The Digital Environmental Footprint - a holistic framework of Digital Sustainability

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Abstract: This paper examines the different ways in which the Information and Communications Technology (ICT) sector negatively affects the environment. To capture environmental externalities beyond the common but limited carbon footprint, a novel holistic framework of digital sustainability was created - the Digital Environmental Footprint (DEF). To apply and test the DEF, the ICT sector was evaluated regarding its impacts on the sustainability dimensions of global carbon footprint, biodiversity, and availability of non-renewable resources. It was found that the production phase of digital devices has the most severe impact on these dimensions, followed by the end-of-life phase. The use phase was found to have moderate but significant impacts on sustainability that are expected to decrease over time alongside the global Carbon Intensity of Electricity (CIE). This paper emphasizes the importance of considering dimensions of digital sustainability beyond carbon footprint and the need for establishing holistic metrics for evaluating the sustainability of the ICT sector.

Table of Contents

1 Introduction

Climate change, biodiversity loss, and the destruction of natural resources are core challenges for our global society as they threaten the wellbeing and long-term survival of humans and the ecosystems we depend on. As such, the concept of sustainability and the importance of making efforts towards achieving a more environmentally sustainable future have become a main focus in global policy. In many countries, sustainability considerations have become evident in central areas of human life such as nutrition and transportation (Gössling, 2020; Holmberg & Erdemir, 2019; Springmann et al., 2021; Willett et al., 2019). Remarkably, however, a focus on the negative environmental impacts stemming from digital life is rarely observed despite the rapid digitalization occurring in every region (Berthoud et al., 2019; Manhart et al., 2016).

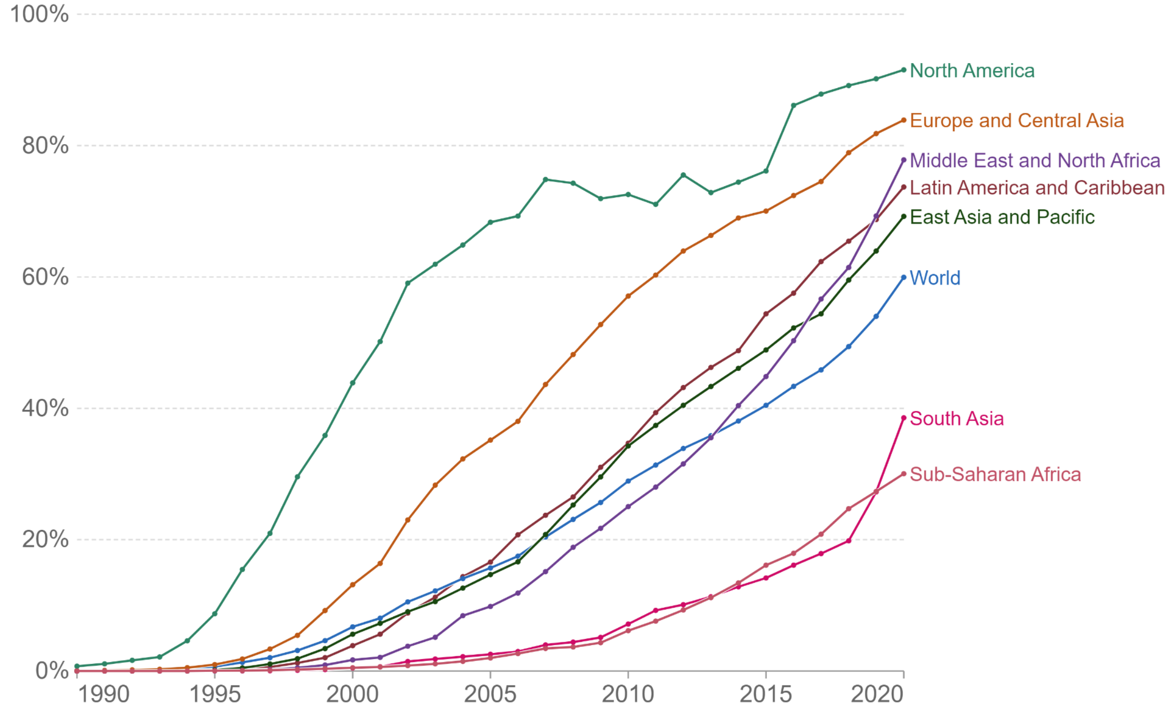

Figure 1: “Share of the population using the Internet“. Adapted from “Our world in Data” who visualized data collected by the International Telecommunication Union (*Share of the Population Using the Internet*, 2022). Internet users are defined as those having used the internet in the last three months, from any device and location.

Figure 1 impressively demonstrates how most regions of the world have ramped up their access to the internet from insignificant percentages at the end of the 20th century to above 60% in 2020. This upward trend is generally expected to continue, especially as the COVID pandemic has further fueled digitalization, leading to a rapid increase in the development and use of digital technologies (Hantrais, 2020).

Due to this rapid digitalization, It is crucial to understand the adverse effects that digital life carries with it to adequately evaluate and navigate this transition. As will be shown in this paper, the production, use, and end-of-life phases of digital devices are creating negative externalities[1] that damage the environment by generating carbon emissions, depleting non-renewable resources, and compromising the health of our ecosystems.

However, only the carbon footprint is generally employed to evaluate the sustainability of the Information and Communications Technology (ICT) Sector[2] despite significant shortcomings of this single-variable analysis (Belkhir & Elmeligi, 2018; Berthoud et al., 2019; *Ericsson*, 2020; Gröger, 2020). In the following sections, I present a compelling and holistic conception of digital sustainability that is based on the three sustainability dimensions of carbon footprint, resource availability, and biodiversity - the “Digital Environmental Footprint (DEF)”. Digital sustainability being a rising field of research and discourse, it is crucial to investigate fundamental questions such as the following:

RQ: Can sustainability evaluations of the ICT sector be improved by including the relevant variables of biodiversity and resource availability beyond carbon footprint?

Cultivating the most important variables for sustainability analyses of the rising ICT sector is important to inform industry and policy makers about the most pressing sustainability concerns within the industry. As the concept of “digital sustainability” is still emerging, researchers have the opportunity to create high-quality frameworks that effectively inform ICT stakeholders.

The research question is answered by constructing an integrated framework of digital sustainability based on differentiated definitions and a review of current sustainability analysis practices in Section 2. In Section 3, the Digital Environmental Footprint (DEF) framework is then applied and tested via a sustainability evaluation of the global ICT sector, examining environmental externalities for the production, use, and end-of-life phases of digital devices for each of the framework’s variables. Finally, impact hotspots[3] within the life-cycles of digital devices are identified based on the results in Section 4, before the results and the DEF are evaluated in the Discussion and conclusion (Section 5).

2 Theoretical Framework

2.1 Conceptions and Models of Sustainability

Given the importance of the concept of sustainability to this paper, it makes sense to define it properly from the get-go. I will roughly adopt the most widely used definition which was established in 1987 by the Brundtland Report of the United Nations as “**seek[ing] to meet the needs and aspirations of the present without compromising the ability to meet those of the future**” (Secretary-General & Development, 1987). What emerges as the core of this definition is the aspect of *balancing* present actions to ensure that the possibilities and the wellbeing of future generations are met. While “those of the future” usually refers to humans, we should acknowledge that humans are part of the global ecosystem

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[1] Negative externalities are negative effects caused by a product or service to a third party (neither producer or consumer). For example, by throwing broken headphones into a lake, negative externalities are possibly incurred by local fishers, tourists, flora, and fauna.

[2] A definition of the ICT sector can be found in section 2.2.

[3] Impact Hotspots are the parts of a product’s lifecycle where most of the impact is concentrated. See sections 3.1 and 4.2 for a more detailed explanation.

and that humanity's welfare is very much dependent on the welfare of that ecosystem and the future generations of all species inhabiting it.

This *balancing aspect* within this conception of sustainability is present in highly influential sustainability models of our time. The Doughnut Model created by Kate Raworth (Raworth, 2012) highlights the "safe and just space for humanity" in between human shortfall (too little resources for humanity) and overshoot (humanity exploiting earth excessively). Quite similarly, the Planetary Boundaries Model proposed by Rockström et al. (2009) is a quantitative framework in which respecting planetary boundaries is deemed sustainable while disrespecting them is unsustainable (*Ten Years of Nine Planetary Boundaries*, 2019). Even the classic and superseded Three Pillars Model asks us to balance the demands of the social, environmental, and economic pillars of society (Purvis et al., 2019). It seems clear then that sustainability is about balancing out the needs and demands of different stakeholders of present and future societies.

2.2 Defining the Digital Sphere

Digitalization is a major concept and development of our time. Before addressing "digital sustainability", we should first define what we mean by "digital". For the purposes of this paper, these are the most important terms that encompass the digital sphere.

Digital Device - electronic device that can create, generate, send, share, communicate, receive, store, display, or process information, and such electronic devices shall include, but not limited to, desktops, laptops, tablets, peripherals, servers, mobile telephones, smartphones, and any similar storage device which currently exists or may exist (*Digital Device Definition*, n.d.).

Digital Service - service that is primarily provided via digital devices as defined above, for example a smartphone messaging app or a cloud to upload files onto the internet.

Information and Communications Technology (ICT) - an umbrella term that is used to refer to the sector that produces, enables, provides, and consumes digital devices and services (*ICT Definition*, n.d.).

Digitalization - The uptake of digital devices and services (as defined above) instead of analog ones. Digitalization can occur in a workplace, an industry, or even in society as a whole.

In this paper, all of these terms will be used. They are never used interchangeably but are very related to each other, as becomes apparent when reading all the definitions.

At this point, it is important to mention the three phases of digital life: production (aka manufacturing), use (aka consumption), and end-of-life (aka disposal). This division is a slight adaptation of what is commonly used when evaluating the impact of digital devices and services (e.g., Berthoud et al., 2019; Manhart et al., 2016). The division into these phases is also commonly used in Life-Cycle Analysis, which is elaborated on in Section 3.1 and serves as a guiding analysis structure of Section 3.

The phases of digital life apply to digital devices and services differently. While knowingly disregarding the human effort that goes into producing and discarding digital services, the analysis of the use phase includes all impacts caused by digital services.[4] While technically, digital services have an

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[4] Digital devices are physically produced while digital services are programmed or designed to be utilized. For the sake of simplicity, *production* shall refer to the physical production of digital devices while *use* refers to the usage of

end-of-life phase (services create a lot of "digital waste"), differentiation is difficult.[5] As I am interested in evaluating the impact of the entire ICT sector, it makes sense to include digital services in the analysis due to their interconnectedness with and importance to digital devices.

2.3 Reviewing the Dimensions of Digital Sustainability

2.3.1 Current Approaches to Evaluating Digital Sustainability

As access to ICT rises all around the world, the energy demand of this process is increasing accordingly (Das & Mao, 2020), and warnings of e.g. ICT's immense energy consumption are becoming louder. However, most of the externalities caused by ICT are "invisible" to the consumer because they occur in data centers and networks (*Towards Digital Sobriety*, 2019).[6] While the exhaust coming from a car is a very noticeable externality of car travel, the negative externalities of digital services are not as easily observed because they occur far away from the consumer.

Commonly, when evaluating the sustainability of the ICT sector, carbon footprint is the single metric considered (*Ericsson*, 2020; *Towards Digital Sobriety*, 2019; Gröger, 2020). The **Digital Carbon Footprint (DCF)** is being calculated for digital services like websites and video streaming, as well as digital products like mobile phones (*Ericsson*, 2020; Gröger, 2020). This focus on the climate implications of digitalization is understandable given the importance of climate change in the public debate and the relative ease of measuring and calculating the carbon footprint. It is commonly expressed in carbon dioxide equivalent (CO2e) where other greenhouse gases (GHGs) are converted into CO2e according to their global warming potential (GWP) relative to CO2 (*CO2 Equivalents*, 2014). For example, a farm responsible for 10 kg of methane emissions would have a carbon footprint of 840 kg of CO2e because methane's GWP is much higher than that of CO2 (*CO2 Equivalents*, 2014).

