as the internet backbone or undersea cables, etc. (Grünwald and Caviezel 2022, 48) (3) Under the category of data centers, I include all servers such as data storage, edge computers, fog computers, network nodes (Internet Exchange Point IXP), etc.

For streaming videos, the share of electricity consumption is significantly higher for ICT at 72%, compared to ICT infrastructure (23%) and data centers (5%) on average when considering consumption habits (Kamiya 2020). Carré and Geneviève refer to data from the French Agency for Environment and Energy (ADEME); according to their information, data centers produce 25%, ICT infrastructure 28%, and ICT 47% of greenhouse gas emissions concerning France's power mix (Carré 2018, 118). The operation of ICT and its infrastructure in Germany produces 33 million tons of CO2 emissions per year and is comparable to the emission volume of domestic air traffic according to Langkau and Hilbig (Höfner 2019, 15).

The Internet

Due to the high complexity, creating an accurate ecological footprint of internet services without detailed model assumptions beyond the scope of this work is impossible, especially as transparency and critical examination of ICT infrastructures and servers are largely lacking in the sciences (Carruth 2014). An estimation is still possible, albeit with uncertain data. It is crucial to use the current state of research. For example, Carruth quotes Robert Marzec, who breaks down energy consumption concretely: "Viewing a simple webpage generates approximately [0].02 grams of CO2 per second; ten times this is required to view a complex website with multiple images; a running PC generates 40 to 80 grams of CO2 per hour; a fifteen-minute Google search, 7–10 grams. All of this activity adds up" (Carruth 2014, 352ff). Unfortunately, this quote cannot be verified for accuracy as the source is no longer accessible. A report from ADEME, the French Agency for Environment and Energy, states that sending 33 emails with 1 MB each per day to two people causes CO2 emissions of 180 kg annually, equivalent to a 1000 km car trip (ADEME 2011). According to Kamiya, this calculation is outdated: an email no longer causes 1g of CO2 (Kamiya 2020). It is worth noting that IT infrastructure and data centers have become much more efficient, but the emission quantity for website visits remains contentious (Nast 2021). While one hour of streaming emitted around 420 g of CO2 in 2011, it was only 36 g of CO2 in 2019 (Kamiya 2020).

In 2017, streaming alone accounted for 60% of global data traffic, with an upward trend (Doleski et al. 2021). From 100 gigabytes per second (GB/s) in 2002, global data throughput grew to 106,000 GB/s in 2021, with streaming being the most significant factor for rapid growth (Höfner 2019, 32-33). Every 20 months, a doubling of global data volume is expected, meaning that every 8 years, data volume grows by a factor of 10, as described in the Rebound Effect. Purchasing a flat rate tends to encourage increased consumption (Höfner 2019, 33). Kamiya says, "One hour of streaming video typically uses around 0.08 kWh, but actual consumption depends on the device, network connection, and resolution" (Kamiya 2020). A 50-inch LED TV consumes 100 times more power than a smartphone and 5 times more power than a laptop (Kamiya 2020). As smartphones are very efficient, data transmission over ICT infrastructure accounts for 80% of the total energy consumption during streaming (Kamiya 2020). The ecological footprint of internet services also depends on the type of power mix (Kamiya 2020). In 2019, streaming on Netflix caused 0.054 kg CO2e per hour in Australia, 0.018 kg CO2e in the UK, 0.004 kg CO2e in France, and an average of 0.036 kg CO2e overall (Kamiya 2020). Kamiya calculates that half an hour of Netflix streaming is equivalent to about 100 meters of driving (Kamiya 2020). ADEME points out that using a search engine produces four times as many greenhouse gases as a normal web request (ADEME 2011).

The so-called cloud services are gaining importance: Cloud services are subscription-based or pay-per-use services that offer real-time access to more storage and computing capacity on the provider's servers, in the form of Software as a Service (SaaS), Infrastructure as a Service (IaaS), or Platform as a Service (PaaS) (Dibbern 2010, 31ff; Carruth 2014, 341ff). Especially during the COVID pandemic, data traffic and the demand for cloud services increased by 15 to 20% in spring 2020, but a saturation tendency was observed afterward (Grünwald and Caviezel 2022, 35-39). The advantages of outsourcing storage and computing capacities are not only for convenience but also for the low capital investment of companies in IT and personnel, as well as the more flexible scaling of IT capabilities (Dibbern 2010, 31ff). However, cloud services require a good network infrastructure with fast and reliable internet connections (Dibbern 2010, 35). Carré points out that cloud services consume twice as much energy for expanded storage capacities as storing data locally on end devices (Carré 2018, 118), but as we will see, cloud services have the potential to be a resource-efficient alternative to manufacturing new ICT end devices.

