Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Impacts of the digital transformation on the environment and sustainability

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Authors

Ran Liu
Dr. Peter Gailhofer
Carl-Otto Gensch
Dr. Andreas Köhler
Franziska Wolff
With support from Michelle Monteforte & Cristina Urrutia (Öko-Institut) as well as Pavla Cihlarova & Rob Williams (Trinomics)

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Disclaimer

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Abbreviations

AI	Artificial Intelligence
CRMs	Critical Raw Materials
EAP	Environmental Action Plan
EPR	Extended Producer Responsibility
EEA	European Environment Agency
EU	European Union
ICT	Information and Communication Technologies
IoT	Internet of Things
GDP	Gross Domestic Product
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LDC	Least developed country
SDGs	Sustainable Development Goals
UN	United Nations
HVAC	Heating, ventilation and Air Conditioning
WEEW	Waste of Electrical and Electronic Equipment
WF	Water Footprint
CRM	Critical raw material
RTO	Research and Technology Organization

Policy summary

On 21st of November 2019, the Luxembourg Times reported that Google's plan to build a vast data centre in central Luxembourg raised significant worries in society, especially concerning the data centre's energy and water consumption.[1] It is estimated that the data centre's operation requires 10 million litres of water per day, which is about 10% of the country's overall water consumption. Another article describes that the data centre is expected to consume 7% of the country's energy supply in phase I, up to 12% in phase II. Other concerns are noise and air pollution[2]. The example shows that digitalisation can have grave effects on the environment.

This paper reviews findings on the (potential) impacts of the digitalisation (or "digital transformation") on the environment, with a focus on non-energy impacts. This decision was deliberate for the purpose of this issue paper since the evidence base on link between digitalisation and energy use or greenhouse gas emission is much wider and well documented already whereas this is not the case for other environmental pressures, impacts and opportunities.

But what is 'digitalisation'? We understand it to mean 'the development and application of digital and digitalised technologies that augment and dovetail with all other technologies and methods' (WBGU, 2019c).

Digitalisation is expected to have profound ('transformative') effects on the economy, society, and politics as well as on the planet itself. This includes the production, use and disposal of hardware (Information and Communication Technologies equipment, data centres, data transmission networks) as well as of software, digital technologies and applications – ranging from robotics, the Internet of Things (IoT), via distributed ledger technologies such as blockchain, to Artificial Intelligence (AI). However, the interactions between the digital transformation and the environmental crisis have not been high on the agenda of the political debates and policy making at EU level over the past 10 years. This is about to change with the launch of the 'European Green Deal' (EGD) and the recent publication of the EEA's State of the Environment Report.

There are many positive expectations and viewpoints that digital transformation and innovation could and should contribute to a better life for all / most and to sustainable development. Meanwhile, there are also numerous studies estimating the environmental benefits or abatement potential, e.g. the indirect GHG reduction achieved through digitalisation, discussing possible opportunities and risks resulting from digitalisation and evaluating the indirect effects, including systemic environmental impacts associated with certain applications. Thus, digitalisation has been both described as a potential ecological "fire accelerant" (WBGU, 2019c) and as an ecological "game changer" (Seele & Lock, 2017).

The overall objective of the paper is to gather a first glimpse on available, up-to-date evidence on positive and negative environmental effects of the digital transformation in a holistic way. However, for practical reasons the focus of this paper is on non-energy and non-GHG aspects because energy and climate related risks and opportunities of digitalisation are generally more well-known.

The key findings are summarised below.

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[1] https://luxtimes.lu/luxembourg/39098-village-worries-about-environment-in-first-google-face-off

[2] https://chronicle.lu/category/ict-services/31104-googles-plans-for-eur1bn-data-centre-in-bissen-get-green-light

I. Environmental opportunities related to the digital transformation

Environmental opportunities related to (selected) issue areas of the European Green Deal (European Commission, 2019) include the following:

- **Mobilising industry for a clean and circular economy**: The (non-energy) environmental opportunities arising from digitalisation can play an important role in relation circular economy, especially with respect to tackling the issue of electronic waste. Most importantly, the technological advancement plays a role in better collection and subsequent recycling of electronic waste and the reuse of the materials used. For example, the advancement in technology, namely the introduction of smartphones and mobile applications encourages consumers to recycle e-waste at official locations in return for financial incentive.

- **Preserving and restoring ecosystems and biodiversity**: Digital technologies may help to alleviate pressures on the natural environment and biodiversity in many respects. ICT-enabled solutions help monitoring biodiversity and ecosystem services. The impact of these technologies and applications on the state of biodiversity and ecosystem services, however, is indirect and uncertain: better information (acquired on the basis of sensor technologies etc.) can help assessing "distance to target" with regard to policy goals on biodiversity protection. ICTs can also help visualise and communicate biological data, thus increasing policy and public awareness. Both are necessary, though not sufficient preconditions for effective policy action. Digitally supported & biodiversity-friendly business models can make business models viable that prevent the degradation of biodiversity or support the provisioning of ecosystem services, for instance through promoting dematerialisation or reduced resource demands through sharing activities.

- **From 'Farm to Fork' (a fair, healthy and environmentally-friendly food system)**: With regard to the environmental effects of smart farming, a number of quantitative assessments have been made. They present evidence on reductions in water use, pesticide use and N_2O emissions. Since these findings stem from trial tests or pilot projects and were made in very different environments, it is not sure whether they can be upscaled and/ or transferred to other locations. As regards potential environmental or sustainability benefits relating to enhanced traceability in agriculture and food supply chains, we could identify very little (qualitative or quantitative) research. There are expectations and claims, but most independent research focusses on economic benefits or benefits relating to risk management and food safety.

- **A zero pollution ambition for a toxic-free environment**: With regards to pollution reduction, non-energy environmental opportunities can also be relevant, especially when addressing reduction of air pollution. The types of technologies most significant in this respect are artificial intelligence and blockchain. AI-based tools have been deployed to monitor and forecast the levels of pollution or for autonomous vehicles and traffic lights. Blockchain technology, on the other hand, can be used for reward-based systems which reward those who reduce pollution with digital rewards, which can be exchanged for daily necessities.

- **Cross-cutting aspects**:

  – Digitization offers major potentials for **improving environmental information and knowledge** which might lead to more sustainable policies and environmental innovation. Digital technologies extend environmental knowledge as they help to create and spread relevant data at high speed and on a massive scale, e.g. by continuously delivering data by remote sensors on Earth observing systems, which can be used for new research approaches and

collaborative experiments. Increasing attention is being given to possibilities to generate and exchange knowledge about the environment by citizen science.

– Based on the potential of data for environmental policy and technological innovation, scientists as well as political actors increasingly argue for the need and the environmental potentials for **exchanging knowledge between diverse actors**. This includes open access and open data policies, which traditionally include the provision of governmental data (open data) and scientific data (open access). Recent publications propose the development of data-sharing platforms, or a "digital ecosystem for the environment" to make available data for environmental policies and innovation on a European or global level. In addition, the awareness is increasing that privately held data is of great value for environmental policies in many respects. For instance, such data might be used for public planning, traffic policies or the effective implementation of environmental law. The issue of general or sector-specific obligations for private enterprises to share their data – as well as more general implications of data-governance for environmental policies and innovations – should therefore be further explored.

– New technologies also supposed to provide for new opportunities for **effective implementation and enforcement of environmental standards**. These potentials prominently result from new technological possibilities to improve monitoring capacities – such as remote sensing or blockchain, which allows for (automated) checks to ensure that environmental data submitted have been complete, accurate and submitted on time.

– Open government data as well as access to scientific data about the environment can potentially support **evidence-based policy decisions** and make the effects of administrative action more transparent. Public transparency and trust might also be improved by technological instruments which allow for participation of citizens and public interest actors in public decision making. For example, environmental organisations could be empowered to carry out their own controls and checks on the basis of data submitted by enterprises or government bodies. Digital technologies, more generally, have the potential to improve political and economic inclusion of citizens.

– Better information about supply chains, environmental costs of products (e.g. provided by QR codes), services or investment flows might **help consumers to make more sustainable decisions**. It is also argued that digital applications such as gaming, virtual nature experience or transnationally networked citizen science projects offer new opportunities for environmental awareness and to understand global interdependencies. In addition, data-based nudging is considered to be an effective tool to incentivize behavior and thus to have a great instrumental potential for effective administration and governance. Nudging technologies however also raise serious ethical and legal questions and political issues which remain to be resolved.

II. Relevant environmental pressures associated with ICT goods and ICT-enabled solutions

Supporters of digitalisation frequently emphasise its enabling potential to solve environmental problems. However, based on the analysis of relevant literature it remains unclear whether (positive) indirect environmental impacts can outweigh the negative direct ones, even from a GHG viewpoint, not to mention impacts on the other environmental categories such as resource depletion, water, land use and biodiversity, which are less well investigated compared to GHG, especially assessing the indirect impacts. Even the evidence on enabled GHG reduction is inconsistent. This could be due to the different methods applied but also numerous complex interconnected factors (economics factors, consumer behaviours, lifestyle and value system, social practices, technical systems, dynamic implications of change and so on). The following sections summarise environmental pressures related to the digitalization:

- **Direct impacts on resources**: The mining and extraction of raw materials (e.g. cobalt, palladium, tantalum, silver, gold, indium, copper, lithium and magnesium) as well as the production of microelectronic components, especially integrated circuits, are the main contributors to fossil resource depletion as well as abiotic resource depletion, global warming, freshwater eutrophication, soil acidification, human toxicity, freshwater toxicity, marine toxicity, and terrestrial toxicity.

- **Direct impacts on biodiversity and land use as well as land use change**: The assessment of related impacts of ICT is challenging, as the cause-impact relationships are very heterogeneous and indirect. However, a lack of data of course does not imply a lack of impact. Rather, it has to be assumed that the biodiversity and land use impacts are rather significant. Major impacts result from the extraction of natural resources needed for the production of hardware, from the release of hazardous materials (such as heavy metals, toxic fumes, acidic leachates) related to raw material extraction processes, as well as from the inappropriate collection, recycling and disposal waste of electrical and electronic equipment (WEEE). Environmental impacts of power generation (e.g. greenhouse gas emissions) can also include biodiversity impacts. The impacts of underwater data transmission cables on underwater species have not yet been thoroughly investigated.