The good quantifiability of CO2e allows for relatively simple estimations of the impact of the ICT sector on the global climate relative to other products and services. For example, Belkhir & Elmeligi (2018) estimate via a sophisticated modeling study that the total global carbon footprint of the ICT sector is estimated to be between 3.2% and 4.2% of the global carbon footprint, depending on the modeling scenario. Belkhir & Elmeligi's (2018) paper was examined alongside other studies as part of a literature review performed by Bieser et al. (2020) who found that the DCF for production, use, and end-of-life phase are commonly estimated to lie between 1.8% and 3.2%.

Digitalization is often thought of as a driver of efficiency - a concept tightly connected to sustainability. This becomes apparent in the concept of "eco-efficiency", which is a philosophy that was embraced by the 1992 Earth Summit and is defined as "creating more value with less impact" by increasing the efficiency of operations (Lehni, 2000). It is thus generally hoped that, besides the developmental benefits of ICT uptake (Ezell, 2012), a more digital economy is a more sustainable one (Beier et al., 2020).

However, "rebound effects" are casting doubt on the fact that more efficient technologies necessarily lead to decreased energy expenses (Sun & Kim, 2021). Once a technology becomes more

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those devices. In that sense, software development does count towards use which is a disfigurement of this categorization I am willing to accept.

[5] Old and unused websites, emails, and files that are stored on the cloud should technically count as digital waste. However, they require the same resources (electricity and whatever else is needed to run a data center) as the websites, emails, and files that are still being used. It is hard to impossible to distinguish between used and unused ones which supports this categorization.

[6] See Section 3 for more information.

efficient, it is also used more, which in turn increases the required energy (Beier et al., 2020). While the gains in efficiency might justify the increase in externalities, they are rarely considered holistically, which is why two other dimensions of sustainability are proposed for evaluating the sustainability of the ICT sector below.

2.3.2 Proposing two crucial dimensions of digital sustainability

While the DCF is a crucial factor to consider when evaluating the sustainability of the ICT sector, there are other environmental implications than carbon emissions that cause unsustainable harm. Two dimensions of sustainability in particular are especially affected by the ICT sector, and I am arguing that they should be addressed whenever the sustainability of the ICT sector is evaluated: **biodiversity** and the availability of non-renewable resources (short **- resource availability**). In the analyses of Section 3, it will become clear that these dimensions are of similar importance to sustainability as carbon footprint as they represent two other areas in which the ICT sector is excessively consuming resources and thereby unsustainably sacrificing the wellbeing of future generations.

By considering measures of sustainability beyond carbon footprint, I want to advocate for holistically assessing the sustainability of digital life. The level of reductionism employed by reducing sustainability to carbon footprint measured in CO2e is an overall insufficient assessment - a grievance that is commonly acknowledged (Gröger, 2020; Manhart et al., 2016) but has so far not been sufficiently addressed. Despite dimensions of sustainability like biodiversity and resource availability being harder to measure (UNEP-WCMC, 2020), it is important to acknowledge that environmental damage caused by digital life occurs outside of GHG emissions and to develop better frameworks and measurement tools to effectively incorporate such measures into established indices. In this sense, this paper is filling a research gap where assessments of digital sustainability have been dominated by carbon footprint considerations and claim holistic legitimacy while disregarding major impacts.

It is important to note that all three sustainability dimensions addressed here are hugely interconnected. Climate change, for example, is majorly impacting biodiversity on a global scale (IPCC, 2002).

2.3.3 Biodiversity Dimension

Biodiversity is a central metric of sustainability, especially considering the ongoing unprecedented biodiversity loss occurring on a global scale (Diversity Secretariat of the Convention, 2020). As of 2020, about one million plant and animal species are under the threat of extinction, and damaged ecosystems have impacted 3.2 billion people worldwide and contributed to the global COVID-19 pandemic (Lawler et al., 2021; UNEP-WCMC, 2020). Accordingly, biodiversity loss is one of the dimensions considered in major comprehensive sustainability frameworks such as the Doughnut and planetary boundaries models described above (Raworth, 2012; Rockström et al., 2009).

Biodiversity is a crucial dimension of sustainability to be considered when evaluating the ICT sector. The mining necessary to source the minerals needed to construct digital devices are causing massive harm to local ecosystems (Cook & Jardim, 2017; Manhart et al., 2016; UNEP, 2017b). Meanwhile, data cables and data centers are putting stress on marine ecosystems and groundwater levels (Andersen, 2021; *ICPC*, 2016; Siddik et al., 2021). Furthermore, discarding digital devices only rarely leads to proper recycling of the metals and too often pollutes the environment, causing harm to the ecosystems humans depend on (Awasthi et al., 2016; Forti et al., 2020; Neitzel et al., 2020).[7] It seems thus clear that biodiversity should be considered in digital sustainability evaluations whenever possible.

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[7] More detail to all of these biodiversity impacts can be found in the relevant subsections of Section 3.

Unfortunately, measures of biodiversity are not nearly as standardized and commonly used as the carbon footprint. Even more than human-induced climate change, biodiversity in ecosystems is a complex system and very hard to measure and predict. There are a host of measures of biodiversity in ecology, and they are differently appropriate depending on the context. Butchart et al. (2010) assessed biodiversity loss using 30 different indicators, ranging from “Exploitation of fish stocks” to “Area of forest under sustainable management”. The lack of measurement compilation and standardization reflects that biodiversity science is young, given that humans only relatively recently started to seriously consider biodiversity on various scales (Gatti & Notarnicola, 2018).

Despite the complexity, there are promising composite biodiversity indices that are gaining increasing importance and that reflect biodiversity in a way useful for policy making. The UN Environment Programme World Conservation Monitoring Center (UNEP-WCMC) developed a composite index of “biodiversity health” - a new concept in the biodiversity sphere to bring together different biodiversity metrics and fields of study to craft one single value representing the state of biodiversity in a given region (UNEP-WCMC, 2020). They criticize that biodiversity measures remain “siloed, fragmented, and biased” and that the scientific community involved maintains that biodiversity is “too complex a concept to be captured by a single score” (UNEP-WCMC, 2020). While individual researchers like me don’t have the ability to calculate composite indices with tens of variables, the biodiversity health index helps me to define which variables to prioritize for this study.

Ecosystem Functions - Term referring “variously to the habitat, biological or system properties, or processes of ecosystems” (Costanza et al., 1997). Put differently, ecosystem functions are “the ecological processes that control the fluxes of energy, nutrients and organic matter through an environment” (*Ecosystem Function*, 2020).

Ecosystem Services - “Benefits human populations derive, directly or indirectly, from ecosystem functions” (Costanza et al., 1997).

Biodiversity Health - From an environmental perspective, an ecosystem is healthy when it is diverse, stable, and resilient (UNEP-WCMC, 2020). From a social perspective, healthy ecosystems provide the services that economies and livelihoods rely upon (UNEP-WCMC, 2020).

There is urgency to create consistent global biodiversity indicators, and the UNEP’s contestant is the most promising. The UNEP conceives biodiversity health as consisting of “biodiversity for nature” and “biodiversity for people” (UNEP-WCMC, 2020) and converts the broad idea of their framework into existing biodiversity metrics.

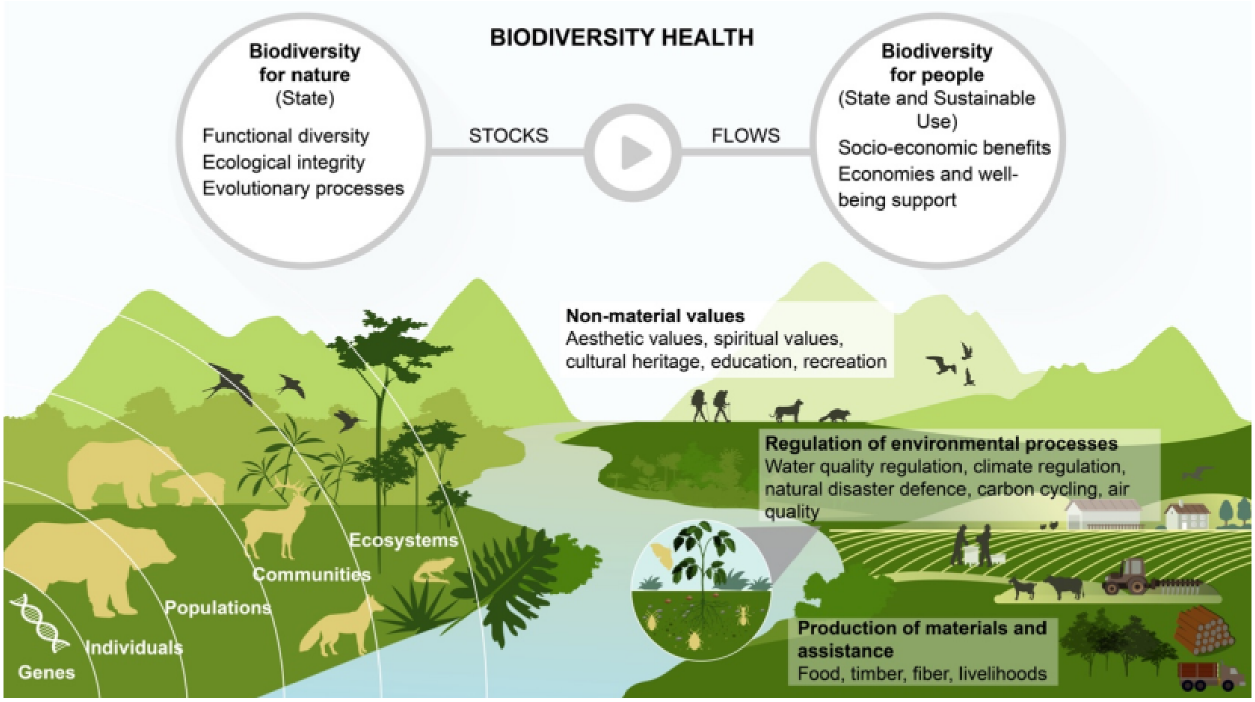

Figure 2: "Conceptualisation of biodiversity health" retrieved from UNEP-WCMC (2020). The visualization beautifully captures their key idea of combining the ecological and social perspectives of biodiversity into one model. Not all aspects of this figure are touched on in the text, but they don't need to be fully understood for the purposes of this paper.

As visualized in Figure 2, I am considering ecosystem functions and services as the two metrics for the biodiversity analysis of digital life in Section 3. Ecosystem functions address the environmental aspect of biodiversity health and ecosystem services the social aspect. Both of these are broad terms, but so are the range of impacts on biodiversity health that will be discussed in Section 3. The disadvantage of such broad metrics is that they are imprecise and often non-quantifiable. However, measuring biodiversity purely via how many distinct species are present in an ecosystem, as is e.g. the planetary boundaries model (Rockström et al., 2009), does not capture the reality of biodiversity loss where most species are not yet extinct but under threat of extinction and where biodiversity needs to be viewed through a social lens as well to become relevant to policy making (UNEP-WCMC, 2020).

The concepts of ecosystem functions and services provide effective tools to bridge the gap between biodiversity science and societal implications. Taking the example of an oil spill (the classic environmental polluter), the affected ecosystem's functions will be very disturbed, habitat will be destroyed, and the nutrient and energy flows will be altered. The oil spill would also affect the ecosystem services of the affected region because social services like *water supply*, *food production* or *recreation* are now severely limited. While it would be possible to quantify the value loss of ecosystem functions in monetary terms, given the complexity and interconnectedness of ecosystems, it is often difficult to accurately predict or assess the damage of destroying a given ecosystem (Costanza et al., 1997).

2.3.4 Resource Availability Dimension

As discussed earlier, a primary goal of sustainability is to ensure that future generations will be able to live lives of similar quality; one obvious way to sabotage that goal is by using up all the non-renewable resources (referred to as non-renewables from now on) required for the development of the products and services that are deemed to be part of a good standard of living (e.g. electronic devices, cars, internet infrastructure, etc.). Of course, it is possible to accomplish certain services via other routes (e.g. by generating electricity with solar panels instead of coal combustion), but there are varying limits to which that compensation is possible. Especially in the case of metals, conditions in which most of them can be formed are incompatible with human life on earth, which means that, unless humans "import" metals from other planets or celestial bodies, they will have to contend with the quantities that are available in the earth's crust today (Langmuir & Broecker, 2012). This is why the ongoing resource depletion caused by human activity has been pointed out as majorly unsustainable (e.g., Petrie, 2007; Prior et al., 2012).