(1) The Digital Information and Communication Systems

In total, ICT end devices consume more power than ICT infrastructure and data centers: The consumption of 1.6 billion computers and notebooks (each 70 to 200 kWh/year), 6 billion smartphones (2 kWh/year each), tablets (12 kWh/year each), etc., adds up (Renzenbrink 2013). Mills calculates a global total consumption of 460 to 550 TWh/year for the residential and commercial sectors (Mills 2013). In 2018, end devices in Germany consumed 15.1 TWh (Grünwald and Caviezel 2022, 17). Considering sustainability, it is important to take into account the life cycle of end devices: while the production of smartphones accounts for 80% of CO2 emissions in the life cycle, it is significantly lower for televisions at 33% (Kamiya 2020). Although smartphones are much more efficient than televisions, they are also replaced more frequently, increasing production emissions and electronic waste. Coroama and Mattern quote: "Annually, we produce the weight of about 4500 Eiffel Towers in electronic waste. Trend: rising" (Höfner 2019, 33). The original source could not be found, but the example serves for visualization. With 53.6 million tons of electronic waste per year (Forti et al. 2020), it was already 5307 Eiffel Towers in 2019.

(2) ICT Infrastructures

The odyssey of an email from sender to recipient consists of the following stages: After being composed and sent by the sender, who uses their email client to send it to the SMTP server, the email undergoes transmission between servers. DNS servers resolve domain names and determine the path to destination SMTP servers. The recipient's SMTP server forwards the email to the recipient's mailbox. Thus, information traverses fixed networks and/or mobile networks, IXP servers and/or data centers, possibly even undersea cables (webtechnologien.com, n.d.).

The total power consumption of ICT infrastructure including data centers in Germany is 22 TWh/year (Grünwald and Caviezel 2022, 8). A realistic future projection for 2030 is 30.6 TWh/year, with a worst-case scenario of 58.5 TWh/year (Grünwald and Caviezel 2022, 8). Of this, telecommunications networks, including fixed, mobile, and broadband cable networks, consume 7.3 TWh/year, with a rising trend (Grünwald and Caviezel 2022, 27). In 2018, the energy demand of ICT end devices decreased, but due to the increasing degree of connectivity and the growing consumption of streaming services, the energy demand of ICT infrastructure rose (Grünwald and Caviezel 2022, 17). Kamiya predicts a 55% annual growth in video streaming consumption via mobile networks (Kamiya 2020).

The annual report from Nokia identifies the operation of ICT network infrastructure in the life cycle as the main driver of greenhouse gas emissions, as opposed to the manufacturing and transportation of network components (Nokia 2020).

(3) Data Centers

In 2018, the electricity demand of data centers was 205 TWh, approximately 1% of the global demand (Masanet et al. 2020; Renzenbrink 2013). In the United States, data centers caused 31.5 million tons of CO2 emissions, accounting for 0.5% of all greenhouse gas emissions in the country (Siddik, Shehabi, and Marston 2021). Data centers in Germany consumed 14.9 TWh in 2019 and 16.0 TWh in 2020, with a rising trend (Grünwald and Caviezel 2022, 27). Data centers include both central computers and decentralized (nano)servers, also known as Edge Computing or Fog Computing (Baischew et al. 2022, 18-19). Edge Computing is an approach in distributed data processing where computational power is offered at the network's edge and closer to end devices to minimize resource consumption in transmitting data over ICT network infrastructures (Baischew et al. 2022, 19). Fog Computing is an extended form of Edge Computing aiming for a more flexible resource positioning (Baischew et al. 2022, 19). However, energy consumption in Fog Computing is higher compared to central servers when the number of requests is low (Baischew et al. 2022, 19).

Data centers also have a direct and indirect water footprint: While the direct water consumption relates to server cooling, indirect water consumption involves, among other things, generating (renewable) electricity, operating other power plants, and treating wastewater (Siddik, Shehabi, and Marston 2021). In the U.S., data centers consumed about 513 million cubic meters of water in 2018, of which 130 million cubic meters were used directly (Siddik, Shehabi, and Marston 2021). Due to the significant water requirements for server operation, careful consideration of the location for establishing a data center is essential (Siddik, Shehabi, and Marston 2021).