- **Indirect and systemic impacts on the environment**: To assess these impacts, it is necessary to fully understand how digitalisation changes economic processes, social aspects and lifestyles as well as the interactions between these. This makes the assessment of environmental consequences complex and very challenging. The complexity of processes and data flows associated with digitalisation increases when taking indirect and systemic impacts into account (beyond direct impacts). Evaluating direct impacts associated with the physical existence of ICT goods is a fundamental step for further assessing indirect and systemic impacts resulting from the application of ICT goods and ICT-enabled solutions in concrete sectors of application. However, there are gaps in the assessment of a number of relevant direct impacts. For instance, direct environmental impacts of data centres, data transmission networks and emerging innovation technologies have yet to be sufficiently explored, especially regarding non-energy aspects. With regard to systemic impacts, findings from the field of energy consumption indicate that such effects can be pervasive. There is an urgent need for similar research on the systemic impacts of digitalisation beyond energy consumption and greenhouse gas emissions.

- **Overall assessment**: One cannot assume that digitalisation will lead *per se* to resource, energy or other environmental benefits. A holistic approach is needed to properly understand the impacts and get robust results. This requires not only looking at the use phase, but also at manufacturing and end-of-life phases; not only focussing on IT equipment, but also on the required infrastructures; not only measuring the carbon footprint, but also other impacts; not only acknowledging direct but also indirect and systemic effects, including incentive structures of digital business models. The digital transformation cannot be sustainable if it is not regulated in a way that mitigates its negative environmental effects. To steer digitalisation in a (more) sustainable direction, it is imperative that efficiency gains are not overcompensated by increases in (energy and) resource consumption caused by economic growth.

III. Assessing the potential of regulation for reducing the negative environmental impacts of digitalisation

The literature on non-energy impacts of digitalisation is sparse, disparate, methodologically incoherent and insufficiently quantified, and very few assessments have been conducted on the environmental relief potential of policy measures; the literature on energy and GHG-related impacts is altogether more substantial but similarly non-integrated across the different types of impact (direct, indirect, systemic), across different fields of application and taking account of their interactions.

Based on this, it is **not possible for us to *quantify* the potential** for reducing negative environmental (non-energy) impacts, should the production, consumption, use and disposal of ICT goods and ICT-enabled applications be more stringently regulated from an environmental perspective. Such a quantified assessment would require a significant coordinated research effort and the development of policy scenarios for "greening digitalisation", for instance within the EU's 'Horizon Europe' research framework.

However, in **qualitative terms** there is sufficient evidence that non-energy (direct, indirect and systemic) impacts related to the digital transformation could be significantly reduced through environmental regulation.

IV. Environmental parameters for governing the digital transformation and recommended policy measures

The following parameters are "entry points" (along the life cycle) for regulating the digital transformation in a way that minimises its environmental threats and maximises its environmental opportunities. They can be grouped into "entry points" for "ICT for Green" and "Greening ICT":

ICT for Green:

- **Improving product information:** Improving (the availability of) product information and sharing it across the value chain is another entry point. This includes sustainability information as well as information relating to a product's material composition. As an example, manufacturers should provide information on the critical raw materials (CRMs) they use in products – firstly, to support remanufacturers and recyclers in making informed decisions on component or product treatment; and secondly to support policymakers in monitoring the use of CRMs.

- **Sustainable ICT consumption**: Policies should also aim at increasing environmental information/ consciousness and social engagement, for instance by guiding consumers to recognize the environmental impacts beyond GHG associated with their behaviours and to choose sustainable solutions (e.g., suitable cloud services fitting their individual demands). Strengthening ICT consumption should also include stringent regulations on advertising by internet providers, combining the demands of consumers and corresponding cloud services regarding data sufficiency and utilisation sufficiency, which will facilitate sustainability-oriented consumer decisions.

- **Improving environmental governance**: Digital technologies imply a wide range of instruments which might be used to improve environmental governance (through collecting and sharing environmental data, monitoring the environment, controlling problematic activities, ensuring a more effective implementation of environmental law, and making possible more inclusive, legitimate environmental policies). These options should be made greater use of, but pilot projects should be supported by research on (social and potentially environmental) side effects.

Greening ICT:

- **Increasing resource efficiency and reducing absolute levels of resource consumption**: An overarching framework is necessary for increasing resource efficiency in the ICT sector and for reducing absolute levels of resource consumption. Options include the adoption of quantified targets for (sector- and resource-specific) resource efficiency and for absolute resource consumption in the future EU sustainability strategy; or the introduction of economic instruments which incentivise greater resource efficiency.

- **Improving the sustainability governance of mining and sourcing**: Since the extraction of critical mineral resources causes a host of impacts on resource depletion, biodiversity and land use (and will cause more in the future), it is important to improve the sustainability regulation and

its enforcement in the EU and strengthen respective capacities in non-EU mining countries. At the same time, responsible behaviour needs to be promoted among the economic actors sourcing extracted resources, for instance through introducing due diligence obligations on human rights compliance and environmentally responsibility. The sustainability of technical options for supply chain management through, for instance, tracking and tracing of raw materials using distributed ledger technologies like blockchain should be further assessed. For blockchain technologies to actually enhance transparency, standards need to be developed prioritising sustainability impacts along specific supply chains.

- **Improving (the framework conditions for) the circular economy**: Digitalisation and circular economy (CE) are closely interlinked. On the one hand and as mentioned above, energy and raw materials used for the ICT sector cause a host of undesired ecological impacts. On the other hand, data and digitally enabled applications could make significant contributions towards a circular economy, e.g. with the help of interconnected digital tools which may help to improve the use of natural resources, design, production, consumption, reuse, repair remanufacturing, recycling, and waste management.

  – An entry point is **Extended Producer Responsibility (EPR)**: The main characteristic of any EPR policy is that it places some responsibility for a product's end-of-life environmental impacts on the original producer and seller of that product. It is understood that EPR will provide incentives for producers to make design changes to products that would reduce waste management costs. Those changes should include improving product recyclability and reusability, reducing material usage and downsizing products, and engaging in a host of other so-called "design for environment" (DfE) activities. EPR could be facilitated by using digitally-enabled solutions, in particular by information sharing along the value chain and especially between manufacturers and recyclers or re-manufacturers.

  – In addition, existing regulatory frameworks and especially the **Ecodesign Directive** should be used and further developed in order to manage both transitions together –digitalisation and the development of a circular economy.

  – **Expanding the lifetime of ICT goods**, especially mobile ICT goods such as smartphones, tablets and laptops: There is a large potential for remanufacturing, recovering and recycling materials from obsolete ICT devices, especially the accumulated stock of unused, so-called hibernating devices in EU households. A large number of these products are replaced even though they are still functional (psychological obsolescence). The influence of short innovation cycles, as well as advertising and the tariff models of service providers seem to play a decisive role in this regard.

  – One option for improving the framework conditions for the **repair of ICT goods** is the certification of reliable and professional repair operators in order to reduce barriers to implementing circular economy. For instance, final consumers have concerns on data privacy which could hamper the second use of devices.

  – It is also necessary to **increase the collection rate of ICT goods** once they reach the end of their life.

  – A **market for secondary (raw) materials** is a prerequisite for the development of well-functioning secondary material supply chains. In this context, quality standards and exchange of information und material characteristics, deliverable quantities, impurities, costs, etc. play an important role. Digital solutions like online platforms may help to improve information sharing on secondary materials.

– Regarding the **remanufacturing of Critical Raw Material (CRM)**, it is necessary to increase the remanufacturers` awareness and knowledge on embedded CRMs to facilitate informed planning for the recovery of CRMs on component level. A **declaration of critical raw materials** could foster the recycling of critical raw materials by providing information about the location of these metals within products.

– **Reducing e-waste streams** and improving recycling technology are therefore essential for building a more circular economy. More efforts must be made to enforce, implement, and encourage more countries to develop e-waste policies.

– Finally, the EU should stimulate the environmentally-sound collection and **recycling of e-waste in developing countries** (e.g. though creating an international recycling fund for e-waste that could make pre-defined premium payments on pre-defined volumes of soundly recycled e-waste).

- **Increasing transparency on chemicals used in the ICT industry**: The semiconductor industry uses an extensive range of ultrapure chemicals and solvents. The transparency of chemicals used in the ICT industry should be increased in order to better evaluate their associated environmental impacts.

- **Greening data centre operation**: Options include encouraging and promoting the utilisation of waste heat from data centres by transforming it into a useful energy source. Also, data centre operators should be obliged to report on their water consumption and disposal routes of obsolete hardware, and to reduce respective impacts over time.

- **Sustainable software**: Promoting relative sustainable software (e.g. voluntary application of the criteria of German Blue Angel label for resource-efficient software could be a first step but should be made binding in the medium term). Software-induced hardware obsolescence should be prevented through product law.

- **Complex algorithms** that are used in search engines and in all kinds of digital applications etc. determine, for example the choice of routes for autonomous driving or selection options offered for products and services on trading platforms. The criteria – or steering targets – which determine these choices, however are highly intransparent. At the same time, algorithms fulfil their functions and thus determine these choices in a very effective way. They therefore can have potentially wide-ranging negative impacts. This raises the fundamental question of how to prevent unsustainable data biases and how to make the orientation of optimisation and the consideration of environmental and sustainability criteria transparent (cf. (Gailhofer, 2019).

- **Governance of the data economy:** Data are the economic and technological means of production of digital technologies and applications. Access to and rights to use data thus are crucial for the development and operation of environmentally promising applications. At the same time, the factual economic distribution of data – e.g. data-based market-concentration favouring few "data-rich" corporations – can disadvantage sustainable applications or business models and privilege the development and dissemination of detrimental innovations (Gailhofer & Scherf, 2019). Existing debates about adequate regulatory levers to support the usage of data in line with the common good therefore are highly relevant for environmental policies. Given the differentiation and scope of these debates regarding adequate policies and legal arrangements and the complexity of their environmental evaluation, this paper however does not elaborate specifically on regulatory alternatives. The general importance of data as well as particular arguments regarding rights to access data for particular use-cases will be emphasized where needed.