Despite its importance to sustainability, resource availability has rarely been incorporated into sustainability frameworks and is absent from the planetary boundaries and Doughnut models (Raworth, 2012; Rockström et al., 2009). However, as will become very apparent later in Section 3, it is a key indicator to consider for digital life and worthy of intensive consideration in this context. That non-renewable minerals will be required for a sustainable development in the future is considered certain (Ali et al., 2017).

One way to maintain high stocks of non-renewables is to reuse and recycle them as often as possible. However, especially for Rare-earth elements (REEs), recycling and reusing rates are very low (Berthoud et al., 2019; Rizk, 2019). If non-renewables are manufactured in a way that makes them hard to recycle (e.g. because quantities are low or because they are hard to extract), they can escape the realm of human influence and become unavailable to future generations.

2.4 Proposing the Digital Environmental Footprint (DEF)

Given the severity of the climate crisis, continuous biodiversity loss, and the constant growth of the ICT sector, finding ways to minimize ICT's negative externalities is an important objective - it is often termed "digital sustainability" and is defined below.

Digital Sustainability - The concept of acting sustainably (as defined in Section 2.1) when producing, using, and interacting with ICT. Digital Sustainability is characterized by minimal negative externalities and thus a low Digital Environmental Footprint (as defined below). If a product or service has a large Digital Environmental Footprint and significant negative externalities, it is not digitally sustainable.

As explained in Section 2.3.1, the Digital Carbon Footprint (DCF) is a key measure to assess sustainability that has achieved political and scientific validity and has also been extended to the ICT sector. The DCF is a concept that has been defined and utilized multiple times (*Ericsson*, 2020; Evangelidis & Davies, 2021; Gnanasekaran et al., 2021) and is a very effective way of creating awareness of one of the major externalities caused by the ICT sector - carbon emissions. However, as was discussed in Section 2.3, the carbon footprint is only one of many relevant metrics of digital sustainability. It thus seems necessary to extend this concept to include metrics like biodiversity and resource availability via the "Digital Environmental Footprint" (DEF). While the DCF certainly matters, the focus of this paper lies on the DEF, in an effort to extend the focus of evaluating sustainability to key metrics beyond carbon footprint.

Digital Environmental Footprint (DEF) - The environmental footprint of the ICT sector, specifically of the production, use, and end-of-life phase of digital devices and the performance of digital services. The DEF is assessed in this paper via the sustainability dimensions of carbon footprint, biodiversity, and resource availability but generally also encompasses other metrics relevant to sustainability. A digital product or service that is found to have significant negative externalities in any of these three dimensions would have a significant DEF.

In this paper, the terms digital sustainability, DEF, and negative externalities of the ICT sector are all used somewhat interchangeably.[8] They are differently relevant to the context that is being discussed and have a different scope. Negative externalities are specific occurrences related to a product or process and might be very small and only affect one dimension of sustainability and phase of digital life. The DEF encompasses the negative externalities of all three phases of digital life for all dimensions of sustainability (three of which are evaluated in this paper) and could still refer to a specific individual product or service. Digital sustainability, then, is the overarching concept of a global digital life that has a minimal DEF and is removed from individual digital products or services.

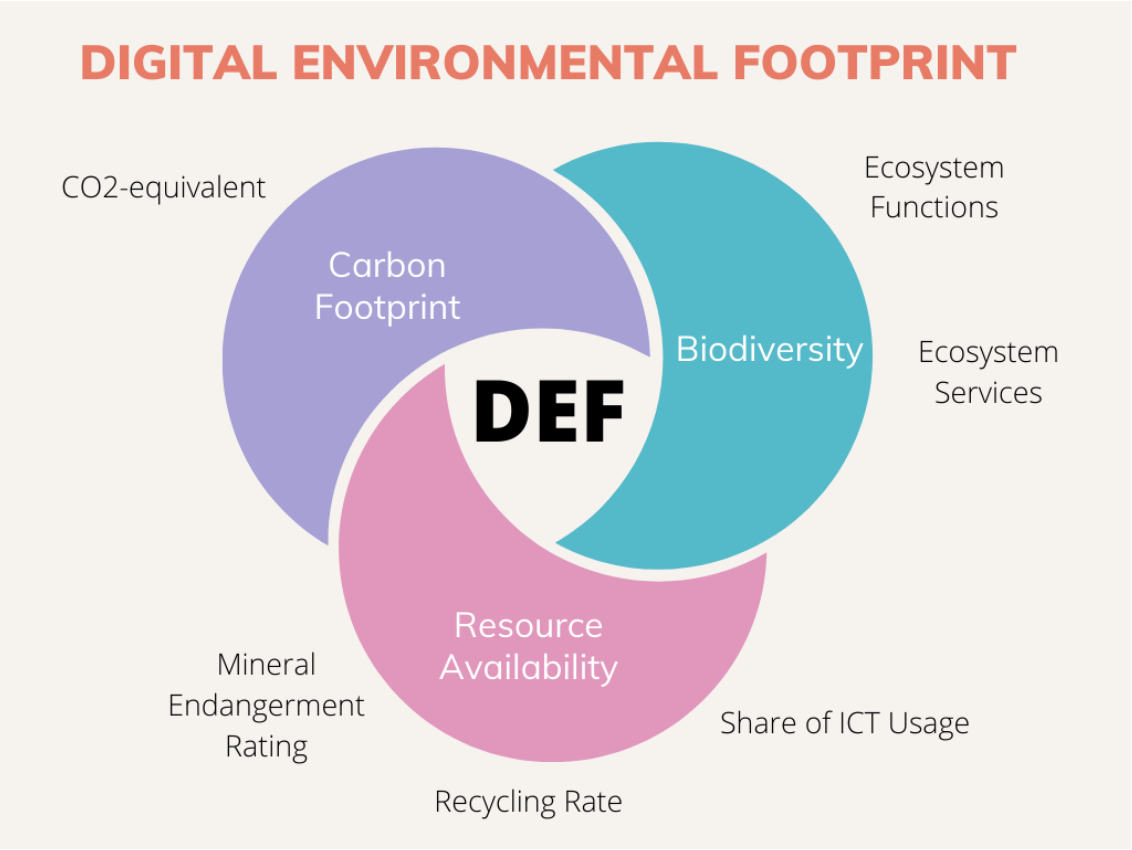

Figure 3: Visual representation of the Digital Environmental Footprint (DEF) as defined in this section. The circles making up the DEF represent the dimensions of sustainability that are employed to measure the DEF in this paper. However, the DEF encompasses more dimensions of sustainability that are relevant to sustainability (as defined in Section 2.1) but are not included in this paper. The individual terms surrounding the dimensions in the visual are the metrics via which the dimensions are measured in Section 3.

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[8] Revisit the definition of digital sustainability to see how they relate to each other.

3 Assessing the Digital Environmental Footprint (DEF)

Given the substantial disagreements over the general size and individual aspects of the DEF (Freitag et al., 2021; Kamiya, 2020), it is necessary to perform individual research on each of the phases. One general observation from Figure 4 below, taking the example of smartphones, is that the production phase is generally estimated to have the largest climate impact, at least in terms of carbon footprint. However, the significant differences in the estimations of different producers show that it is necessary to consider the underlying assumptions of these estimates. While only assessing the carbon footprint of these smartphones allows for comparisons like these, the insights we can take away from such visualizations are limited as they don't represent the true environmental cost of smartphones. The research in the following sections will help to evaluate and compare and the different impact areas, which ultimately helps to address the most severe environmental damages.

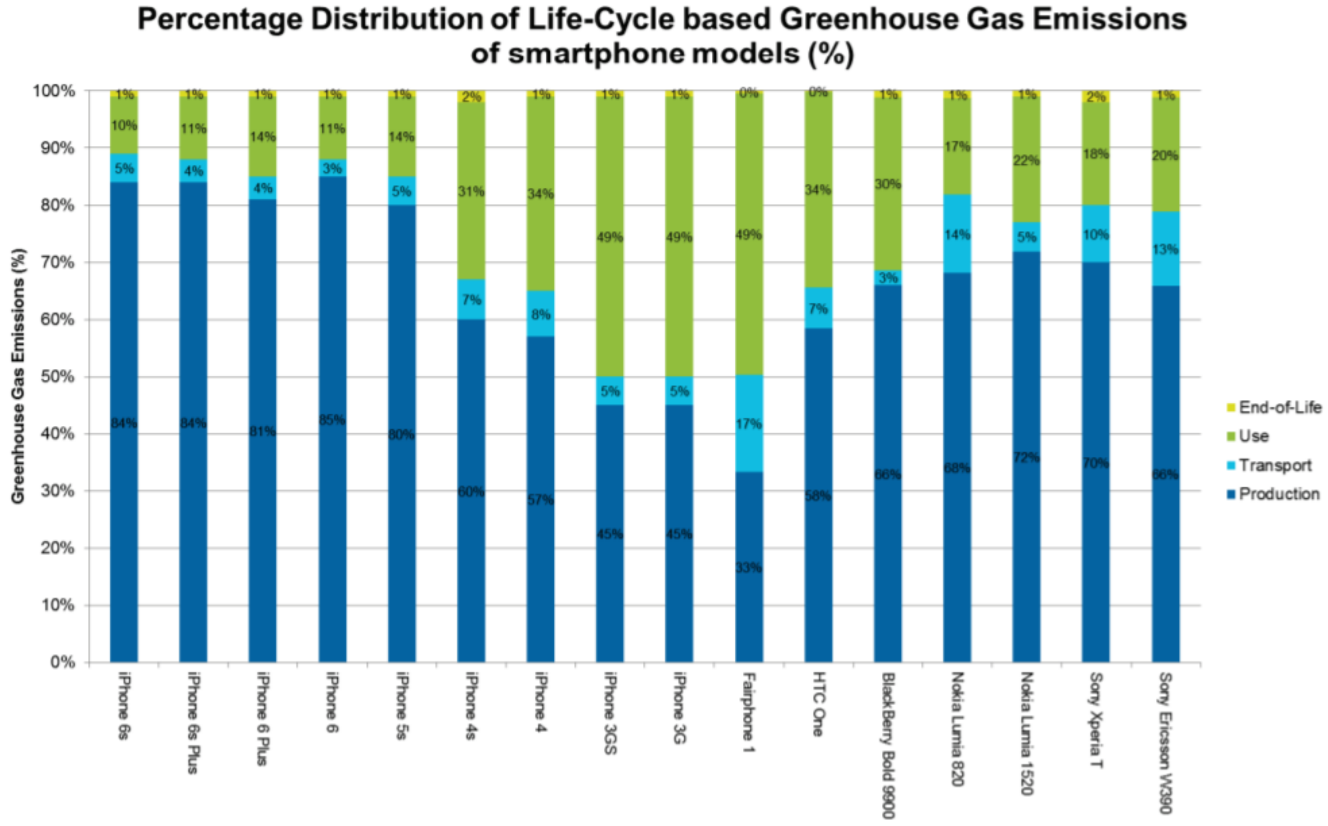

Figure 4*:* Percentage breakdown of the share of GHG emissions each phase of each smartphone is responsible for. The data was sourced from Apple, Fairphone, the HTC Corporation, BlackBerry Ltd, and third-party researchers. It was combined into this graph by Manhart et al. (2016). Notice that Manhart et al. (2016) differentiates between the transport and production phases, which are both grouped into the production phase for this paper. Note also that the total GHG emissions of each bar vary significantly between the different smartphone models and that this graph is only showing relative shares. In fact, the estimated End-of-Life emissions of the iPhone 6 Plus are much higher than those of the Fairphone 1 (Manhart et al., 2016).

3.1 Methodology

To determine the areas and actions that carry the highest potential for minimizing the DEF, all three phases of digital life were investigated: production, use, and end-of-life. Considering these three phases is common practice in holistic assessments of environmental impact. *Life-cycle assessment* (LCA) is the most common and established form of such assessments and acts as a model for the study design. The aim of LCA is to evaluate all parts of the life cycle of a given product or service regarding the important variables selected to then identify the areas that cause most damage - impact hotspots (Golisano Institute for Sustainability, 2020; *ISO 14044*, 2006). The research sections in the following analysis are structured according to the order of the phases of digital life to create a storyline and to facilitate understanding of the phase-specific vocabulary and considerations.