Predictions

Future achievements of technological progress can be forecasted using generally accepted and employed "rules of thumb":

(a) Moore's Law states that the computing power of computers doubles every two years (Grünwald and Caviezel 2022, 9; Höfner 2019, 24-27). After Moore's Law slowed down from the beginning of the 21st century, Koomey's Law is used to depict the efficiency gains of data centers (Koomey et al. 2011). Energy efficiency is expected to double every 2.7 years since 2000, and power consumption is halved every 2 years (Aslan et al. 2018; Koomey and Naffziger 2015). Although data center workloads tripled since 2015, they still consistently consume 1% of global electricity (Kamiya 2020). Between

2010 and 2018, the computer workload of data centers increased by 550%, while electricity consumption only increased by 6% (Siddik, Shehabi, and Marston 2021). Despite observations that websites and software tend to be programmed more inefficiently, potentially leading to a larger ecological footprint (Carré 2018, 128-131), overall energy per retrieval is decreasing due to increasing efficiency in data centers.

(b) Wirth's Law states: "Software is getting slower more rapidly than hardware is getting faster" (Wirth 1995; Höfner 2019, 24-27). This implies that due to additional software extensions, computational intensity increases, and the software functions less efficiently and slower on the same ICT devices; simultaneously, the thesis suggests that technological progress for hardware cannot keep up with software requirements. Nevertheless, an infinite progress of software is not expected because innovation exists only in the interplay of software and hardware. Wirth's Law describes the tendency for software to be a driving factor for hardware developments and the replacement of ICT devices.

(c) The previously described Jevons Paradox (Rebound Effect) implies higher resource consumption due to efficiency gains (Carré 2018). Kamiya raises the pertinent question: "[C]an efficiency keep pace with exponential growth in demand?" (Kamiya 2020).

The following trends can be observed: Whether through iCloud, Dropbox, Facebook, or Google Drive, the outsourcing of storage capacities is increasing among consumers (Carruth 2014, 341). Furthermore, the consumption of content produced by multimodal AI systems, such as ChatGPT or Dal-E, is on the rise (Albrecht 2023; Potrimba 2023). These interactive AI systems enable the creation of personalized content specialized for consumers. AI models have a very high but one-time energy consumption during their training phase, although the lifespan of a model variant is not long and requires constant adjustment (Albrecht 2023). New technological gadgets like Virtual Reality (VR) or Augmented Reality (AR) (Kamiya 2020), such as the Apple Vision Pro glasses (Apple 2023), open up new virtual possibilities for work and consumption that, at least in the short term and overall, increase energy consumption. As the internet is commercial in nature, different cloud services compete for users' attention (Bronner 2022), either to display advertisements or to improve AI systems through interactions. The internet aims to be used.

A trend is that large cloud and data centers are built for efficiency reasons instead of many small decentralized servers to reduce the ecological footprint (Siddik, Shehabi, and Marston 2021). This results in the locations of these data centers being subject to highly focused environmental impact (Siddik, Shehabi, and Marston 2021).

In the securities trading sector, high-frequency traders, i.e., computer algorithms (algo traders), are gaining importance. They perform rapid transactions to earn cents and are among the drivers of the increasing speed of information exchange (Carruth 2014, 358). Furthermore, the number of energy-intensive blockchain applications is increasing, especially cryptocurrencies like Bitcoin, which consume 10 to 20% of the world's electricity through the so-called Bitcoin mining (Grünwald and Caviezel 2022, 14-34). While Bitcoin mining consumed 41 to 64 TWh for 120 million transactions in 2019—equivalent to 340 to 530 kWh per transaction—it was around 100 TWh in 2022 (Grünwald and Caviezel 2022, 32-33; Stoll, Klaaßen, and Gallersdörfer 2019)—equivalent to the energy consumption of the countries Jordan and Sri Lanka (Stoll, Klaaßen, and Gallersdörfer 2019). Crypto mining even consumes more energy per $1 than mining for $1 worth of gold, copper, platinum, or other rare earth oxides (Krause and Tolaymat 2018). In the period from January 2016 to June 2018, Krause and Tolaymat estimated the emissions of the four cryptocurrencies—Bitcoin, Ethereum, Litecoin, and Monero—to be between 3 and 15 million tons of CO2e (Krause and Tolaymat 2018).

Ecological Sustainability Factors

What does sustainability mean in this context? "Sustainability or sustainable development means satisfying the needs of the present without limiting the possibilities of future generations. It is important to consider the three dimensions of sustainability—economically efficient, socially just, ecologically viable—equally." ("Nachhaltigkeit (nachhaltige Entwicklung)" n.d.). Socially just sustainability, in the context of the internet, deals with issues such as fair globalization, dealing with electronic waste, working conditions, the diffusion of content, but also with the quasi-monopoly and hegemony of the USA in the global distribution of data centers (Carré 2018, 139). Approximately 30% of all data centers are located in the USA (Siddik, Shehabi, and Marston 2021). Albrecht points out the outsourcing of large amounts of low-paid work, such as coding data, for training AI systems (Albrecht 2023). Social sustainability is a broad field that examines and critically questions structures and developments; in this work, I will not delve further into it. Although economic and ecological sustainability have overlaps, I will focus only on the latter.