V. Limitations of the available research and recommendations for further work

There are significant methodological limitations, data gaps and blind spots in the evidence on environmentally-relevant digitalisation impacts. We recommend:

- **Developing standardised methods** for quantifying and assessing direct and indirect impacts on biodiversity as well as for assessing systemic impacts (including rebound effects resulting from complex cause-effect chains).

- **Promoting life cycle assessment beyond energy and GHG aspects** of network infrastructure along with the technology generation.

- **Promoting life cycle assessments** of innovative technologies and technology trends associated with their resource depletion and environmental impacts. Relevant technologies that should be assessed include, notably, 5G, blockchain and sensor technologies.

- **Assessing digital applications and business models**, which would be much easier and more quickly based on **standardised Life Cycle Inventories** for the most relevant current and for upcoming ICT components and infrastructure.

- **Broadening the scope of impact categories** (beyond the energy and carbon footprint) In environmental assessment studies.

- **Carrying out case studies** to analyse systemic **impacts of ICT-enabled solutions**. Such studies should review the state of recent research and discuss the methodologies, as a first step towards standardising them.

- **Identifying sectors or applications in which digitalisation can be expected to induce more environmental benefits than risks/ threats**, and sectors or applications in which (negative) systemic impacts are likely to outweigh environmental benefits.

- **Tackling the data gap on the (impacts of) chemicals** used in the semiconductor and ICT industries.

- **Establishing standard secondary databases** to model the upstream processes which increase the comparability of environmental assessment results and also reduce the sources of uncertainty**.** Complementing the ongoing standardisation activities on data exchange in the context of IoT and **distributed production systems** with requirements on the reporting of input-output-data on energy and material flows would support the collection and development of more reliable data bases for Life Cycle Inventories.

- **Exploring 'big points' of sustainable ICT consumption and options for educating consumers**: Research is necessary to identify the 'big points' – i.e. activities through which individual consumers create substantive environmental impact (from ICT hardware via applications to practices such as google searches or videostreaming). In addition, it is necessary to explore the state of knowledge / attitudes of consumers regarding these big points as well as regarding sustainable consumption options in the field of ICT goods and applications, and to collate information on effective options for educating consumers and strengthening their capacities with regard to a sustainable digitalisation.

- **Identifying policies and institutions** that can help to shape digitisation in a sustainable way (beyond the proposals above), including with respect to Big Data and the **data economy**. Given the impact and effectiveness of the new data-driven technologies, such regulations would affect the distribution of agency between private, public or civil society actors. Despite the prominence of the technologies' environmental impacts, however, environmental policy objectives have yet to be considered in these legal policy debates.

VI. Digitalisation and the European Green Deal

Implementing the plan and measures of the European Green Deal is inextricably linked to the digital transformation. The European Green Deal stresses the need for the EU to provide resources for the necessary digital change and digital instruments, which are essential preconditions for change. As early as March 2020, the Commission will adopt an EU industrial strategy to address the twin challenges of environmental and digital change. Digital change is regarded as a key factor in achieving the Green Deal objectives.

The importance of digitalisation is emphasised repeatedly in the Green Deal for individual economic sectors: For the further decarbonisation of the energy system, it should be ensured that the European energy market is fully integrated, networked and digitised. Digital solutions such as intelligent traffic management systems will play an increasingly important role in the transition to sustainable and intelligent mobility. Against this background, the Commission will explore measures to ensure that digital technologies can accelerate and maximise the impact of policies to deal with climate change and protect the environment.

The European Green Deal also stresses the role of accessible and interoperable data as a prerequisite for data-driven innovation. This data, combined with digital infrastructure and artificial intelligence solutions, will facilitate fact-based decisions and strengthen the ability to understand and address environmental challenges. Other new opportunities opened up by digitalisation include remote monitoring of air and water pollution or monitoring and optimising the use of energy and natural resources.

On the other hand, the Green Deal recognises that digital technologies themselves pose environmental risks and that Europe needs a digital sector that focuses on sustainability. Specifically, the Commission will examine measures to improve energy efficiency and the closed loop orientation of the ICT sector. The further development of the existing Ecodesign Directive proposed in this paper could form an important basis for the concrete implementation of these initiatives.

Annex I: Issue Paper "Impacts of the digital transformation on the environment and sustainability"

1. Introduction

1.1. Background and rationale

This paper reviews findings on the (potential) impacts of the digitalisation (or "digital transformation") on the environment, with a focus on non-energy impacts. We understand "**digitalisation**" to mean 'the development and application of digital and digitalised technologies that augment and dovetail with all other technologies and methods' (WBGU, 2019c). This includes the production, use and disposal of hardware (final goods of Information and Communication Technologies (ICT), data centres, data transmission networks) as well as of software, digital technologies and applications – ranging from robotics, the Internet of Things (IoT), via distributed ledger technologies such as blockchain, to Artificial Intelligence (AI).

As a long-term deep development that revolutionises the social, political, business and economic conditions in which we life, digitalisation represents a 'classical' **megatrend** (Naisbitt, 1982). Not only does digitalisation have profound ('transformative') effects on the economy, society, on political orders and policy-making, but also on the planet itself. It has been described as a potential "fire accelerant", exacerbating growth patterns that breach the planetary guard rails (WBGU, 2019c). From the perspective of sustainable development, it is therefore necessary that policy-makers give direction to the process of digitalisation, so that it supports rather than contradicts sustainability, ideally 'reach[ing] across traditional policy silos' (OECD, 2017). The following courses of action are relevant for **environmental policy-making**:

- identifying and making use of the opportunities offered by digital technologies for protecting the environment – through making possibly new (ecological) business models and services, though greening production and consumption and through monitoring changes in the state of the environment;

- identifying and making use of the opportunities offered by digital technologies for rendering environmental policy-making more transparent, democratic, legitimate and acceptable;

- identifying and mitigating the negative impacts that digitalisation has on the environment, either in a direct, indirect or more systemic way (e.g., by fuelling unsustainable economic growth); this includes negative impacts of the digital transformation on environmental policy-making.

In the **European Union** (EU) digitalisation is a major driving force of economic and social change, though the process has been described as uneven (McKinsey & Company, 2016). The EU has started shaping a European approach to digitalisation with its '**Digital Single Market Strategy**' (DSM)[3] (since 2015) which so far has focussed largely on economic growth, innovation and competitiveness. The interactions between the digital transformation and the environmental crisis have not been high on the agenda of the political debates and policy making at EU level over the past 10 years. In June 2019, however, the **European Council** stressed 'the need to consider and adequately address the opportunities and challenges of digitalisation for environmental, climate and nature protection through targeted policy-instruments at EU level, thus contributing to a sustainable

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[3] COM (2015) 192. The DMS followed the eEurope 2002 plans, eEurope 2005, the i2010 Strategy, the 2010 Digital Agenda for Europe and the mainstreaming of digital policies in the flagship initiatives of the Europe 2020 Strategy.

approach to digitalisation in the EU'.[4] While the President-elect of the European Commission von der Leyen in her political guidelines tended to juxtapose digitalisation and environmental sustainability,[5] the European Council in October 2019 again called for their integration: It highlighted 'the need to accelerate the transition towards a resource-efficient, circular, non-toxic, safe and climate-neutral economy with safe and sustainable production and consumption patterns, and to ensure that the design of the EU's competitiveness, industrial, trade and digital policies also contributes to this objective'[6]. In its call for an **8th Environment Action Programme** (EAP), the Council encouraged the Commission 'to address the opportunities and possible risks and challenges of the digital transformation in a systematic way'. This is in line with the recent **State of the Environment Report** by the European Environmental Agency (EEA) which holds: "Accelerating technological innovation is fuelled by the widespread digitalisation of economies and societies worldwide. While this can increase productivity and energy efficiency, it is not yet clear whether the energy and materials savings are enough to outweigh the negative sustainability impacts of information and communications technology (ICT) (UN Environment, 2019), such as its huge demand for critical raw materials. (…) Widespread digitalisation is also the key enabler of the 'Fourth Industrial Revolution', which fuses digital technologies with nanotechnologies, biotechnologies and cognitive sciences (…) Concerns also exist over the implications for human health (especially from nanotechnologies and synthetic biology), and the implications for the environment are largely unknown (UNEP, 2017a) (EEA, 2019, p. 46).

Against this background, the "**European Green Deal**" (EGD), presented by the Commission in December 2019, acknowledges that "Europe needs a digital sector that puts sustainability at its heart" (European Commission, 2019, p. 9; see Box 1 for statements on the digital transformation in the European Green Deal Communication).

This paper can contribute to providing a basis for such an endeavour. It is intended to be a starting point for discussion and further evidence gathering.

Box 1: The European Green Deal & the digital transformation

"To deliver the **European Green Deal**, there is a need to rethink policies for clean energy supply across the economy, industry, production and consumption, large-scale infrastructure, transport, food and agriculture, construction, taxation and social benefits. To achieve these aims, it is essential to increase the value given to protecting and restoring natural ecosystems, to the sustainable use of resources and to improving human health. This is where **transformational change** is most needed and potentially most beneficial for the EU economy, society and natural environment. The EU should also **promote and invest in the necessary digital transformation and tools as these are essential enablers of the changes**."

"… it is essential to ensure that the **European energy market** is fully integrated, interconnected and digitalised."

"… the Commission will adopt an **EU industrial strategy** to address the twin challenge of the green and the digital transformation. Europe must **leverage the potential of the digital transformation, which is a key enabler for reaching the Green Deal objectives**."

"Digitalisation can also help improve the availability of **information on the characteristics of products sold in the EU**. For instance, an electronic product passport could provide information on a product's origin, composition, repair and dismantling possibilities, and end of life handling."

"Digital technologies are a critical enabler for attaining the sustainability goals of the Green deal in many different sectors. The Commission will explore measures to ensure that digital technologies such as

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[4] Council of the European Union, Conclusions on the Future of a highly digitised Europe beyond 2020: "Boosting digital and economic competitiveness across the Union and digital cohesion". Brussels, 7 June 2019, 10102/19.