For the current research, a global scope was chosen to be able to most closely respond to the general research question. While a case-study or regional analysis might also have been insightful, using a global scope aims to generally establish the suggested evaluation variables in digital sustainability research. Given the limitations posed regarding accessibility of data as well as expertise of the researcher in the various research fields necessary to holistically assess this research question, one can not expect significant validity arising from this analysis. Instead, the aim of choosing a global scope is to allow for a meaningful analysis of a truly global system of digital devices being sourced, used, and discarded. The global scope does turn the analysis more exploratory than definitive and validating, which seems appropriate for the nascent research field of digital sustainability.

Most of the analysis below is presented in the style of a literature review. However, each sub-analysis arrives at a conclusion as to the DEF created in that area. An impact hotspot analysis will be conducted in Section 4.2 after each phase of digital life has been evaluated for each variable of the DEF.

3.2 Evaluating the Production Phase

There are various necessary steps to produce a digital device. The required raw materials first need to be extracted, refined, and distributed. Then, the individual parts are assembled into subcomponents (e.g. into CPUs or RAM Chips in case of laptops), which are shipped again to be assembled into final products (Chandler, 2012), which in turn need to be delivered to stores and customers.

Furthermore, there are multiple digital devices required to run a digital service. For example, in order for me to use the digital service “Google Docs”, I need a laptop, a charger, a WiFi router, network cables to transmit the information to data centers, and the data centers who process that information. On top of that, I use a mouse, an extension cord, and an ethernet cable, all of which need to be produced and require energy.

The production phase influences all three dimensions of sustainability outlined earlier: carbon footprint, biodiversity, and availability of resources. The analysis below focuses on the negative externalities created in each of these dimensions by the production of digital devices.

It is important to point out that there are significant negative social externalities related to the production of digital devices that are not covered here due to the analysis’ focus on environmental externalities, such as those related to the child labor employed to extract Mica minerals in Madagascar which are then exported to China and manufactured into electronic devices (Hodal, 2019).

3.2.1 Resource Availability of Production Phase

In this section, I will evaluate the impact of ICT production on the long-term availability of non-renewable resources. This is primarily relevant to “minerals” (will be used interchangeably with “elements” and “metals”[9]) which will be the focus of this section.[10] The question I aim to answer, as already set up in Section 2.3.4, is to what extent nowaday ICT production is contributing to creating a situation where future generations don’t have access to certain minerals anymore or need to pay significantly more to have access to such resources.

ICT production ultimately leads to wasting large quantities of minerals. In their 2020 report, the ICT Policy Section of the United Nations Conference on Trade and Development (UNCTAD) defined 24 minerals that are key to ICT production, including cobalt, lithium, tantalum, etc. (UNCTAD, 2020). The global demand for digital devices directly leads to these minerals being mined, manufactured, and incorporated into such devices, often in tiny quantities that are hard to recover.[11] Given that there is generally a low recycling rate for such minerals (Forti et al., 2020), most of them will ultimately escape the realm of human influence (further discussed in Section 3.4).

The ICT sector is directly responsible for the demand of a specific group of minerals. With rising world population, and increasing economic development and digitalization, there is a rising demand for most of these 24 “ICT minerals” defined by the UNCTAD (2020). However, following their thorough analysis, the UNCTAD (2020) identified seven specific minerals, including the Rare Earth Element (REE) group, for which the ICT sector represents most of the overall demand and is therefore directly increasing that demand as more digital products are being produced. As the demand for digital devices is increasing, there is a growing demand for these seven minerals.

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[9] There are distinct differences between minerals, metals, and elements scientifically, but for the purpose of this study, they are rather insignificant because the focus is on the overall environmental impact rather than on the impact of specific minerals.

[10] The ICT sector also requires some oil and gas for the production of plastic, but such quantities are not significant in the global context.

[11] The trend of producing smaller and smaller devices is called miniaturization. This has the effect that individual minerals are both challenging to recover physically and that disassembly is rarely profitable.

Mineral	Volume produced in 2018 (t)	ICT Usage (% of total usage)	Endangerment rating by the American Chemical Society
Indium	835	90	Red - Serious threat in the next 100 years
Gallium	323	81	Red - Serious threat in the next 100 years
Germanium	101	80	Red - Serious threat in the next 100 years
Tellurium	524	70	Red - Serious threat in the next 100 years
Tantalum	1,799	32	Orange (Rising threat from increased use)
REEs (18 minerals in total)	164,000	20	Some: Yellow (Limited Availability - Future risk to supply) Most: No endangerment rating
Selenium	2988	16	Orange (Rising threat from increased use)

Figure 5: Copy of three columns of Table 3 from UNCTAD (2020) combined with endangerment ratings by the Green Chemistry Institute. REEs are not listed in detail because they don't individually matter for the sake of the analysis. ICT Usage data was partially older than from 2018 but was assumed to still be valid. Table was organized in decreasing order of ICT usage. Sources: (*The Periodic Table of Endangered Elements*, n.d.; UNCTAD, 2020)

The list of the seven ICT minerals also happens to include some of the most endangered minerals. The ACS Green Chemistry Institute lists nine endangered elements on the "red list" that are likely to face serious supply threats in the coming 100 years and seven "orange list" minerals that are under "rising threat from increased use" (*The Periodic Table of Endangered Elements*, n.d.). Looking at Figure 5, we can see that it includes four red list elements and two orange list elements. The fact that four out of nine elements that are most under the threat of extinction are demanded by more than 70% by the ICT sector is highly worrying.

The example of indium demonstrates how threatened the elements on the red list are. Indium is mainly used for LCD Displays and total reserves on earth are somewhere between 15,000t and 50,000t (Lokanc et al., 2015). The ICT sector uses ~750t per year (see Figure 5; 90% of 835) which is very significant relative to these limited all-time reserves. If the demand continues at the 2018 rate, it would mean that indium reserves will be depleted in the next 20 - 67 years. However, indium demand is expected to increase by 41 - 52% by 2040 which could further shorten that time (Marscheider-Weidemann et al., 2021). Furthermore, because indium is mainly extracted as a by-product of zinc, increasing its production beyond current levels would only be possible at a much higher cost, which would also need to be paid by future generations (Lokanc et al., 2015).

The example of indium in combination with Figure 5 effectively highlights how much pressure the ICT sector is putting on global resource availability. In some way it is an unlucky coincidence that the minerals that are most demanded for digital devices are also not very abundant. However, that does not take away from the fact that the ICT sector is actively depleting some of the most endangered elements, thereby threatening the ability of future generations to use them. For example, compared to a smartphone, the production of a connected TV requires more than 1000 times the amount of Indium and 400 times the amount of Gallium (Berthoud et al., 2019). These sorts of negative long-term externalities of production are not commonly known or taken into account by digital users.

The employed metrics clearly show that ICT production has a high impact on resource availability. In Figure 5, the endangerment rating shows under how much threat each of the minerals are and the causal relationship to the demand ICT can be safely assumed.

3.2.2 Carbon Footprint of Production Phase

To give a good impression of the size of the DEF in this area, I am taking the example of the widely-used devices of laptops, smartphones, and tablets.

Production of	Resulting Carbon Footprint
Laptop (with SSD)	~ 311 kg CO2e
Tablet	~ 150 kg CO2e
Smartphone	~ 100 kg CO2e

Figure 6*:* Standardized average expected carbon footprint of three commonly used digital devices. The values for the carbon footprint are those that Gröger (2020) recommends as a reasonable estimate for carbon footprint calculators, even as the carbon footprint of these devices is currently increasing. Some of them are thus overestimates of current values and are more applicable to higher-end or future devices.

The digital devices in Figure 6 all have a very significant carbon footprint. It becomes apparent and seems natural that larger devices have a higher carbon footprint than smaller ones. For the reader, it might be hard to picture how much 150 kg of CO2e are relative to other carbon footprints, which is one of the obstacles education on this topic faces. One effective comparison was put forward by the Shift Project, stating that it takes “80 times more energy to produce ‘a gram of smartphone’ than to produce ‘a gram of car’" (Berthoud et al., 2019).[12] Another way to look at this is to consider the roughly estimated average carbon footprint of a human on this planet (~4000 kg of CO2e), which would mean that the purchase of a tablet represents 3.75% of that annual footprint (*What Is Your Carbon Footprint?*, n.d.).

3.2.3 Biodiversity of Production Phase

As explained in Section 2.3.3, biodiversity loss is an umbrella term referring to a decrease in biodiversity health, measured in this study by the broad metrics of ecosystem functions and services. In this section, I examine to what extent the activities necessary for the production of digital devices cause biodiversity loss.

Mineral extraction and the primary stages of manufacturing are the biggest concern for biodiversity, as these tend to be much “messier” than the final stages of assembly and packaging (Gordon, 2017). This analysis thus excludes later parts of the manufacturing process, assuming their relative unimportance.

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[12] Values used for this analogy by the Shift Project are different from those presented in Figure 6. The Shift Project actually estimated only 61 kg CO2e per smartphone, but the comparison calculation they did was in primary energy, a concept not worth elaborating on for the current paper (Berthoud et al., 2019).

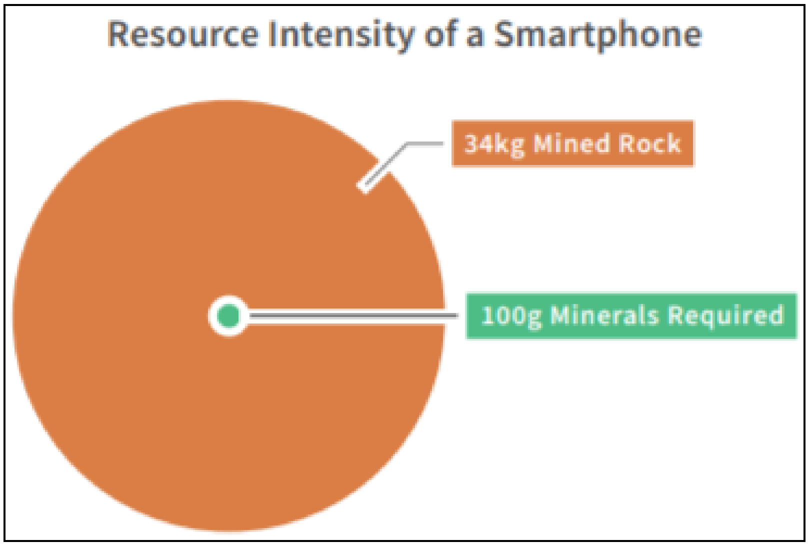

Figure 7: Visual representation of the ratio between the amount of rock that needs to be mined to extract the minerals required for the production of a smartphone. As the text states, the visual is not to scale and the stark difference is an underrepresentation of the 340 to 1 ratio. The extreme ratio exists because ore deposits of especially valuable minerals are mined even if only a few percent of the rock contains the desired mineral. Retrieved from Cook & Jardim (2017).

Figure 7 demonstrates the amount of physical effort required to extract the minerals for the production of a smartphone. Each kilogram of extracted rock leaves an impact on the local ecosystem. Because of the large impact of the mining sector on biodiversity, biodiversity science has pushed for more sensitivity regarding biodiversity in the global coordination of mining at international conferences (UNEP, 2017b).

Generally, there are externalities on biodiversity caused by mining on several spatial and temporal scales, all of which are hard to assess and quantify (Sonter et al., 2018). There are numerous challenges regarding the scope, methodology, aggregation, sensitivity, cost, and quality of biodiversity data on extractive operations (UNEP, 2017a), and the global consequences of mining on biodiversity are “largely unknown” (Sonter et al., 2018). Furthermore, given the unequal distribution of minerals across the earth surface, each mineral comes with a different geographic distribution and threats to biodiversity that are dependent on how mining is managed in that specific region or country (Sonter et al., 2018). While it would be very informative to have comprehensive quantitative data for variables like *ecological value destroyed* or *percentage of species severely impacted by mining*, such global estimations are currently impossible given the lack of data standardization, and the enormous diversity and quantity of minerals that would need to be estimated.

However, much is already known about the direct externalities of the mining operations at and around the mining site and how these externalities affect human and animal lives. Given the general difficulty of quantifying and aggregating findings on biodiversity impacts of mining, I decided to base my judgment of ICT mining’s overall biodiversity impact on specific cases. This inductive approach has been successfully employed by other authors reporting on the topic (Manhart et al., 2016; Sonter et al., 2018). Figure 8 below lists minerals that (1) are primarily produced in one country and (2) that are crucial for the production of digital devices (Manhart et al., 2016).