In the context of the internet, a "richtige Weichenstellung in Richtung Nachhaltigkeit" is crucial for future development (Baischew et al. 2022, 4). In the following, I will focus on ecological sustainability factors, identifying (A) the extension of the life cycles of ICT, (B) the use of renewable energies, and (C) the increase in efficiency.

(A) Extension of ICT Lifecycles

The lifecycle of an Information and Communication Technology (ICT) encompasses the extraction of raw materials, the manufacturing of both hardware and software, including promotion and sales, usage, and ultimately, the disposal of electronic waste or recycling (Carré 2018, 119-120; Höfner 2019, 14-17). The lifecycle also includes environmental consequences such as health, toxicity, groundwater pollution, and further biodiversity destruction, etc. (Carré 2018, 119-120). Gröger and Herterich explain that extending the lifespan of ICT is the most crucial lever for reducing the ecological footprint of consumers, aiming to curb the emission-intensive production of new ICT (Höfner 2019, 24-27).

Gröger and Hertrich argue that software developers also have a responsibility to implement sustainability in software development (Höfner 2019, 24-27). Software contributes to hardware obsolescence because it is programmed to align with the latest technological hardware standards, leading to the need to replace older hardware with newer versions and indirectly inducing environmental impact (Höfner 2019). The so-called Feature Creep in programming describes the tendency to add additional requirements and functionalities in subsequent versions of the software, causing the software to run inefficiently and requiring a hardware upgrade (Höfner 2019). To enable resource-efficient handling and long-term usability of hardware, Gröger and Hertrich propose the option to install selected core modules of software independently during updates of a software system (Höfner 2019, 26ff). This backward compatibility and longevity can be promoted through quality seals (Höfner 2019, 26ff).

(B) Use of Renewable Energies

An ecological sustainability factor involves the use of renewable energies, among other things, to reduce CO2 emissions. Although the Climate Protection Act (KSG) in Germany fixes the annual emission quantity, it does not explicitly address the information and telecommunications sector (Baischew et al. 2022, 4). Providers of digital infrastructure and cloud services seem to be aiming for climate neutrality on their own initiative, increasingly investing in renewable energies such as solar and wind energy, thereby reducing their ecological footprint (Siddik, Shehabi, and Marston 2021; Carruth 2014). The ecological footprint depends on the geographical location and the local power mix (Siddik, Shehabi, and Marston 2021). Reliability and fail-safe power supply are among the highest priorities for data centers, making the full provision of renewable energy a challenge (Grünwald and Caviezel 2022, 13).

ICT infrastructures and data centers constitute only a part of the energy consumption of the internet; the most significant consumption occurs through the ICT itself. A green energy transition, providing households and businesses with regeneratively generated electricity, is essential for sustainability in this regard as well.

(C) Increasing Efficiency

Moores's Law and Koomey's Law were mentioned to predict technological progress and efficiency improvement. Kamiya notes that data centers consume only 1% of global electricity, even though the workload has tripled since 2015 (Kamiya 2020). The increase in efficiency can be implemented through several methods across different pillars of the internet. Doleski suggests a digital decarbonization method, where more computing power can be used to reduce the ecological footprint (Doleski et al. 2021).

One approach is to utilize smart home, smart building, smart grids, or smart city concepts to save electricity and optimize heating (Grünwald and Caviezel 2022, 19 & 42ff; Doleski et al. 2021, 237). Doleski advocates for the electrification of the heating and transportation sectors (Doleski et al. 2021, 237). For ICT infrastructures, copper-based Digital Subscriber Line (DSL) technologies can be replaced by fiber optic technologies (FTTB, FTTH), which would require less than half the electricity (Grünwald and Caviezel 2022, 30-31; Baischew et al. 2022, 8ff). Nevertheless, both copper and fiber networks would be used in parallel during the transitional phase, initially increasing energy consumption (Grünwald and Caviezel 2022; Baischew et al. 2022).