[5] e.g., 'Europe must lead the transition to a healthy planet *and* a new digital world' von der Leyen (2019a); 'In striving for digital leadership, we must … support industry to adapt to globalisation and the twin climate and digital transitions' von der Leyen (2019b) (own italics).

[6] Council of the European Union, The 8th Environment Action Programme - Turning the Trends Together - Council conclusions. Brussels, 4 October 2019, 12795/19.

Box 1: The European Green Deal & the digital transformation

artificial intelligence, 5G, cloud and edge computing and the internet of things can accelerate and maximise the impact of policies to deal with climate change and protect the environment. Digitalisation also presents new opportunities for distance monitoring of air and water pollution, or for monitoring and optimising how energy and natural resources are used. At the same time, Europe needs a digital sector that puts sustainability at its heart. The Commission will also consider measures to improve the energy efficiency and circular economy performance of the sector itself, from broadband networks to data centres and ICT devices. The Commission will assess the need for more transparency on the environmental impact of electronic communication services, more stringent measures when deploying new networks and the benefits of supporting 'takeback' schemes to incentivise people to return their unwanted devices such as mobile phones, tablets and chargers."

"[The Commission] should ensure that the design of new and renovated buildings at all stages is in line with the needs of the circular economy, and lead to **increased digitalisation** and climate-proofing **of the building stock**."

"**Automated and connected multimodal mobility** will play an increasing role, together with smart traffic management systems enabled by digitalisation. The EU transport system and infrastructure will be made fit to support new sustainable mobility services that can reduce congestion and pollution, especially in urban areas. The Commission will help develop smart systems for traffic management and 'Mobility as a Service' solutions, through its funding instruments, such as the Connected Europe Facility."

"The Commission will explore new ways to **give consumers better information**, including by digital means, on details such as where the food comes from, its nutritional value, and its environmental footprint."

"**Accessible and interoperable data are at the heart of data-driven innovation.** This data, combined with digital infrastructure (e.g. supercomputers, cloud, ultra-fast networks) and artificial intelligence solutions, facilitate evidence-based decisions and expand the capacity to understand and tackle environmental challenges. The Commission will support work to unlock the full benefits of the digital transformation to support the ecological transition. An immediate priority will be to boost the EU's ability to predict and manage environmental disasters. To do this, the Commission will bring together European scientific and industrial excellence to develop a very high precision digital model of the Earth."

Source: (European Commission, 2019).

1.2.　Goal and scope of this study

The overall objective of the paper is to gather evidence on positive and negative effects of the digital transformation on the environment as well as of its opportunities and risks. Since there is significantly more research on the energy consumption and greenhouse gas (GHG) effects related to digitalisation (e.g., Corcoran & Andrae, 2013; Fraunhofer ISI, 2019; IEA, 2017; Morley, Widdicks, & Hazas, 2018; Prakash, Baron, Liu, Proske, & Schlösser, 2014; Røpke & Christensen, 2012), this paper focusses on its non-energy, non-GHG effects. Specifically, impacts on resource and water consumption, land use and land use change as well as on biodiversity are screened. We differentiate environmental effects of digitalisation into direct, indirect and systemic effects, taking account of the complex impact pathways related of the digital transformation. Both opportunities and risks for achieving the UN Sustainable Development Goals (SDGs) will be addressed.

Legal policy debates about adequate regulation of algorithms and the data economy cannot be addressed here in detail. However, the general importance of data as well as particular arguments regarding rights to access data for particular use-cases will be emphasised where adequate (among others, see 'Recommendations for further work', Section 5).

Methodologically, the paper is based on a literature review. Both academic and grey literature have been screened, the latter including a host of publications by inter- and transgovernmental organisations or governmental advisory bodies.

Key questions of the paper are:

- What environmental opportunities are related to the digital transformation?

- Which are the big environmental pressures of digitalisation – beyond energy demand & GHG emissions? (use of resources, water consumption, land use and biodiversity)

- What policy conclusions can be drawn from these insights?

- What aspects require (more) evidence gathering and research?

1.3.   Approach and methods considered in this study

The study is based on a review of literature, structured along the questions outlined above. The studies screened include various methods, including Life Cycle Assessments (LCAs), environmental assessment studies, carbon footprint studies as well as more qualitative analyses. As regards temporal scope, we have limited the literature screening largely to studies published after 2010: given the rapid pace of technological progress in the ICT area, older studies may not be (fully) valid any more (criterion of 'external validity').

In order to estimate the global demand for digitisation of material and energy resources, the available information is structured in accordance with a conceptual framework by the OECD (Mickoleit, 2010) that differentiates between three levels of environmental impact in the interaction of ICTs and the natural environment – direct, indirect and systemic impacts:

- Direct impacts ('first order' effects) include the use of natural resources and emissions into the environment that are caused by the production, use, and disposal of ICT products.

- Indirect impacts of ICTs ('second-order' effects) arise from ICT applications that reduce environmental impacts across economic and social activities. ICTs affect how other products are designed, produced, consumed, used and disposed of. This can make production and consumption more resource efficient. Potential negative effects need to be factored in when assessing "net" environmental impacts, such as greater use of energy by ICT-enabled systems compared to conventional systems.

- Systemic impacts of ICTs and their application on the environment (or 'third-order' effects) involve behavioural change and other non-technological factors, triggered by the transition towards the widespread use of digital technologies. Systemic impacts include the intended and unintended consequences of wide application ICTs such as the medium- or long-term adaptation of behaviour (e.g. consumption patterns) or economic structures.

Although this classification of effects is helpful and widely accepted, it is often difficult to apply. The classification of negative direct effects and desirable positive effects is a challenge, not least because very complex allocation questions have to be dealt with and generally accepted scientific conventions do not exist. This limitation is even more true with regard to the systemic effects, because complex cause-effect chains have to be taken into account here and research work has only recently begun to systematically understand rebound effects, for example.

2.   Environmental opportunities related to the digital transformation

The use of ICT indirectly influences the resource efficiency of other processes such as transport or industrial production. In addition to the influence of ICT on the amount of resources consumed by other processes, this also includes the frequency and duration of use of these processes. Digitisation also has more systemic, wide-ranging effects which transcend issues regarding efficiency or optimization of processes: it transforms services, business models and changes complete value chains. Powered by vast amounts of data, it boosts our level of information about the environment, economic dynamics and social and individual behaviour. At the same time, it makes technologies available which instrumentalize this information to automatically and very effectively exert influence on the physical and social world. New instruments of amplified information, management and control hold potentials for more sustainable products, business models and policies.

There is presently a lack of quantitative evidence on the ecological relief potential through digitalisation, and the causal attribution of such relief to 'digitalisation' is often difficult. At the same time, it is important to keep in mind, that – while positive examples and opportunities emerge more and more, there are also known potential negative effects and uncertainties about the application of digital solutions (cf. Section 3).

The evidence identified in the following is presented focussing on selected issues forming part of the European Green Deal (European Commission, 2019), notably:

- Mobilising industry for a clean and circular economy
- From 'Farm to Fork': Designing a fair, healthy and environmentally-friendly food system
- Preserving and restoring ecosystems and biodiversity
- A zero pollution ambition for a toxic-free environment

2.1.   Mobilising industry for a clean and circular economy

2.1.1.   Case study: E-waste

Digitalisation and the advancement in technology could have a positive impact on mitigating the negative effects caused by electronic waste (e-waste). A number of measures can be deployed to ensure the waste resulting from electronics is minimal. First of all, producers of electronics can offer buy-back/return systems for old equipment. Consumers would be financially incentivised to do so and it would also ensure the end-of-life process is handled properly. Secondly, electronic waste needs to be properly collected, their components re-used and the rest of the materials recycled (WEF, 2019). Furthermore, a number of digital applications and technologies can help when putting into practice measures to limit the amount of electronic waste:

- An **e-waste recycling app** ("Baidu Recycle App"),[7] tested in China, has resulted in 152.74 million of pieces collected in a year (2015). The success of the app results from its user friendly platform and the fact that it connected all relevant stakeholders in relation to e-waste on one platform, namely consumers, manufactures and recyclers. It allows consumers to locate legitimate e-waste pick up services where their product can be recycled in return for a financial incen-

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[7] Similarly, blockchain technology has been used to motivate people in Northern Europe through financial rewards in the form of cryptographic tokens in exchange for depositing (non-e-waste) recyclables like plastic containers, cans, or bottles (Saberi, Kouhizadeh, Sarkis, and Shen 2018). For example, the "Social Plastic" and "RecycleToCoin" projects use blockchain technology to incentivise people to reduce plastic waste, and respectively to return plastic containers (ibid).

tive (UNDP, 2016). The success of the app was also recognised by the UNDP, which co-organised a workshop to share the experience and knowledge with other relevant stakeholders (ibid).

Another, EU-based, example of such a mobile app that aims at reducing electronic waste is "Volpy". It claims to be able to bring smartphones into the circular economy by allowing users to swap their smartphone for another one of their choice and paying the price difference.[8] The potential of the application has been recognised at EU level, by the European Circular Economy Stakeholder Platform. It works on the basis of quickly assessing and then exchanging a smartphone (whether new or refurbished) between users, within the application. Given that the production of each new smartphone requires 70kg of raw materials, applications like Volpy can contribute to the reduction of material use and waste and serve as a simple tool to enhance the circular economy. The application was launched in 2016 and has been one of the top applications downloaded (in France, where it was introduced), with approx. 800 000 downloads and approx. 90 000 accounts being created.[9]

- Providing products with so called **product passports**, which would include valuable information about the product and/ or its packaging contents (e.g. which valuable materials and/or hazardous materials are included). If such information was available, the material flow could be made more efficient and the value of the product be enhanced in relation to circular economy, which could potentially lead to more materials being recycled (Climate-KIC, 2018).

  The WEEE Directive, obliges producers to provide information about preparation for re-use and treatment of electronic devices on the market.[10] Therefore, a single online platform, the **Information for Recyclers (I4R),** has been established. The I4R collects information about preparation for re-use and treatment of new equipment placed on the EU's market for the first time.[11] This information is then subsequently shared with treatment and recycling facilities, which provides them with crucial knowledge on recycling of electronic devices (Digital Europe, 2019). The I4R platform can be considered as an important tool to support sustainable digitalisation and a platform enabled through digitalisation.