By only investigating these cases, I am consciously accepting enormous sampling bias. This seems justified given that (1) most of the available data is focused on sites that have caused biodiversity loss and (2) the general difficulty to find reliable data, which would make an analysis of minerals that are produced in many different countries very difficult. Furthermore, this quantitative analysis is provided in a context where it is very clear that mining is causing biodiversity loss, an issue that is a priority for policy makers (UNEP, 2017b). More quantitative data like that provided in Figure 8 can nonetheless help evaluate the size of the impact to weigh between different impacts.

Name of mined mineral	Country of concern (and percentage of total extraction volume of the mineral in the country)	Observed impacts on ecosystem functions	Observed impacts on ecosystem services
Cobalt	Democratic Republic of Congo (51%); (Manhart et al., 2016)	Permanent land degradation of mined areas and areas that are explored for mining (Manhart et al., 2016)	Pollution of the surrounding ecosystem by sulfidic and radioactive mining by-products (Manhart et al., 2016)
Palladium	Russia (43%); (Manhart et al., 2016)	"Release of heavy metals and sulfur dioxide" (Bernhardt, 2013; Manhart et al., 2016)	"The snow is black, the air tastes of sulfur, and the life expectancy for factory workers is 10 years below the Russian average" (Bernhardt, 2013)
Lithium	Australia (49%); (*Mineral Commodity Summary Lithium*, 2021)	Contamination of surrounding environment by waste water (Prior et al., 2013)	Massive amounts of water used for mining are mostly (95%) lost to evaporation (Kaunda, 2020)
Tantalum	Rwanda (50%); (Manhart et al., 2016)	Extensive removal of vegetation (Gakwerere, 2013); however, negligible or no contamination of surrounding plants, streams, or sediments (Flügge et al., 2009; Gakwerere, 2013)	Increase of radioactivity in surrounding areas (Manhart et al., 2016; Schulz et al., 2017)

Figure 8: Presentation of various minerals, their mining regions, and the biodiversity impacts that are experienced locally due to the mining activity and generally in the country. These findings rely on the implicit assumption that similar mining activities in other places are causing similar externalities and that other mined minerals not included in the figure have impacts similar to those found for the mining of these minerals.

Given Figure 8 above, ICT mineral mining seems to have numerous impacts on ecosystem functions and services. These impacts vary from mineral to mineral and from country to country, being affected by social and economic factors alike. We can conclude that there are severe negative externalities incurred via the damage of ecosystem functions and services but that their total size remains unknown.

It should be noted that, besides the ecosystem damages caused during mineral extraction, the manufacturing process in factories also often leads to significant damage to the ecosystems that surround those factories (Gordon, 2017). Such impacts are, again, entirely dependent on the type of mineral or material processed and on local and international regulations (Clément et al., 2020). The factor of manufacturing adds further uncertainty to the estimation of overall impact for this section and makes the possibility of severe impacts on biodiversity seem less likely. More data collection, data synthesis, and data and variable standardization is needed, both for life cycle analyses performed on digital devices and for corporate reporting on biodiversity impacts (Clément et al., 2020; UNEP, 2017a).

3.3 Evaluating the Use Phase

The use phase considers all negative externalities that occur to run digital services. As we could see in Figure 4, the use phase is estimated to account for between 10% and 49% of the carbon footprint of smartphones, mainly on the lower end of that spectrum. However, such calculations from life cycle assessments often only take into account the emissions required by the device itself and disregard the other processes that are necessary to make a digital service function (Manhart et al., 2016).

We can generally divide the processes that require energy during the use phase into three categories: user devices, networks, and data centers (Our Changing Climate, 2019). The main environmental impacts in these categories are caused indirectly by the production of electricity, which in turn majorly depends on the method of electricity production (Ferreira et al., 2018). This will be further discussed in Section 3.3.3 on carbon footprint. However, there are also externalities caused by the intrusions into ecosystems that occur as a result of the placement and maintenance of networks and data centers, which will be discussed in the section below.

3.3.1 Biodiversity of Use Phase

3.3.1.1 Submarine Data Cables

Only around two percent of the world's internet traffic moves via satellite and the rest is transferred via cables (*Submarine Cables*, 2017). Figure 9 demonstrates how many submarine data cables (SDCs) there are, and there are countless more data cables inside countries, connecting houses to local cables and local cables to SDCs. Given the extent of cable deployment, many have wondered about the environmental impact.

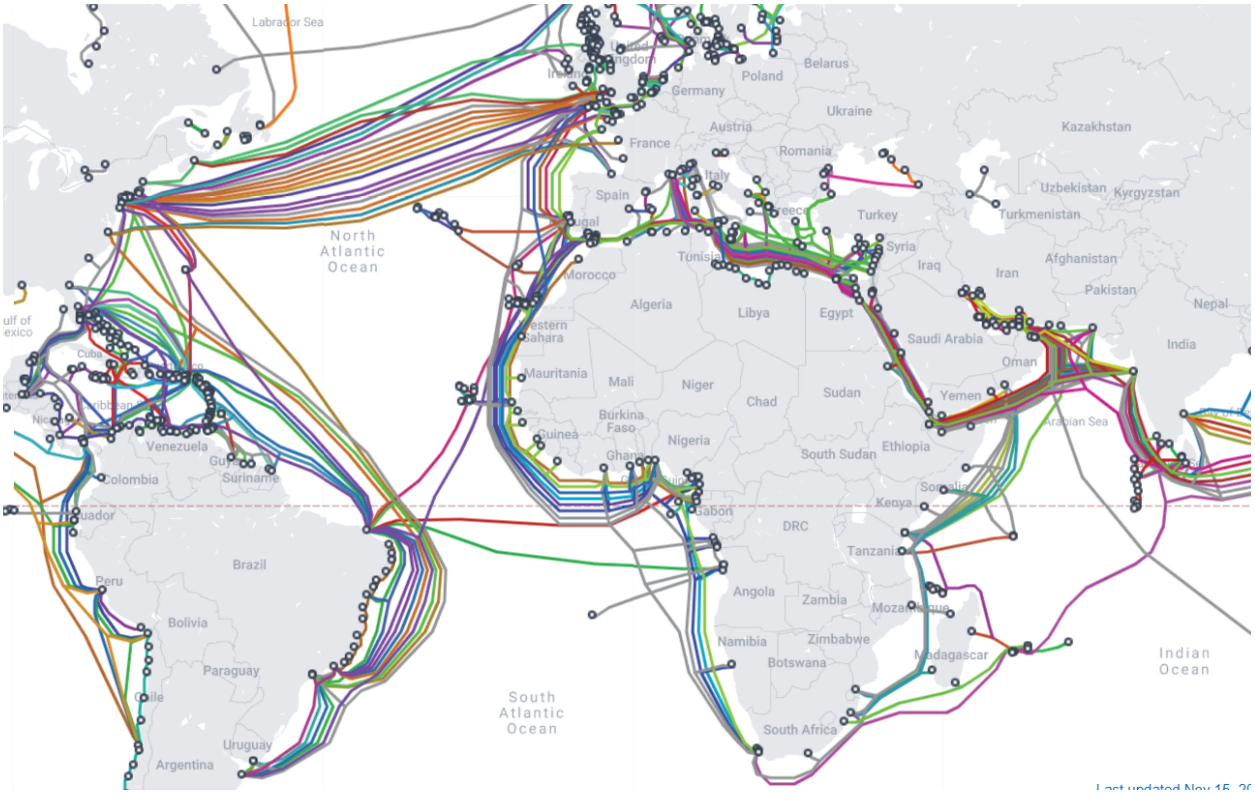

Figure 9*:* Screenshot from the *Submarine Cable Map* (2021), showing parts of North and South America, Europe, Asia, and all of Africa alongside the submarine telecommunications cables that connect these continents. Each line represents a different cable with a different name.

At least in our current understanding, SDCs have a surprisingly low negative impact on marine ecosystems (*ICPC*, 2016). While data cables on land are commonly using the pathways that have been used for electricity cables already (whether that is underground or overground), SDCs are deployed in areas that have not yet been used for cables and thus present a disturbance to the local ecosystem. However, in contrast to submarine power cables that transport electricity e.g. from an offshore wind energy plant to the mainland of a country, SDCs don't have a significant electromagnetic field (Donovan, 2009; Taormina et al., 2018). Unlike the heavier power cables, SDCs "with a diameter of about 17 to 22 mm" don't require being buried in the seafloor either, thereby avoiding significant disturbances like plowing (*Submarine Cables*, 2017; Taormina et al., 2018).

SDCs have a neutral effect on marine ecosystems because they offset their small ecological footprint by supporting protective zones (*ICPC*, 2016). Because of their immense importance to the global communications networks, there have been some protective measures put in place for SDCs that also protect these areas from more disturbing activity like fishing (*Undersea Fiber Optic Cable*, 2014). Given their small size, their high efficiency and utility, and evidence of only sporadic incidences where they have seriously disturbed marine wildlife and ecosystems, SDCs are this regarded as having an overall neutral impact, according to the International Cable Protection Committee (*ICPC*, 2016; *Undersea Fiber Optic Cable*, 2014). Still, for the purposes of identifying negative externalities of the use phase, the de facto impact of SDCs is overall slightly negative because their physical disturbance of the marine ecosystems cannot be denied.

3.3.1.2 Data Centers

However, SDCs are not the only structures that affect ecosystems with data centers having very significant externalities. Siddik et al. (2021) calculated the average amount of water required for a US data center to consume “1 MWh of energy” as “7.1m³ of water” with a range of 1.8–105.9 m³.[13] Assuming the average amount of 7.1m³/MWh, Bitcoin’s annual consumption of around 80 TWh translates into an annual usage of 568M m³ of water[14] (Huang & Tabuchi, 2021). As a comparison, that is more than half of what France’s entire agricultural sector uses annually (~3B m³; Trompitz, 2011). Furthermore, this estimation uses direct water footprint, meaning the amount of water that was used by the data center itself. The indirect water footprint is not included, which would be the water that was required for the production of the electricity, the materials required for producing the physical components of the data center, etc. (Siddik et al., 2021).

Data centers’ water consumption has significant impacts on ecosystems, especially where it directly contributes to groundwater depletion. Siddik et al. (2021) found that the water demand of a data center is positively correlated with the water scarcity of the region it is located in. This makes sense considering that water is primarily used to cool data centers, which is more important in hot regions. However, groundwater depletion is often an issue in such hot regions, and it comes with significant damages to the ecosystem. The ecosystem service of soil stability is often compromised as groundwater levels are lowered (*Groundwater Decline and Depletion*, 2018). Other effects include “loss of riparian vegetation and wildlife habitat”, decreased water quality, and higher costs of water extraction (*Groundwater Decline and Depletion*, 2018).

While data centers didn’t create the problem of water scarcity, they are actively and directly contributing to its aggravation. Unfortunately, it seems that at least for the US, data centers are disproportionately relying on groundwater basins that are already experiencing water scarcity (Siddik et al., 2021). Given that climate change is likely to worsen groundwater scarcity in most locations (Andersen, 2021), the stress exerted on groundwater levels by the water demanded by data centers is likely to become even more significant. While in theory, groundwater is one of the natural resources that gets replenished the quickest, it still takes thousands of years, which are timescales in which numerous human generations have the opportunity to deplete it (Seltzer et al., 2021).

In summary, the use phase has unexpected but significant biodiversity-related externalities via the immense water requirement of data centers which is aggravating water scarcity and impacting local ecosystems including everyone relying on them.

3.3.2 Resource Availability of Use Phase

This is likely the most relieving section of this paper as there are little to no impacts of the use phase on resource availability. There are no new resources required for using digital devices during this phase. The only impact could be caused by resources used to construct the data networks. However, while often complicated to produce, fiber optic cables and data infrastructure do not rely on any scarce resources (*ICPC*, 2016). Kevlar used in cables might be difficult to produce, and copper might be very

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[13] The high values around 105.9 m³ come from very hot places where more cooling is required. As humans usually avoid building data centers in such hot places, the average of 7.1m³ is much lower.