In ICT infrastructure, 5G technology is praised for its energy efficiency, as it could save 85% of greenhouse gas emissions compared to 4G mobile technology (Grünwald and Caviezel 2022, 30; Baischew et al. 2022, 16ff). The 5G network has higher energy elasticity and can be scaled down outside peak hours (Baischew et al. 2022, 17). However, the 5G network is controversial because the overall energy demand would increase due to the shorter range of the radio connection and the need for more transmitter antennas (Grünwald and Caviezel 2022, 30; Baischew et al. 2022, 16ff).

Efficiency in the context of software means programming it as resource-efficiently as possible - "climate-friendly websites" (Nast 2021). According to Gröger and Herterich, Windows 10 requires forty times more processing power, 250 times more RAM capacity, and 320 times more hard drive capacity compared to Windows 95 (Höfner 2019, 24-27). Despite the same functionality of certain software, there is a different energy consumption, for example, in internet browsers and content management systems (CMS) (Höfner 2019, 24-27). Gröger and Herterich propose loading only necessary applications into the memory to achieve resource-efficient usage and long-term usability of hardware (Höfner 2019, 24-27).

Data centers generate a lot of waste heat. Many servers are cooled by air cooling; however, liquid cooling, such as with water, is much more powerful and efficient, requiring up to 80% less energy (Grünwald and Caviezel 2022, 11). In terms of sustainability, it is possible to feed this waste heat into district heating networks (Baischew et al. 2022), saving about 4 million tons of CO2 emissions annually (Grünwald and Caviezel 2022, 10). However, the conversion costs to district heating networks are unfortunately not lucrative with existing low natural gas prices and require longer-term investments (Grünwald and Caviezel 2022, 29ff). Regarding more efficient cooling, strategic consideration of specific geographies where a data center is built is crucial: taking into account the climate zone, water availability, building energy standards, and local regulatory frameworks can save energy (Doleski et al. 2021; Siddik, Shehabi, and Marston 2021).

There is also potential savings of about 4 to 10% in data centers by converting servers to use direct current (DC) (Grünwald and Caviezel 2022, 11-12). Although the power grid provides alternating current, which needs to be converted twice for accumulators functioning with direct current (Grünwald and Caviezel 2022, 11-12). The conversion process from alternating current to direct current and back to alternating current results in avoidable losses (Grünwald and Caviezel 2022, 11-12).

Lastly, finding an efficiency optimum in distributing computing and storage capacities across various environments is essential. On one hand, there is the possibility to decentralize computing and storage capacities: the establishment of local edge and fog computers can avoid long distances through relatively energy-intensive ICT infrastructures (Baischew et al. 2022, 13-14 & 18-19). Since smartphones function so energy-efficiently, computing and storage capacities could be implemented on end devices. Besides the qualitative advantages of convenient cloud services, the limitations of a device in terms of advancing software capabilities are limited. On the other hand, there are ways to centralize computing and storage capacities: Green IT, for example, involves virtualizing servers through cloud computing, outsourcing the workload to large data centers, "increasing their utilization by up to 60% compared to traditional servers, and at about the same energy consumption under full load" (Dibbern 2010, 33). Grünwald confirms that larger data centers function comparatively more energy-efficiently (Grünwald and Caviezel 2022). In centralized data centers, waste heat could be synergistically utilized.

It is crucial to establish a balanced relationship between centralization and decentralization for optimized load management (Doleski et al. 2021). Through prediction and optimization services, electricity generation from renewable energies could be intelligently integrated (Doleski et al. 2021, 237-238). One idea involves spatially coordinating the workload through intelligent swarm platforms, favoring data centers where renewable energy is available (Grünwald and Caviezel 2022, 14ff).

Conclusion

The internet often eludes the ecological discourse in environmental sciences, despite being built on the three material pillars of ICT, ICT infrastructures, and data centers, with an energy-intensive resource consumption. However, when the entire digital ecosystem accounts for 10% of all electricity used by humans, it becomes essential to contextualize it within our social lifestyle. Although the internet, along with its high-profile cloud services, is a fundamental part of our consumption culture, it currently consumes (still) relatively little energy. Looking at technological progress and the rebound effect as a response to efficiency gains, coupled with the computation-intensive individualization of entertainment offerings through multimodal AI systems, digital consumption and energy use are expected to continue growing. This prompts the question of how quickly efficiency can keep up with demand. Nevertheless, there is room for sustainable developments that reduce the ecological footprint while the volume of data continues to rise. Subsequently, I identify three ecological sustainability factors: extending the life cycles of ICT, investing in and using renewable energies, and increasing efficiency constitute the most potent lever for a sustainable future. The primary focus was to raise awareness about the materiality of the internet; aspects of social sustainability require a more in-depth exploration beyond the scope of this work.

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