- Technology can also have the potential **to enhance Extended Producer Responsibility (EPR)** and play a role in **tackling free-riding on EPR**. Non-compliance with EPR has a number of negative impacts, such as lower collection rates for end-of-life products, reducing the finance for waste management or underestimating the number of products on the market and thus potentially over-estimating national recycling rates. For example, a **single electronic register of producers** could be established, which would also allow for reporting of non-registered producers. Furthermore, digital solutions, such as blockchain technologies or smart contracts, could also play a role in promoting this, which is currently being explored (OECD, 2018).

- The circular economy would be enhanced and the negative effects of e-waste could be mitigated if the **lifetime of electronic devices** was prolonged. A practical example of such can be named the use of mobile phones in the EU. If their lifespan was extended from 21,6 months to 33,6 months, 20,3 million tonnes of CO_{2e} could be reduced over a period of 10 years. With an even more ambitious target and a lifespan extended to 45.6 months, the amount of CO_{2e} saved could be as high 30,5 million tonnes (Rizos, Bryhn, Alessi, Campmas, & Zarra, 2019); significant relief potential would also be tapped as regards resource consumption, though this was not covered

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[8] See 'https://www.volpy.com/'

[9] European Circular Economy Stakeholder Platform, 'Volpy brings smartphones into the circular economy' [online] available at <https://circulareconomy.europa.eu/platform/en/good-practices/volpy-brings-smartphones-circular-economy>

[10] Directive 2012/19/EU, Art. 15

[11] COM(2019) 190 final

by the study. Policy action would be required to close the collection gap for mobile phone devices.

- Very recently, a new **power saving chip** was developed which has a potential to extend battery life and, in consequence, to prolong the lifespan of electronic devices. The chip would become a part of Internet of Things (IoT) devices and would ensure that devices wake up only when necessary (i.e., when they need to communicate or perform their functions). This would mean that the devices would remain 'asleep' the rest of the time, reduce power use and as a result, batteries would need to replaced less frequently (Jiang et al., 2019).[12]

- **Robots** are employed to **dismantle hard drives** and increase the recovery of valuable components. For instance, e-waste recycling centre Greentec and Conestoga College developed a robotic cell ('Project Lexi') that is claimed to completely dismantle a hard drive in less than a minute and to allow Greentec to recover all components within the drive. To date, a major obstacle with dismantling hard drives is the separation and recovery of useful materials such as rare earth magnets if these get commingled with steel, or are caught in screens and shredder blades during processing. The robotic cell learns how every make and model of hard drive is constructed and can thus more efficiently disassemble these.[13]

2.2. Preserving and restoring ecosystems and biodiversity

Digital technologies may help to alleviate pressures on the natural environment and biodiversity in many respects. This section provides examples for such environmental relief potential with respect to the monitoring of biodiversity and ecosystem services and to new digitally supported business-models with potentially positive effects on the natural environment and biodiversity.

2.2.1. Case Study: Monitoring of biodiversity and ecosystem services

ICT-enabled solutions help monitoring biodiversity and ecosystem services. The impact of these technologies and applications on the state of biodiversity and ecosystem services, however, is indirect and uncertain: better information (acquired on the basis of sensor technologies etc.) can help assessing "distance to target" with regard to policy goals on biodiversity protection, thus putting pressure on policy-makers (which may or may not result in policy action). ICTs can also help visualise and communicate biological data, thus increasing policy and public awareness. Both are necessary, though not sufficient preconditions for effective policy action.

In the following, we give some examples:

- **Monitoring of biodiversity trends and achievement of biodiversity targets**: Various ICT solutions are employed to monitor the trends of ecosystems and biodiversity. For instance, the Earth Observations Biodiversity Observation Network (GEO BON) uses Earth Observation through remote-sensing (via satellite sensors) as one tool to support the monitoring of biodiversity and ecosystem service change for a number of indicators, including those of the international "Aichi Targets" of the UN Convention on Biological Diversity. O'Connor et al. (2015) conclude that existing earth observation technology shows considerable potential for measuring biodiversity indicators, among others in the context of monitoring achievement of the "Aichi Targets", but that this potential has not yet been fully realized (see also Tallis et al., 2012).

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[12] See also Science Daily, 'New chip for waking up small wireless devices could extend battery life' (2019) [online] available at <https://www.sciencedaily.com/releases/2019/11/191112073540.htm>

[13] https://www.ewaste-expo.com/greentec-robots-helping-to-dismantle-hard-drives-to-recover-valuable-components/

- **Monitoring of special data, geodata and bio-geophysical parameters** is also part of the EU's spatial information system – based on the INSPIRE Directive – and its Earth Observation Programme "Copernicus". The "Infrastructure for Spatial Information in the European Community" (INSPIRE) Directive (to be fully implemented by 2021) creates a EU spatial data infrastructure for the purposes of EU environmental and environmentally relevant policies and enables the sharing of environmental spatial information.[14] Data sets relate, among others, to land cover, land use, geology, protected sites, habits and biotopes, soils, agricultural and industrial facilities.[15] Copernicus provides free information services based on satellite Earth Observation and in situ (non-space) data. The Copernicus Land Monitoring Service (CLMS) provides geographical information on land cover and its changes, land use, vegetation state, water cycle and earth surface energy variables.[16] Similarly, the Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic reference information on the physical and biogeochemical state, variability and dynamics of the ocean and marine ecosystems for the global ocean and the European regional seas.[17] The information provided by the Copernicus programme is used by policymakers and public authorities to develop environmental policies or to take decisions in the event of an emergency, such as a natural disaster or a humanitarian crisis. In the US, NASA's Applied Remote Sensing technology ECOSTRESS addresses three critical questions around vegetation, health and agriculture: How is the terrestrial biosphere responding to changes in water availability? How do changes in diurnal vegetation water stress impact the global carbon cycle? Can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumption and improved drought estimation?[18]

- **"Smart conservation" through advanced mapping and big data analytics, sub-marine, coastal and inland smart sensors, drones, re-al-time satellite imaging, smart monitoring etc.** (GeSI & accenture, 2016) harnesses further potentials to explore and understand conditions and dynamics biodiversity and land use. Projects like "Whaletrack"[19] use satellite tagging to reveal many insights into the migratory behaviour of whales. Acoustic sensor data can be analyzed and evaluated using machine learning to identify different species in a field and study their behaviour. Remote acoustic monitoring practices, in combination with other methods thereby can provide a holistic picture of biodiversity (Ross et al., 2018). Nature apps like those of "Sunbird Images" serve as modern field guides, support ornithological mapping for nature enthusiasts (citizen science) and can thus promote biodiversity awareness. "Data4All" is a crowdsourcing geographic data collect project, aiming to develop an easy to use mobile application to facilitate geographic data collection.[20]

- **Digital visualisation of data**: The digital atlas of the EU initiative "Mapping and Assessment of Ecosystems and their Services" (MAES) is designed to present in a systematic way maps of ecosystem types and ecosystem services.[21]

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[14] https://inspire.ec.europa.eu/about-inspire/563

[15] https://inspire.ec.europa.eu/Themes/Data-Specifications/2892

[16] https://www.copernicus.eu/en/services/land

[17] https://www.copernicus.eu/en/services/marine

[18] https://ecostress.jpl.nasa.gov/

[19] https://en.uit.no/prosjekter/prosjekt?p_document_id=505966; see also https://www.orcireland.ie/whaletrack-project-tracks-humpback-whales-all-the-way-from-artic-feeding-grounds-and-to-tropical-breeding-areas-and-back-again

[20] http://www.capacitylab.org/project/data4all

[21] https://biodiversity.europa.eu/maes/maes-digital-atlas

2.2.2.   Case Study: Digitally supported & biodiversity-friendly business models

ICT can also make business models viable that prevent the degradation of biodiversity or support the provisioning of ecosystem services.

- **Payments for ecosystem services**: Blockchain technology has been discussed as a potential tool for enhancing the provision of ecosystem services through providing payments. For instance, the Programme for the Endorsement of Forestry Certification (PEFC) expects that blockchain "could be used as a basis for carbon credits exchange systems and for the enhancement of avoided impacts. The system, developed to manage and exchange virtual currency, would be directly usable on dedicated and guaranteed carbon emission trading platforms."[22]

- **Dematerialisation**: Digitalisation holds potential to substitute material products by virtual services, e.g. by using e-readers instead of paperback books, or by streaming media online instead of buying CDs or DVDs which some consider full-fledged dematerialisation (Santarius, 2017); (Sühlmann-Faul, 2019) Dematerialisation could thus help to save resources and reduce pressures on the natural environment and biodiversity. However, the question of whether the overall outcome of the respective technologies is environmentally sustainable depends on various conditions.[23]

- **Sharing economy**: Potentially sustainable business-models are proposed in large numbers.[24] For example, platforms or other digital tools of the sharing economy might often help to save resources and to lower pressures on the land, biodiversity and other resources. The question whether the overall effects actually lead to an environmentally positive outcome, however, is complex and has to be answered on a case-by-case basis.[25]

- **Biological information and genetic resources**: A project which is noteworthy regarding the question of new biodiversity-friendly business-models, is the "**Earth Bank of Codes**" (EBC).[26] The project aims to build a database of biological information using blockchain technology. The idea is to create, beginning with the Amazon, an open library of the world's biological data (particularly, but not exclusively, DNA sequences).[27] The proclaimed aim is to unlock a "multi-trillion dollar Inclusive Forests-Standing, Rivers-Flowing Bio-Economy powered by the Fourth Industrial Revolution"; "the custodians of Nature [shall] be duly rewarded, bio-diverse nations [shall] benefit from local new bio-industries and the forests and critical biomes [shall] be conserved".[28] "Smart contracts" shall help to track who does what with the data and thus provide transparency. They shall improve access to genetic resources and encourage people to experiment with and use the data, but they shall also prevent biopiracy and guarantee fair and equitable sharing of benefits in accordance in alignment with the UN Convention of Biodiversity's Nagoya Protocol.