[14] One TWh equals one million MWh. Thus, Bitcoin mining requires 80M MWh/year, which equals 568M m³. These are rough estimations based on US data on water consumption of data centers and applied to Bitcoin data centers that are located throughout the world. While the order of magnitude of the estimate is likely adequate as most Bitcoin data centers are built in countries with temperate climates like the US (*Bitcoin Mining by Country 2021*, 2022), this estimation should be treated as a rough one.

expensive, but both can rely on an abundant supply of required primary resources ("Kevlar," 2022; Urban, 2013).

3.3.3 Carbon Footprint of Use Phase

The DCF of the use phase arises from the electricity required to run the digital devices themselves, the networks that transport the electricity and the data, and the data centers that process the data. As the electricity consumption during the use phase is one of the primary suspected culprits of the ICT sector, let us take a closer look at it and disentangle how and how many GHG emissions are currently generated and are projected to be generated.

The carbon footprint of data centers and networks is generally highly dependent on the energy mix of the local electricity grid (Ferreira et al., 2018). For example, 65% of China's energy supply comes from coal, compared to only 3% in Brazil (Ferreira et al., 2018). This also means that, as countries are moving towards more renewable energy (*COP26: Key Outcomes*, 2021), this impact will decrease. However, the 2021 climate conference in Glasgow has shown that this transition might be slower than was expected by some policy makers. A key frustration of climate activists was that the phrasing on the agreement on coal usage was changed from wanting to "phase down" rather than to "phasing out", due to India's opposition (*COP26: Key Outcomes*, 2021). As this significant carbon footprint of networks and data centers is thus expected to stay significant for the next decades, it is important to quantify it into externality evaluations for the present and future.

For this section it is important to define the carbon intensity of electricity (CIE), which is how many grams of CO2e are produced during the generation of a kWh of electricity. The CIE varies from country to country and decreases when countries move towards a "greener" energy mix, for example by phasing out coal and relying more on solar power (*Carbon Intensity of Electricity in Europe*, 2021). While, in 2020, the CIE was 368 in the USA (*U.S. Energy Information Administration*, 2021), it was 479.2 in Greece and 8.8 in Sweden (all values in gCO2e/kWh). The last reliable estimated average global CIE is 475 gCO2/kWh from 2019 from the International Energy Agency (*Global Energy & CO2 Status Report 2019*, 2019).

Data centers are major contributors to the DCF. Ironically, data on data centers varies drastically and doesn't lead to a simple conclusion as to the size of their impact, which confuses industry, scientists, and users alike and leads to diverse assumptions (Masanet et al., 2020). There are many claims out there, but few sources reveal the methodology of how they arrived at their conclusions. Electronics company Ericsson claims that data centers used "approximately 110TWh in 2015", which equaled about 0.5% of global electricity demand (*ICT and the Climate*, 2020). The European Investment Bank states that data centers were responsible for about "19% of the global digital energy consumption" in 2017 but that there is rapid increases in demand, again without an explanation of their methods. Furthermore, there is some more high-quality scientific data with quality predictions on the impact of data centers that is outdated but still frequently cited (Hintemann, 2015). That is because it is easy to underestimate how fast the global ICT sector is evolving and growing, which completely changes the underlying assumptions for any modeling study that tries to estimate the regional or even global impact size caused by data centers.

However, there are clear figures that reliably estimate present figures. Two strong data-based global estimates put data center electricity demand at 205 TWh in 2018 and 299 TWh in 2020, which represent 0.9% and 1.3% of global energy demand of those years (both at around 23,170 TWh), respectively (Andrae, 2019; Masanet et al., 2020; *World Power Consumption*, 2021).[15] These figures are

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[15] The papers by Masanet et al. (2020) and Andrae (2019) are reliable because they were published by field experts who are basing their estimations on data from institutions like the International Energy Agency and utilize a highly

not that far apart and suggest a significant but reasonable impact of data centers on global electricity demand.

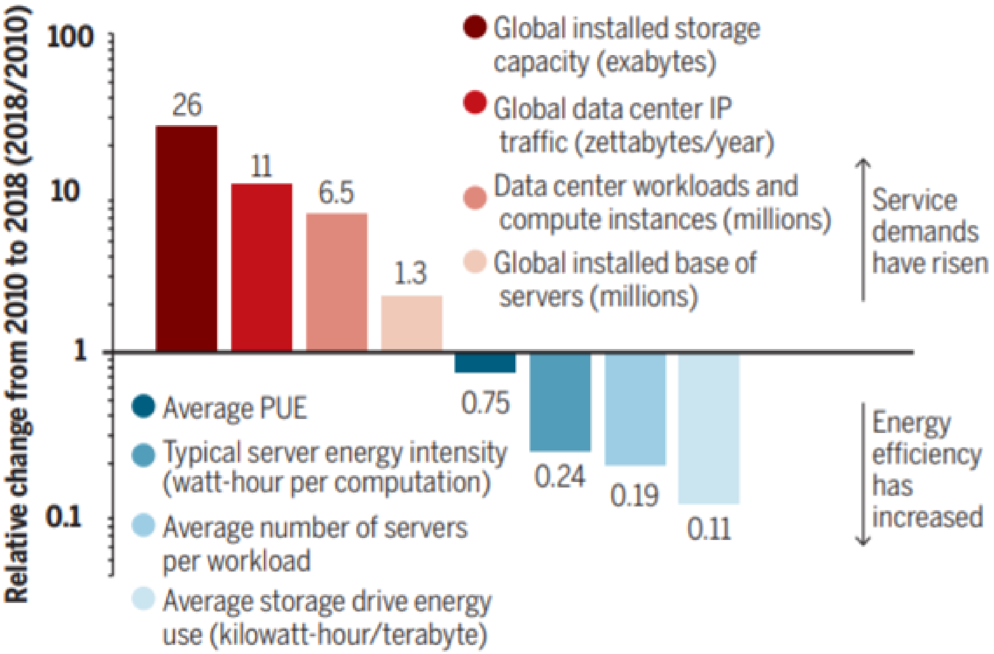

Figure 10: Trends in global data center energy-use drivers. PUE stands for power usage effectiveness while IP is short for internet protocol. Retrieved from Masanet et al. (2020).

Still, there are heated scientific debates over the evolution of the energy demand of data centers, which depend on the assumptions about whether the increases in efficiency will manage to offset the increased supply of data centers globally. This is not just a debate regarding the electricity demand of data centers but one that is held globally regarding the evolution of climate change between technocrats and realists (Pirsoul & Smith, 2020; Rao, 2015). Masanet et al. (2020) state that efficiency gains will outperform growth in the data center sector and make their carbon footprint insignificant (see Figure 10), while Andrae (2019) doubts that efficiency gains will be very significant and predicts that the data center energy demand will increase to 974 TWh by 2030 (from 299 TWh in 2020). That would be 4.2% of global energy demand (2020 levels) and be a very significant increase. While it might be unreasonable to get overly caught up in thoughts about the future, this future size of externalities matters a lot for the necessity to counteract them, especially if one wants to tackle them.

While the carbon footprint of *networks* is significant and might comprise up to 29% of the DCF (Our Changing Climate, 2019), it is not a factor that demands for any action and is thus only superficially covered here. Upgrading data grids is not controversial - everyone agrees that data networks should be more efficient, and networks are usually upgraded as soon as funding becomes available or otherwise strongly demanded by the public (Swartz, 2021). This is more of a social than an environmental issue, even though energy consumption per GB transferred decreases drastically for each step when moving from 2G to 3G to 4G to 5G (Gröger, 2020). However, when faster internet becomes available, it is also used more - the rebound effect often arises and energy needs don't actually decrease (Beier et al., 2020).

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differentiated analysis. Instead of basing their estimation on one value, Masanet et al. (2020) distinguish between data center type, region, and end-user category.

To summarize: network efficiency is the one digital sustainability issue that citizens are already fighting for because it comes together with internet speed.

In total, adding up the emissions caused by digital devices, data centers, and networks, the global rough estimations for the use phase are around 1,270 metric tons of CO2e for 2020, which would have been 2.3% of global GHG emissions (Bieser, 2020).[16] The largest share of those emissions comes from data centers, for which there is a significant uncertainty regarding whether these will increase or decrease over time.

3.4 Evaluating the End-of-Life Phase

In this section, I will evaluate how much externalities related to the end-of-life phase contribute to the DEF. Even though the end-of-life phase is generally assumed to have a significant DEF (e.g. Awasthi et al., 2016; Bazilian, 2020), it is rarely considered in major reports on digital sustainability (Berthoud et al., 2019; Bieser et al., 2020; Cook et al., 2017; Gröger, 2020). This is often justified with the lack of available data or the incompatibility of the negative externalities caused in this phase with the dominant variable of carbon footprint. However, another reason could be that, traditionally, economics only considers externalities of production and consumption (Kenton, 2020). What happens after products are sold to consumers is not traditionally part of the major considerations and is left to municipalities, the consumers themselves, or whoever can make some value off the waste (Braungart & McDonough, 2009).

Separating the technical and biological metabolisms has the opportunity to support resource availability and biodiversity. The former groundbreaking book “Cradle to Cradle” proposed an economic model for design where designers consider how products can be re-used at their end-of-life stage (Braungart & McDonough, 2009). The authors Braungart & McDonough (2009) critiqued that humans are extracting, altering, and concentrating natural resources (like minerals), for e.g. ICT production, and thereby make them toxic for the “natural metabolism” - the natural environment with its flora and fauna. The most beneficial course of action, they argue, would be to keep all the toxic and highly altered materials in the “technical metabolism” once they have been extracted and concentrated - in something nowadays referred to as “circular economy". This would both be beneficial for production (and *resource availability*), because the resources can be re-used at a low cost, and do not harm the biological metabolism (*biodiversity*). Circularity would require a product design, production, and resource management that transports resources from “cradle to cradle” instead of disposing them in a “grave” (Braungart & McDonough, 2009). This terminology will be relevant in the following two sections.

I also want to introduce the term “e-waste”, which refers to discarded electronic devices (whether still usable or not), to discuss the end-of-life stage of digital devices. There were 53.6 million metric tons of e-waste generated in 2019 (Forti et al., 2020), about 7.3kg per capita.[17] As a comparison, the entire Golden Gate Bridge does not even weigh one million tons (894,500; *Design & Construction Stats*, n.d.).

It must be noted that e-waste also includes electronic devices that are not digital devices as defined in Section 2.2., e.g. electronic devices that have nothing to do with sending, storing, or processing information like toasters and lamps. In waste management, digital devices fall under the category of