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[22] https://medforest.net/2019/04/26/wood-chain-project-the-technology-for-strengthening-traceability-and-pefc-certification/

[23] See above, Section 0

[24] For example, cf. https://toolbot.de/.

[25] For example, see Section 3.2 below.

[26] https://www.earthbankofcodes.org/.

[27] E.g. data regarding snake venoms of the sort used to create ACE inhibitors or behavioural characteristics like the congestion-free movement of army-ant colonies, which has inspired algorithms for co-ordinating fleets of self-driving cars.

[28] https://earthbankofcodes.worldsecuresystems.com/.

2.3. From 'Farm to Fork': Designing a fair, healthy and environmentally-friendly food system

In April 2019, 25 EU member states signed a Declaration of cooperation on 'A smart and sustainable digital future for European agriculture and rural areas'.[29] In it, the countries agree to work closer together in order to strengthen support for research in areas such as smart farming and food traceability; to establish a Europe-wide innovation infrastructure for a smart European agri-food sector; and create a European dataspace for smart agri-food applications.

ICT-enabled solutions in the food system can be grouped into different processes along the life cycle: production, processing, distribution as well as retail and consumption (Yuan, 2019). Data on the environmental opportunities related to selected of these processes is presented as case studies.

The table gives an overview of different digital technologies and their impact on agriculture, cutting across the different stages of the value chain:

Table 2-1: Digital technologies employed in agriculture

Digital technology	Impact on agriculture
Internet of Things (IoT)	IoT to collect and publish information on the production processes and the farm
Automation and Robotization	Increased productivity by reducing the need for human workforce
Artificial Intelligence (AI)	Contribute in agricultural robotics (e.g. automatization of farm equipment), soil and crop monitoring (e.g. identify plant diseases), and predictive analytics (e.g. detect pest infestation)
Big Data	Contribute in the decision-making process to increase efficiency in crop planning, intelligent irrigation systems development, pest control, weather alerts implementation
Global Navigation Satellite System (GNSS)	Improve crop yield and reduce environmental impact through the application of for example farm machinery guidance, automatic steering, variable rate applications, yield and soil condition monitoring
Drones	Soil, field and crop analysis and monitoring, variable rate applications, e.g. crop spraying and irrigation
Blockchain	Enhance transparency, accountability and efficiency in agricultural insurance, land registration, and agricultural supply chains
Augmented Reality	Optimization of the farming process

Source: (Ferreira et al., 2019, p. 24; based on VVA).

In the following, we describe opportunities for the environment related to Smart Farming and supply chain traceability in agriculture and food systems. Whilst such opportunities emerge more and more, there are also some known potential negative effects or uncertainties about the application of digital solutions, see Section 3.3.

2.3.1. Case Study: Smart Farming

In food production, ICT-enabled solutions are applied in the context of precision agriculture, robotic farming, urban farming, aquaponic system, crop selection and protection, weed, pesticide and disease control, soil monitoring, oestrus prediction, fish capture monitoring and counting, knowledge

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[29] https://ec.europa.eu/digital-single-market/en/news/eu-member-states-join-forces-digitalisation-european-agriculture-and-rural-areas

and information support, weather prediction, index-based insurance and community communication networks (Yuan, 2019).

Precision agriculture makes use of ICT to improve farming accuracy and efficiency by analysing real-time data collected by drones and sensors on field, including through the Global Position System (GPS), Geographic Information System (GIS), image processing, robots and the Internet of Things (IoT), and more targeted and economical use of inputs. PF has not yet been taken up widely in the agricultural sector at large (Finger, Swinton, Benni, & Walter, 2019). Robotic farming is a branch of precision farming which uses AI and robots to achieve high automation (Yuan, 2019).

ICT-solutions in food and agriculture have been publicly promoted in the EU, among others through the "SmartAgriHubs" project (2018-2020), a €20 Million Euro effort under the EU's research programme "Horizon 2020" bringing together over 160 partners.[30]

With regard to the **environmental effects** of smart farming, a number of quantitative assessments have been made, mostly in the context of trial tests or pilot projects:

- Philipps (2018) reports that a system generating field-level evapotranspiration (ET) measurements using machine learning and satellite imagery is tested on a large national **irrigation project** in Uganda, where water is becoming scarce because of a growing population and climate change. The system can determine the right amount of water for effective irrigation. The project team predicts that this technique could **reduce water use** by up to **30 percent** for the same yield within the district. They hope the technique will pave the way for better irrigation practices in other drought-prone countries around the globe.

- Finger et al. (2019) synthesise some key quantitative environmental benefits based on studies reviewed:

– Machine guidance and controlled traffic farming cause a **6%-25% reduction of fuel use** which results in several co-benefits including reductions in soil compaction, runoff and erosion.

– A case study on maize production in Germany shows that the variable rate technology of nitrogen application resulted in nitrous oxide **(N_2O) emission reduction of 34%.**

– A comparison between an airborne multispectral technique with human inspection for Texas citrus production shows that the airborne multispectral technique combined with variable rate technology led to **reductions in the use of pesticides by more than 90%.**

– **Herbicide use could be reduced between 11% and 90%** by precision application in different arable crops.

– An experiment in Germany shows that sensor-based precision control of aphids could reduce **insecticide use in wheat production by more than 13%.**

– Variable rate irrigation was found to increase water use efficiency and potentially lead to water savings of up to **20-25%.**

Finger et al. (2019) also point out that at present, **the magnitudes of these effects are largely uncertain. The effects are very case-dependent**. For instance, the reduction of nitrogen under adoption of variable rate technology by 4-7% does not change the runoff water quality compared to a uniform application, which was shown in an experiment on corn in Texas. A study using a modelling approach for corn-soybean rotations in Illinois shows that nitrate pollution can be re-

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[30] https://smartagrihubs.eu/about

duced through improved timing of fertiliser application. Variable rate technology for fertiliser application is just one solution.

- The "SMARTer 2030 Project" (GeSi 2015, cited by Yuan 2019) made an estimation at a macro-level that smart agriculture could contribute to avoiding **2 Gt CO₂e annually** by 2030. Moreover, crop yields could be increased by 30% with less water and fuel resource consumption. However, it is unclear which scope and methodology were considered here.

- Yuan (2019) shows that emission reductions enabled by precision fertilizer solutions, precision irrigation solutions, and fishery information support solutions can add up to **9 Mt in a low reduction potential scenario and 31 Mt in a high reduction potential scenario** according to the data and assumptions of this study. The overall GHG emissions reduction could account for **0.014%-0.049% of the global GHG emissions** in 2030.

- A range of **digital tools** are employed to deal with **crop health**. For instance, AI-enhanced 'noses' (or 'electronic noses') are considered a fast and non-invasive approach for the diagnosis of insects and diseases that attack vegetables and fruit trees (Cui, Ling, Zhu, & Keener, 2018).

- **Digital monitoring of compliance**: Digital technologies are not only used by farmers and agribusiness but also by enforcement agencies, to monitor non-point sources of pollution from **agriculture** (OECD, 2019, p. 14). In the US, the Environmental Protection Agency operates a "Next Generation Compliance Strategy" to assess how digital technologies can be used to better enforce regulations related to point-source agricultural enterprises. On a regional scale, it employs a network of solar-powered water quality sensors to identify cases which warrant field-level enforcement action due to relatively higher probabilities of non-compliance. In the EU, remote sensing and digital land parcel identification have been used by inspectors to verify farmers' eligibility for EU Common Agriculture Policy direct aid (ibid, p. 9). In Brazil's **forest management**, the Real-Time System for Detection of Deforestation (DETER) programme transmits information from satellite images to the enforcement agency. It allows the agency to distinguish naturally occurring cases of forest cover reduction from human induced deforestation (ibid). (On digital compliance monitoring in fisheries management, cf. Section 2.4.2.)

2.3.2. Case study: Traceability in agriculture and food supply chains

Tracking and tracing of food enables producers to monitor their supply chains and consumers to identify food sources and food safety. Tracing and tracking has become standard in agri-logistics, driven above all by food safety issues (dioxine crisis, bovine spongiform encephalopathy) and European law (Poppe, Wolfert, Verdouw, & Verwaart, 2013). Food traceability refers to "the ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution"[31]. Apart from their history, the location of products can be traced. The following six elements in the food chain are held to be important in terms of traceability (Opara, 2003, pp. 102–103), and various of these can be relevant from a sustainability perspective: product traceability;[32] process traceability;[33] genetic traceability;[34] inputs traceability;[35] disease and pest traceability;[36] and measurement traceability.[37]

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[31] EC Regulation 178/2002

[32] It "determines the physical location of a product at any stage in the supply chain to facilitate logistics and inventory management, product recall and dissemination of information to consumers and other stakeholders" (Opara (2003, pp. 102–103)).

[33] It "ascertains the type and sequence of activities that have affected the product during the growing and postharvest operations (what happened, where, and when). These include interactions between the product and physical/mechanical, chemical, environmental &

Technological innovations of tracing supply chains relate to **product identification, process and environment characterization, information capture, analysis, storage and transmission, and overall system integration (Yuan 2019)**. Smart packaging and labelling, monitoring and reporting together support the operation of food supply chain.

Radio frequency identification (RFID) is one of the most prevalently used ICT technologies in this context (Costa et al., 2013). Data stored with radio waves in an RFID tag can be read with an RFID reader to identify and track the tagged objects. RFID infotracking systems provide a reference web interface to access product information by the manufacturer, wholesaler, reseller, retailer and consumer. Another technology for (sustainable and other forms of) supply chain management are distributed ledger technologies like blockchain.[38] It allows "tracking and sharing all transactions or digital events among participating parties that can be verified at any time in the future (Galvez et al. 2018). Blockchain applications for the agri-food sector are currently mainly focused on pilots (Saberi et al., 2018).

There is very little research into the environmental or sustainability benefits relating to enhanced traceability in agriculture and food supply chains. There are expectations and claims, but most independent research focusses on economic benefits or benefits relating to risk management and food safety (e.g., related to the implementation of Hazard Analysis and Critical Control Points, HACCP). Some (non-quantified) information and assumptions that could be identified include:

- **Sustainable supply chain management**: The Programme for the Endorsement of Forestry Certification (PEFC) funds the "Wood-chain project" to test and stimulate the application of block chain to enhance wood and timber products traceability in line with the chemes's Chain of Custody certification.[39] Tracking also takes place with regard to fish

- **Preventing food losses**: It is assumed that ICT may help to reduce the high waste levels in the food system both in emerging and developed countries (IMechE, 2013).

- **Sustainable consumption**: Traceability through blockchains can help establishing that a product meets prerequisites for regulations and standards, such as being environmentally friendly, sustainable, adhering to human rights, labour standards, rules of origin, etc. (Saberi et al., 2018)

- **Sustainable business models**: The existing ICT technology for tracing and tracking enables new business models (as well as new policy options); for instance, a food processing company could offer a premium to farmers to increase the supply of commodities with 'sustainability' characteristics (Poppe et al., 2013).

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atmospheric factors which result in the transformation of the raw material into value-added products; and the absence or presence of contaminants" (Opara (2003, pp. 102–103)).

[34] It "determines the genetic constitution of the product. This includes information on the type and origin (source, supplier) of genetically modified organisms/materials or ingredients as well as information on planting materials (such seeds, stem cuttings, tuber, sperm, embryo) used to create the raw product" (Opara (2003, pp. 102–103)).

[35] It "determines type and origin (source, supplier) of inputs such as fertilizer, chemical sprays, irrigation water, livestock, feed, and the presence of additives and chemicals used for the preservation and/or transformation of the basic raw food material into processed (reconstituted or new) food products" (Opara (2003, pp. 102–103)).

[36] It" traces the epidemiology of pests, and biotic hazards such as bacteria, viruses and other emerging pathogens that may contaminate food and other ingested biological products derived from agricultural raw materials" (Opara (2003, pp. 102–103))

[37] It "relates individual measurement results through an unbroken chain of calibrations to accepted reference standards[15]. To achieve this, measuring and test equipment and measurement standards are calibrated utilizing a reference standard whose calibration is certified as being traceable to a national or international standard[16]. The other aspect of measurement traceability relates to the property of the measurements (data and calculations) generated throughout the supply chain and their relationship to the requirements for quality" (Opara (2003, pp. 102–103)).

[38] Blockchain technology is a distributed database of records or shared public/private ledgers of all digital events that have been executed and shared among blockchain participating agents. It differs from most existing information systems designs by including four key characteristics; non-localisation (decentralisation), security, auditability, and smart execution (Saberi et al. 2018).

[39] https://medforest.net/2019/04/26/wood-chain-project-the-technology-for-strengthening-traceability-and-pefc-certification/

2.4. A zero pollution ambition for a toxic-free environment

2.4.1. Case study: Air pollution

Digital applications can also play an important role when addressing air pollution. The most important potentials to contribute to clean air are artificial intelligence and blockchains.

- **Artificial intelligence (AI)** is a key emerging technology and is also expected to have a deep impact on all industries. At the same time, it also presents a drastic change as to how the challenges the environment is facing can be addressed. With regards to clean air, it can play a role in several aspects. First of all, AI applications can provide predictions and/or forecasts of pollution levels 2 to 7 days ahead. As a direct result, the systems based on AI can also provide for air quality alerts. Secondly, AI-based systems also play a role in monitoring and prevention of air pollution as they allow for real-time pollution monitoring and for air-pollutant source detection (PWC, 2018). Furthermore, it can also help when reducing the amount of pollutants being emitted into the air as, for example, they allow for the use of autonomous traffic light, the use of which, can lead to reduction of driving time and subsequently reduction in emissions (Vox Creative, 2018), as the introduction of a 'green wave' can potentially lower the levels of air pollution by 10-40% (Coensel, Can, Degraeuwe, Vlieger, & Botteldooren, 2012). Additionally, it has been confirmed by the academia that deployment of AI-based autonomous vehicles can also lead to emission reduction (e.g., Igliński & Babiak, 2017; Liu, Zhao, Liu, & Hao, 2019); annually by 2 - 4% (Pyper, 2014).

  In practice, the **pollution forecasting/early warning AI-based tools**, developed by IBM and Microsoft, are being deployed to monitor air pollution in Beijing (Laursen, 2016). The tool can incorporate data from traditional monitoring systems, such as the city's monitoring stations or weather satellites, of atmospheric chemistry with statistical tools, such as machine learning. This combination allows for more accurate forecasts to be delivered in a shorter period of time. It has been reported that 3-day forecasts have accuracy level 80% and 7-10 day forecasts have accuracy level of 75% (PWC, 2018).

- The emerging **blockchain** technology enables a range of assets to be transferred among parties securely, inexpensively and without third-party intermediaries. At the same time, it also has a potential to address environmental challenges as it allows for next generation sustainability monitoring, reporting and verification. It has a potential to go beyond the conventional self-reporting due to the deployment of independent sourcing and verification. Furthermore, it allows for automated data collection and management of greenhouse gases emissions established on the basis of 'smart contracts', which enable access to real life data.

  Furthermore, blockchain technology can be deployed to reduce the amount of pollutants being released into the air by the means of a **blockchain reward system**. Such a system has already been put into place in South Korea where a project (CYCLEAN) encourages citizens to shift from using oil and gas based vehicles and to make use of environmentally friendly vehicles. The more often they make use of such vehicles (e.g., bicycles, electric cars) or walk, the more coins they receive (KTrade, 2019).

- A recently developed new type of **satellite**, **MethaneSAT**, can measure methane pollution from oil and gas, with three major innovations. Designed and built by an affiliate of the US-based environmental organisation Environmental Defence Fund, the satellite will focus solely on methane, which means it will be a less expensive and operationally faster option than current multi-function satellites. It is claimed to also provide the measured data faster, which would allow for a faster response. Secondly, the data will be publicly available. And thirdly, the satellite provides

for a larger monitoring coverage than conventional satellites (covering 50 major regions that account for more than 80% of world's oil and gas production) and it has the capacity to detect lower emission sources (EDF, 2018). (Note that given the fact that the satellite is yet to be launched, these claims have not yet been independently verified).

- Lastly, under the SynchroniCity project (under Horizon2020), additional digital applications have been put forward that can have a potential to address air pollution. For example, **Autonomous Air Quality Management (AAQM)** aims at providing tailor-made solutions to improve air quality in public spaces. It provides a full cycle solution and integrates all the necessary steps, namely it i) collects the data on air quality via data sensors; ii) applies relevant open data for analytics to the planning process; iii) provides automatic alerts and schedules necessary maintenance tasks; and iv) executes the required follow-up and reporting. To ensure all this, the AAQM combines Internet of Things and artificial intelligence. The AAQM is expected to have positive impacts for citizens but also for cities themselves. Citizens are more likely to understand the importance of air quality, the maintenance system is likely to become more efficient, real-time overview of air quality will be provided and costs will be saved through autonomous planning (SynchroniCity, 2019). Another example is the **Clean Air School District (Leapcraft)** which implements air quality sensors as a part of smart cities. In this pilot emissions data will be collected, which will then be used to test new strategies to control emissions, drive awareness and encourage change in behaviour (SynchroniCity, 2019). However, both of these initiatives are still pilots and no tangible outcomes are yet available.

2.4.2. Case study: Ocean pollution and fisheries management

In addition to air pollution, emerging technologies can also have a positive impact on addressing pollution in the oceans:

- **Blockchain technology** has been deployed to fight ocean pollution as it can, as with air pollution, provide an incentive to fight ocean plastic pollution by the means of recycling initiatives. As such, IBM has introduced a **blockchain-based reward system** and has applied it in Haiti, Indonesia and Philippines. In practice, the system awards those who collect plastic waste from the ocean and deliver it to a 'plastic bank' with digital rewards, which they can store on their mobile phone. These digital rewards can be spent on daily necessities. Its developers aim at designing the system so that it can be put into practice in any location (Frankson, 2019).

- Advancement of technologies is also expected to have an impact on improved monitoring of **fisheries**. For example, **drones** show some potential for fish stock assessment as they can provide the same service for lower costs than oceanographic vessels. They can also play a role in law enforcement because they can provide fisheries officers with sufficient evidence that an illegal act has taken place. For example, an association between the European Maritime Safety Agency and a private company (CLS) plans to launch a drone mission to track illegal fishing vessels as well as smugglers. However, this technology is still facing a challenge in that drones (and other un-manned vehicles) are not currently covered by any international maritime treaties (e.g. UNCLOS or IMO Convention) and are currently only allowed in territorial waters (Girard & Du Payrat, 2017). Demand for the use of digital technologies has increased with adoption of the "landing obligation" under the EU Common Fisheries Policy (CFP) – which requires fishermen to land all species subject to a catch limit (TAC), rather than discarding them, inducing a need to document catches by species (OECD, 2019). So far, pilot tests have been undertaken to assess a combination of **remote electronic monitoring** (REM) and **closed circuit TV**. In Australia, the fisheries management authority monitors compliance with certain conservation measures

through electronic monitoring based on hardware (cameras, **gear sensors** and GPS) and software to collect and transmit relevant information.

- Lastly, as of 2017, **blockchain technologies** have begun to be implemented in the seafood industry. Three companies have partnered to establish a blockchain system for origin data and tracking. It is expected that this will increase the traceability of seafood products. However, this is still a hypothetical potential given that a large interest group ought to be fostered first, to ensure further effective application and implementation (OECD, 2017).

2.4.3.　　Case study: Water pollution

Lastly, alongside addressing air pollution, ocean pollution and fisheries, advancement in digital applications can also play a role when working towards the good status of water bodies. Digital solutions for water domains can facilitate real-time monitoring and reporting data on water quality:

- For example, the technology of **Internet of Things (IoT) integrated Big Data Analytics** has the potential to provide real-time monitoring data and also has the capacity to wirelessly stream the collected data to a relevant server. It is therefore considered a solution that is reliable, persistent and fast (Chowdury et al., 2019). A number of ICT companies, such as Microsoft and Nokia, are currently investigating how they can incorporate water quality monitoring using IoT into their approaches towards smart cities. There is a pilot project in Sweden to develop an IoT based solution for water quality monitoring. Lessons learned from the project include that there is a large discrepancy between the collected data and their applicability in practice, namely that end-users often have difficulties understanding and interpreting the data collected and thus evaluating whether there have been any changes with regards to water quality (Paska, 2018).