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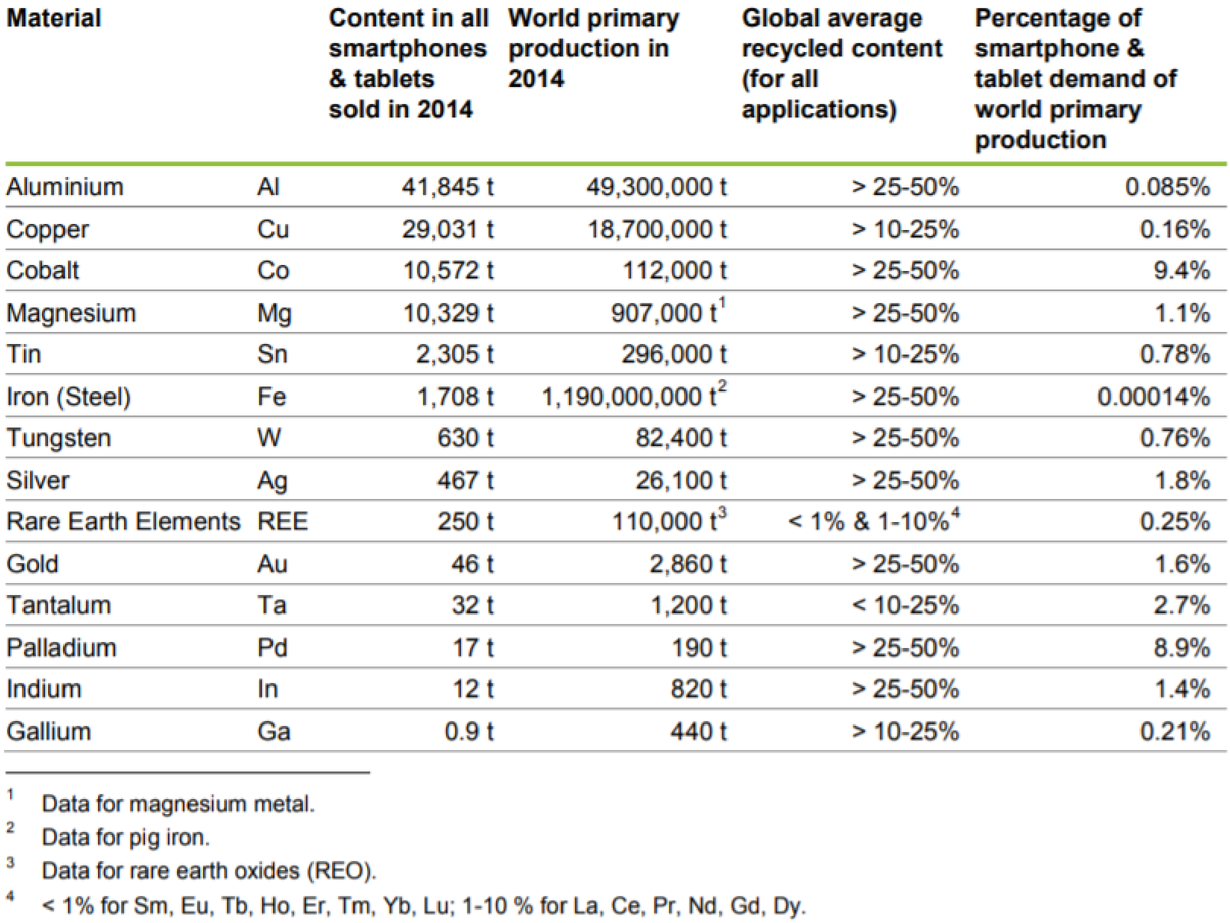
[16] These figures are in CO2e instead of TWh. There was a conversion from TWh to CO2e via the estimated global CIE - a generally uncertain value due to the lack of high-quality global data.

[17] Forti et al. (2020) published the “Global E-waste Monitor 2020” for the United Nations University, the United Nations Institute for Training and Research, and other partner organizations. The document is the the most current and reliable source of information on e-waste (and thus the end-of-life stage of digital devices) and will be cited throughout this Section 3.4. By the end of 2023, the new Global E-waste Monitor will be published and should be used as an updated source of information.

e-waste and are not specifically monitored further. The e-waste-related externalities in this section will thus exceed the impact of ICT which I will take into consideration when evaluating the size of the externalities in later analyses.

3.4.1 Resource Availability of End-of-Life Phase

In Section 3.2.1, it became clear that the production of digital devices requires the extraction of numerous minerals, putting immense pressure on some of the most endangered minerals on the planet. While this development is worrying, the end-of-life stage theoretically provides an opportunity to "save" these minerals and keep them in the technical metabolism to make them available for the production phase again. This section focuses on an analysis of why humanity currently fails at recycling these minerals, how much we are thereby contributing to the extinction of crucial minerals, and how difficult it would be to recycle them.



Material		**Content in all smartphones & tablets sold in 2014**	**World primary production in 2014**	**Global average recycled content (for all applications)**	**Percentage of smartphone & tablet demand of world primary production**
Aluminium	Al	41,845 t	49,300,000 t	> 25-50%	0.085%
Copper	Cu	29,031 t	18,700,000 t	> 10-25%	0.16%
Cobalt	Co	10,572 t	112,000 t	> 25-50%	9.4%
Magnesium	Mg	10,329 t	907,000 t[1]	> 25-50%	1.1%
Tin	Sn	2,305 t	296,000 t	> 10-25%	0.78%
Iron (Steel)	Fe	1,708 t	1,190,000,000 t[2]	> 25-50%	0.00014%
Tungsten	W	630 t	82,400 t	> 25-50%	0.76%
Silver	Ag	467 t	26,100 t	> 25-50%	1.8%
Rare Earth Elements	REE	250 t	110,000 t[3]	< 1% & 1-10%[4]	0.25%
Gold	Au	46 t	2,860 t	> 25-50%	1.6%
Tantalum	Ta	32 t	1,200 t	< 10-25%	2.7%
Palladium	Pd	17 t	190 t	> 25-50%	8.9%
Indium	In	12 t	820 t	> 25-50%	1.4%
Gallium	Ga	0.9 t	440 t	> 10-25%	0.21%

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[1] Data for magnesium metal.
[2] Data for pig iron.
[3] Data for rare earth oxides (REO).
[4] < 1% for Sm, Eu, Tb, Ho, Er, Tm, Yb, Lu; 1-10 % for La, Ce, Pr, Nd, Gd, Dy.

Figure 11*:* "Total material requirements of smartphones and tablets in relation to the world primary production of mineral commodities", retrieved from Manhart et al. (2016). Total share of demand for some of the listed minerals is shown in Figure 5 in Section 3.2.1.

The unfortunate reality is that recycling rates for ICT minerals are very low. Figure 11 does a good job at showing the quantities that were required for the production of smartphones and tablets in 2014 in conjunction with the average recycling rates for each mineral. While there are large uncertainties for the recycling rates of all materials listed, the column "Global average of recycled content" of Figure 11 shows that none have a recycling rate higher than 50%. That means that using any of them causes at least half of the given mineral quantity to escape the technical metabolism so that they are lost for future generations. We remember from Section 3.2.1 that Indium and Gallium at the bottom of Figure 11 are the two minerals of which the ICT sector demands the biggest share (90 and 81%, respectively) and that are both on the red list for endangerment. Looking at the entire table, recycling rates of 10 - 50% are unfortunately common for most minerals.

One main reason for low recycling rates is poor international and local regulation of e-waste. If e-waste is recycled "properly", which generally happens in the documented sector, most minerals can be recovered and recycled unless such a process is strictly cost prohibitive[18] (Forti et al., 2020). However, most (82.6%) e-waste is recycled in the undocumented sector (Forti et al., 2020) in countries like China, India, and Vietnam via methods like acid baths and open burning which only allow for the recovery of about three minerals (Awasthi et al., 2016). In 2019, 78 countries had legislation on e-waste (although many are non-binding), and only 17.4% of global e-waste was documented and properly recycled (Forti et al., 2020). Part of the problem is inadequate e-waste collection systems by municipalities, but another is illegal transnational trade (Forti et al., 2020). The Basel Convention of 1992 clearly classified e-waste as hazardous, which means that its cross-border transport requires a governmental approval process (Forti et al., 2020). However, it is generally hard to distinguish between used electronics that are to be sold as second-hand products (export legal) and e-waste (export illegal), which is a gray zone smugglers happily exploit (Efthymiou et al., 2016; Forti et al., 2020; UNEP, 2013). Despite China having banned the import of used electronics in 2000 (UNEP, 2013), it remained the major market for e-recycling until today. Illegal e-waste trade is in fact affecting every populated continent (Efthymiou et al., 2016; UNEP, 2013).

While there are clear pathways towards higher recycling rates of e-waste, there are plenty of obstacles that need to be tackled locally and internationally. In the scientific community, there seems to be a clear consensus that it fundamentally doesn't matter whether e-waste treatment is financed by the producer, consumer, state, or a combination of the three (Forti et al., 2020; Sepúlveda et al., 2010; StEP, 2018). More important is that there are clear international definitions and strong national systems in place to coordinate e-waste trade and recycling, increase recycling yields, and tackle adverse effects on the environment and workers. It must, however, be noted that even a recycling rate of 100% of all minerals used in ICT would not suffice for the production of all new demanded goods given the immense growth in the sector (Forti et al., 2020).

3.4.2 Biodiversity of End-of-Life Phase

Besides not being available to the technical metabolism anymore, e-waste can also seriously impact biodiversity when e-waste or the by-products of its recycling process are discarded into the realm of the biological metabolism. This section is evaluating to what extent e-waste and the end-of-life phase of digital devices in general are responsible for negative externalities on biodiversity.

As for the production and use phases, biodiversity impacts are hard to quantify and need to be evaluated using case studies, estimations, and generalizations. Given how unregulated the e-waste sector is (Forti et al., 2020), reliable information and global figures of biodiversity loss caused by e-waste are unavailable or highly reliant on estimation. Still, there are several case studies of undocumented e-waste recycling that effectively capture local impacts, sometimes even over time.

It has become increasingly clear that e-waste recycling impacts biodiversity in developing countries, which also has long-term effects on the local population. Awasthi et al. (2016) reviewed six

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[18] This is often the case for minerals like REEs that are used for manufacturing in tiny quantities, sometimes layers are applied that are only a few layers thick. This "miniaturization" makes it very difficult to extract these minerals from the digital device while also only presenting a tiny value to the recycling company.

studies on e-recycling in the informal sector in different regions of India which linked pollution of heavy metals, dioxins, and furans in both environment and the surrounding population to the recycling activity. While it is difficult to directly prove causation, the common e-recycling practices of open burning and acid baths are known to release these pollutants (Awasthi et al., 2016), which makes the connection pretty clear. Sepúlveda et al. (2010) also found pollution levels several orders of magnitude above healthy levels in soils at recycling sites in Guiyu, China, a province that continued to cultivate rice. Seeing that the pollution caused by e-waste is primarily impacting soils and that rice is easily contaminated due to its cultivation methods, the casual links of environmental damage and long-term developmental impact on the locals seems very clear (Sepúlveda et al., 2010). These findings highlight how the contamination of the biological metabolism with substances from the technical metabolism can directly affect the ecosystem services (like rice production) for local populations. While of less interest to the public and thus less studied, we must assume that ecosystem functions not affecting humans were equally impacted by the pollution described.

This analysis shows that e-waste disposal and undocumented recycling can have serious externalities on the local biodiversity of recycling and disposal sites. It seems to be that the immense quantities of e-waste are mainly improperly handled, if they even make it to any recycling site and are not dumped in the general waste bins like 8% of total e-waste (Forti et al., 2020). There is still a large uncertainty associated with this assessment given the sparse data on the main, undocumented chunk of the e-waste recycling industry.

It should also be noted that e-waste recycling causes major damage to involved workers working in the undocumented sector. While such externalities related to work activities are qualitatively different to the depreciation of ecosystem services,[19] they have similar effects in that they are impacting human wellbeing. Such impacts that have been found to be positively correlated with hours spent in the vicinity of e-waste recycling include increased cancer risk, blurred vision, and also affect the mortality, neurodevelopment, and immune system of workers' children (Forti et al., 2020; Neitzel et al., 2020; Okeme & Arrandale, 2019).

3.4.3 Carbon Footprint of End-of-Life Phase

This section evaluates the extent to which the end-of-life phase impacts how many carbon emissions are released into the atmosphere. As discussed earlier, the end-of-life stage is always an opportunity to recover, re-use, and recycle resources and thereby decrease emissions generated during the production phase. This section builds on the information provided in other parts of Section 3.4 and uses the terminology introduced there.

There are three possible scenarios for the destiny of e-waste: recycling, incineration, landfill, or open burning (Devika, 2010), and each destiny comes with its own carbon footprint. Estimating the carbon footprint of e-waste is difficult because, as stated in previous sections, only 17.4% of e-waste is documented (Forti et al., 2020). However, all of the documented e-waste is being recycled. Below is a brief overview of each of the four scenarios.

What is very clear is that recycling e-waste is not only an opportunity to maintain resource availability but is also reducing the carbon footprint of newly produced products. Eisinger et al. (2022) conducted an analysis comparing the carbon footprint of all the metals in a laptop with the carbon

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[19] One could argue that workers working in these industries are knowingly accepting the damages incurred by their work while people consuming the rice that was produced in Guiyu assume to have bought unpolluted rice and are experiencing a "more unjust" externality. This logic is of course controversial because unsafe working conditions are not desirable either.

footprint of the primary production of these metals. They found that primary production requires five times the carbon footprint of any recycling method. This is consistent with earlier research that found some, but no major, variability in carbon footprint between e-waste recycling methods (Chaturvedi et al., 2012). While e-waste recycling does have a small but significant carbon footprint, it presents overall carbon footprint savings relative to any other e-waste scenario and the carbon footprint of the primary production of the minerals required for new production.

Incineration is one of the causes of e-waste-related carbon emissions, albeit a smaller one than would be expected. An estimated 8% (or 4.3 million metric tons) of e-waste is discarded into the general waste of municipalities. General waste is either dumped into landfills (causing biodiversity loss, see previous section) or burned in incineration facilities. Taking the example of the highly industrialized country Germany, the amount of generated e-waste per capita per year is about 20kg (Brandt, 2021). Only 44.3% of that was brought to recycling facilities which leaves more than 55% that went either into the general waste or was exported for undocumented recycling (Brandt, 2021). All of Germany's general waste is burned in incineration facilities. While such facilities are usually very efficient and filter out a lot of carbon dioxide, they still generate around 1,100kg of CO2e per burned ton of waste (UNEP, 2019). Such emissions are often argued to be carbon neutral as they replace the need for the burning of other fossil fuels. However, especially in countries like Germany that are increasingly moving towards renewable energy in general to decrease their CIE, such argumentation starts to fall apart (UNEP, 2019).

Depositing e-waste in landfills is likely causing even more carbon emissions than incineration. According to the UNEP (2019) report on general waste burning, waste deposited in landfills emits 1,610 kg CO2e per tonne deposited, which is 510 kg CO2e more than the value generated via incineration in specialized facilities. It thus becomes clear that any waste that is not recycled and goes into the general waste will have a significant carbon footprint. While Forti et al. (2020) estimated the amount going to general waste at 8%, German data suggests 55%. While Germany might be an outlier, this discrepancy shows the difficulty of aggregating global data. The assessment of the carbon footprint for e-waste ending up in landfill is further complicated by the fact that the devices that have significant carbon emissions are not digital devices. For example, improper disposal of fridges and air conditioners was responsible for 98 million tonnes of CO2e in 2019, which would have been 0.3% of global energy-related GHG emissions for that year (Forti et al., 2020).

Open e-waste burning most likely produces a large carbon footprint, but the public and scientific interest in this environmental issue is low due to even more human-health related consequences of such practices. Unfortunately, e-waste open burning produces a range of toxic fumes and substances that can then be absorbed by plants, soils, and other organisms (Cao et al., 2020; Cogut, 2016; Li et al., 2018). In that context, the carbon footprint of open e-waste burning has been less of a focus of scientific research so that there are no current estimations. However, it needs to be assumed that a lot of undocumented e-waste is being burned openly as about 41% of other waste is burned this way (Cogut, 2016).

Concluding, despite there being reliable data for the documented e-waste recycling sector, the most important quantities of GHG emissions cannot be properly estimated due to the lack of knowledge about how the undocumented sector handles e-waste. Furthermore, environmental differences with regards to how deposited e-waste will react and decompose provide more obstacles to accurate assessments. While Europe recycles much more of its e-waste than other continents (42.5% documented e-waste recycling in Europe vs. 11.7% in Asia), middle- and low-income countries countries generally process more of the undocumented e-waste due to the existence of an undocumented sector (Forti et al., 2020). The situation is further complicated by digital waste only comprising a share of e-waste. We thus need to hope that future e-waste regulations will improve the amount of e-waste flows that can be tracked as part of the documented sector or that our information about the undocumented sector improves enough to estimate the impact of e-waste on the global carbon footprint.

4 Results

4.1 Data Synthesis

Figure 12 summarizes the subsections of Section 3, providing key findings and figures. These are not comprehensive summaries because they do not capture the detail and rationale of the sections. However, these summaries are meant to provide a better understanding as to how the findings from Section 3 translate into impact hotspots identified here in Section 4.

	Carbon Footprint (CO2e or relative Carbon Footprint)	**Biodiversity** (Destruction of ecosystem functions and services)	**Resource Availability** (relative direct impact of ICT sector on depletion and extinction of minerals)
Production	The production of a tablet represents 150 kg CO2e (3.75% of annual average carbon footprint), 311 kg CO2e (7.8%) for a laptop.	Mining of ICT minerals causes diverse externalities ranging from land degradation to increased radioactivity levels. Large uncertainty and overlap with social causes. Significant pollution by manufacturing processes.	Major extinction pressure on four minerals and significant depletion contributions to a number of other minerals.
Use	Data centers, networks, and devices account for ~2.3% of the global carbon footprint. Prospects for a long-term decrease with efficiency gains and a decreasing CIE.	Little to no impact from Submarine Data Cables. Data centers often contribute to groundwater depletion and water scarcity.	No significant impacts.
End-of-Life	E-waste has a large carbon footprint, of which digital waste only makes up a small share. Large uncertainties regarding undocumented e-waste recycling sector. Potentially large GHG emissions.	Contamination of soils and waters by e-waste and by-products from improper e-waste recycling. Large data uncertainty.	Failure to make-up for the damage caused during the production phase. While recovery is easier for some minerals than it is for others, e-waste recycling is hugely trailing behind its potential.

Figure 12: Simplified summaries of subsection analyses in Section 3 for the three dimensions of sustainability and three phases of digital life this paper is focusing on to evaluate the DEF.

While one might want to convert indicators into one composite indicator, that would not be scientifically sound and introduce bias, especially given how qualitative the metrics for the indicators in Figure 12 are already. To summarize the results, I need to thus rely on my understanding of how significant I assess the change of the dependent variables (e.g. extinction risk of minerals) relative to the independent variables (e.g. amount of minerals mined for the production of a laptop). According to Hiemstra et al. (1992), such methods are very acceptable for evaluating sustainability, especially when the system has been analyzed to a sufficiently large extent and the underlying assumptions are clearly stated. Furthermore, the practice of considering variables of varying quantifiability is common practice in the field of LCA where it is not allowed to weigh or convert indicators into each other when findings are communicated to the public as these actions would include subjective judgements (Hellweg & i Canals, 2014).

4.2 Impact Hotspot Identification

After having summarized the research findings from Section 3 in the previous section, it is time to recapitulate impact hotspots. As explained in the Methodology section 3.1, impact hotspots are the parts of the life of a digital device that have the most environmental externalities and are core to LCA. After the LCA, impact hotspots can be targeted to reduce the overall environmental impact of the product or service examined in the LCA. In our case, we are looking at the entire ICT sector which makes such an assessment more difficult. In that light, it is not surprising that the findings are based on less available data and are less reliable and precise than would be expected for an LCA with a narrower scope.

In a matrix analogous to Figure 12, the findings from the subsections of Section 3 were translated into a general damage level (high, medium, or low) accompanied by a measure of certainty associated with that assessment:

	Carbon Footprint	**Biodiversity**	**Resource Availability**
Production	Medium Damage (High certainty)	Medium Damage (Medium certainty due to insufficient data on mining and construction)	High damage (High certainty)
Use	Medium Damage (Medium certainty for the present, low certainty for the future)	Low to medium damage (High certainty)	No significant damages known (High certainty)
End-of-Life	Low to high damage (largely dependent on the disposal scenario - low certainty for undocumented e-waste)	High damage (Low certainty and locally dependent)	Low damage but high unrealized potential of undoing the damage during production (High certainty)

Figure 13*:* Summary Table of the research performed in Section 3 based on Figure 12, the sources utilized in the research sections, and a reasoned subjective assessment of the overall damage alongside the certainty of that assessment.

From Figure 13, Production seems to be the most damaging phase, which is in agreement with calculations from various sources used for this paper (e.g. Berthoud et al., 2019; Gröger, 2020). The use phase comes out as least damaging, and the End-of-Life phase comes in between. This is an interesting finding because reducing the use has been the main focus on consumer efforts to achieve digital sustainability (Scouler, 2019; Smith, 2020). The end-of-life phase, however, carries significant uncertainty, and the resource availability dimension is highly interlinked with the significantly damaging externalities from production.

5 Discussion and Conclusion

The ICT sector is responsible for a large DEF, but businesses and policymakers are struggling to effectively address the issue. One of the challenges is identifying the impact hotspots within the lifecycle of digital products which is complicated by the lack of holistic frameworks of digital sustainability. In this paper, the DEF is proposed as a holistic framework to fill that gap and tested via an LCA-style analysis with a global scope.

A framework involving the broad concepts of digitalization and sustainability requires solid definitions and a theoretical basis; this is why Section 2 started out properly defining sustainability and the digital sphere. Having provided that foundation, the state of current digital sustainability research was analyzed. The diagnosed excessive focus on carbon footprint as the ultimate factor of sustainability was then addressed by proposing the integration of two majorly relevant sustainability dimensions of biodiversity and resource availability. The DEF was presented as an integrated model of digital sustainability that extends the current scope of sustainability evaluation within the ICT sector.

Within Section 3, the three dimensions of sustainability of the DEF were evaluated for each phase of digital life, reviewing and summarizing various externalities caused by the ICT sector. The results of this LCA-style analysis were summarized in Section 4 and evaluated through the lens of impact hotspot identification, a method borrowed from LCA.

What was expected but impressive is that including the metrics of biodiversity and resource availability entirely redefined which phases of digital life are most in need of sustainability considerations. The production phase is the most environmentally damaging according to the dimensions of DEF defined. The end-of-life phase can either create a large DEF when devices are disposed of improperly or represent an opportunity to mitigate production externalities when devices are properly recycled. The use phase came out as the area of least concern despite being the focus of much sustainability effort. The unidimensional understanding of viewing sustainability via the carbon footprint is understandable given the threats of climate change, but this analysis again highlighted that this extreme level of reductionism is ultimately inappropriate.

There are significant obstacles and constraints to accurately assessing the global DEF, including the unavailability of data on the undocumented e-waste sector, an extreme concentration of ICT minerals in very specific locations, and poor international regulations on e.g. data centers and e-waste trade. These are hindrances for any scientific inquiry that won't change within the next year. However, if there continues to be a push for digital sustainability on an international level, regulations could improve the conditions and monitoring of the mining and e-waste sectors.

Performing research on the DEF, huge scientific gaps became apparent. More long-term studies are needed that monitor biodiversity indicators in the surrounding areas of mining and e-waste recycling facilities. Furthermore, it needs to be established how e-waste disposal in landfills impacts carbon emissions and biodiversity. Only if researchers fill these gaps can educators confidently craft their materials, can policymakers improve dire conditions directly via effective regional and international policy.

The fields of digital sustainability and biodiversity are both in dire need of consistent and clear indicators to showcase policymakers and non-professionals the much needed insight into the severity of the situation. While the field of biodiversity science is slightly more mature and has promising candidates for composite indicators such as “biodiversity health”, the field of digital sustainability is still in its infancy and should establish clear and coherent metrics from the start.

Despite the shortcomings of using the less quantifiable variables of biodiversity and resource availability, including them in the DEF showed that they enrich digital sustainability analysis. Resource availability came with less quantification and data availability issues than biodiversity and should certainly be included in future analyses of regional and global digital sustainability. Furthermore, unlike many biodiversity variables that are hard to relate to ecosystem services humans can harvest, resource availability is a variable entirely and directly focused on human benefit. This provides a convincing basis for policy that aims to guarantee the wellbeing of future human generations. However, biodiversity should by no means be discarded as a key variable to include in digital sustainability evaluations. The severity of the biodiversity damages identified in Section 3 shows that biodiversity should be considered whenever possible, whether it is to evaluate the sustainability of a digital product or of the ICT sector as a whole.

With regards to the research question, yes, sustainability evaluations of the ICT sector can be improved by including biodiversity and resource availability. However, the additional sustainability dimensions beyond carbon footprint should be chosen wisely and appropriately given the scope and objective of the study at hand. It should especially be ensured that there is a sufficient availability of data to make sure the evaluations are conclusive.

In this paper, I proposed evaluating the DEF via the dimensions of carbon footprint, biodiversity, and resource availability. While I think that this proposal yielded a richer and holistic analysis of the ICT sector, many other metrics could and should be considered in the field of digital sustainability. Importantly, contenders beyond carbon footprint should be included in the analysis. As the findings of this project show, the carbon footprint is one of the lesser concerns of the DEF, especially in times of a decreasing CIE for most countries.

Digitalization is one of the big developments of our time, and its achievements in the areas of efficiency and global connectivity are enormous. It would be great if we could look at digitalization in a purely positive light without getting upset about the environmental damages caused by us purchasing, using, or disposing of our digital devices. Digital sustainability offers a challenging but possible vision that can be achieved if individuals and institutions work together to overcome our DEF.

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