- Within the EU, under the Digital Single Market for Water services, together with ICT4Water[40] (a cluster of EU-funded research and innovation projects on digital innovations for water), an Action Plan was developed to promote the integration of digital applications into the water sector.[41]

2.5.　　Cross-cutting aspects

The following text discusses environmental opportunities related to the potential use of ICT solutions for environmental governance.

2.5.1.　　Better data and use of technology to assess the state of the environment

Enhancing scientific knowledge about the environment is a key condition of environmental innovation. Digital technologies hold major potentials for completing our knowledge and providing for information (WBGU, 2019d). Data growth and technological innovation, both inside ecology and beyond thus might create great opportunities for ecology "to move toward its fundamental mission of understanding the interactions among all organisms and their environments across all scales and using this information in service of society" (Farley, Dawson, Goring, & Williams, 2018).

- According to Farley et. al. (2018) a wide range of growing data streams can be described which could be utilised to study ecological systems at high resolution and on a broad scale. Such ecologically-relevant data streams accordingly include (a) the continual delivery of petabytes of data

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[40] https://www.ict4water.eu/; see also the ICT for Water Observatory at https://iwo.widest.eu/.
[41] European Commission, 'Digital Single Market for Water Services Action Plan' (2018) [online] available at
< https://ec.europa.eu/digital-single-market/en/news/report-action-plan-foster-digital-single-market-water-services-ict4water>

by remote sensors on Earth observing systems; (b) the aggregation of individual scientific ob-servations and experiments into larger curated community data resources (e.g. Global Biodiver-sity Information Facility); (c) investment in long-term ecological monitoring networks at national to continental scales (e.g., LTER, NEON; INSPIRE); (d) the deployment of automated and inex-pensive sensor networks (e.g., phenology cameras, wildlife camera traps, and temperature log-gers) and (e) data captured by citizens.

- Digital platforms to share and process data can thus be used for new research approaches and collaborative experiments by scientists. Such platforms might also help to better predict natural phenomena (Hino, Benami, & Brooks, 2018, Fritzsche, Niehoff, & Krug Andreas). In addition to professional scientific exchange and cooperation, citizen science projects are widely considered to have a great potential to generate scientific data on the environment over wider spatial and temporal scales than conventional scientific approaches. Increasing attention is being given to possibilities to generate and exchange knowledge about the environment by citizen science. Thornhill et al. (2019) differentiate contributory from collaborative and co-created projects: In contributory projects participants provide resources otherwise unattainable by a small team of scientists. Citizen scientists for example can improve the capacity of the scientific community to detect and understand the development of populations of threatened species, (Steven et al., 2019); (Pecorelli et al., 2019); (Yardi, Bharucha, & Girade, 2019) or help to measure the water quality in sensitive environments (Křeček, Palán, Pažourková, & Stuchlík, 2019) or the air quality in cities (cf. (Budde, Müller, & Laquai, 2018).[42] In collaborative projects, according to Thornhill et al. (2019), participants provide not only data but may also help to refine the project design, ana-lyse data, or disseminate findings. In this sense, intelligence is distributed, and the citizen oper-ates as a basic data interpreter. Co-created projects are those designed by scientists and mem-bers of the public working together in every stage of project development (Thornhill et al., 2019); (Fraunhofer FOKUS, Fraunhofer IAIS, & Fraunhofer IML, 2018).

- Policies and digital infrastructure which provide additional data can foster the development of a better understanding of environmental issues and improve the conditions of cross-sectoral data sharing (e.g. regarding energy, mobility). As an important example for such a use of environ-mental data infrastructure, the INSPIRE Directive is supposed to provide data for the purposes of EU environmental policies and policies or activities which may have an impact on the envi-ronment. This European Spatial Data Infrastructure shall enable the sharing of environmental spatial information among public sector organisations, facilitate public access to spatial infor-mation across Europe and assist in policy-making across boundaries.[43] Public data can also be combined with citizen monitoring data, sensor-based data, and data from other data sources.

- Other examples include the digital modelling of policy options and scenarios to enable more ef-fective governmental decisions. E.g., the digital twin of the city of Antwerp shall enable the effect of policy action taken on traffic, noise and air quality to be calculated and displayed quickly. Be-cause data from traffic and air quality is supplied in real-time from a range of sensors in the city and because this information is supplemented by simulations based on models, policymakers will have up to supporting their decision-taking.[44]

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[42] At https://deutschland.maps.luftdaten.info/, citizens can participate in order to assemble a fine dust sensor from inexpensive compo-nents and upload the measured data to the central portal via the Internet. Also cf. https://www.bund.net/mobilitaet/schadstoffe/hackair/.

[43] Cf. https://inspire.ec.europa.eu/about-inspire/563.

[44] https://www.imeccityofthings.be/en/projecten/digital-twin.

2.5.2. Data sharing to strengthen the exchange of knowledge across Europe, government bodies and citizens

Given the potential of environmental data for public policy,[45] it is not surprising that research as well as policy papers increasingly highlight the need as well as the technological potential for exchanging knowledge between diverse actors. Various dimensions regarding this exchange of knowledge can be differentiated:

- Open access and open data traditionally include the provision of governmental data (open data) and scientific data (open access). Information that can be provided to the public, e.g. on water quality, the traffic situation or other types of environmental data could, by making it publicly available, be used for research or to create new technological solutions (Fraunhofer FOKUS et al., 2018).

The German government's advisory council WBGU recently highlighted the importance of digital data as an essential instrument to determine and follow-up, as well as optimize target paths to reach the Sustainable Development Goals. Given these potentials, the WBGU proposes an "International Information Union", which would supply the world community with SDG-relevant data related to different regions, on different aggregation levels and covering several years. This open-data policy should specifically focus on issues regarding environmental and social policy and data relevant for governance (WBGU, 2019a). With respect to European policies, the WBGU demands that the EU and its Member States acknowledge an extended public obligation to provide digital infrastructure, accessible digital commons and digital basic services in the public interest. Major elements of such public services and infrastructures include the provision of information (WBGU, 2019b).

In a similar approach, a first flagship discussion paper of the UN Science Policy Business Forum working group proposes to develop a "digital ecosystem for the environment" that could be used for better policy intervention and environmental action. Such a digital ecosystem accordingly would require "citizens, governments, the private sector and intergovernmental organizations to collect and share data, process data and create analytical insights and information". Data from different sources should be integrated and processed and transformed into information, insights, indicators, investment decisions and impacts (UNEP, 2019). This digital ecosystem is supposed to, amongst other things, engage private companies in the evaluation of the sustainability and environmental soundness of their business processes, to lead to increasing citizen engagement and co-creation of knowledge, to monitor specific environmental issues and to automatically detect certain land use changes or movements and to accelerate transformation of science into policymaking and impact monitoring. It however also highlights a range of risks and challenges for data governance and regulation (UNEP, 2019).

- Access to data of private enterprises for public interests (b2g data-sharing): Private companies with their digital services and products are increasingly fulfilling tasks in the sphere of public interest. Search engines, maps and navigation services shape the everyday lives of people in the EU Member States and allow the providers behind them to collect large amounts of data. The same applies to vehicles equipped with sensors such as networked vehicles, agricultural machinery and other "smart" machines (in households or the industry) which collect large amounts of data of potentially high public interest. This data could be of great value for planning and designing public spaces, mobility systems as well as for the effective implementation of environmental law. However, large portions of these data are not accessible for authorities; significant differences already exist in valuable information between public authorities and private provid-

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[45] See above, Section **Fehler! Verweisquelle konnte nicht gefunden werden.**.

ers. (WBGU, 2019b). To unlock the potentials of privately held data for the public sector, the Commission has proposed guidance on sharing private sector data.[46]

- Citizen Science projects[47] promote a kind of "bottom-up" exchange of knowledge between citizens and governments or scientific projects. Modern citizen science programmes mean to "increase the number of engaged and informed citizens who take action for a more sustainable environment in their personal and professional lives" (Thornhill et al., 2019). Proposals and practical projects regarding citizen`s participation and data-sharing in European Cities experiment with potentials of knowledge-exchange also with respect to non-scientific data.[48]

2.5.3. Digital applications to support the implementation of EU law

Digital applications can play an important role in supporting implementation of EU (environmental) law. They can be a major asset for the administrative bodies as they help to collect information and increasingly make and implement administrative decisions automatically (Couldry & Powell, 2014; Djeffal, 2017; Lenk, 2016). Potentials for digitally enhanced administrative action exist in many areas: from traffic control and urban planning to the "real-time capture and guidance" of large numbers of visitors in much frequented tourist areas.[49] New technologies for collecting and processing large volumes of data are also supposed to provide for environmentally relevant information on potentially harmful behavior, thereby creating new opportunities for the implementation and enforcement of environmental standards. The increased possibility of monitoring outcomes directly, for example thanks to advanced and linked sensor technologies, and the availability of data that were previously imperfectly observable, or only observable at significant administrative cost, enables more effective enforcement of existing rules and lowers the cost of policy targeting (OECD, 2019).

An important way in which the advancement of technology and digitalisation can play a role in that respect is to improve monitoring capacity. One of the most prominent technologies relevant for the improvement of monitoring is (satellite-based) **remote sensing**, sometimes also referred to as earth observation.

- Remote sensing can be relied upon when **monitoring and reporting of greenhouse gases (GHG) emissions** as satellites have the ability to produce high-resolution observations of the surface of the Earth and the atmosphere. As such, they measure atmospheric concentrations of CO_2 and methane, on the basis of which the sources of GHG can be estimated. (Hardwick & Graven) This monitoring and reporting of GHG emissions is requested per, for example, the Paris Agreement, to which the EU is also Party. Specifically, Art. 13(1) of the Paris Agreement the Parties should establish "a more enhanced transparency framework" for action[50], the purpose of which is, among others, to track progress of each Parties' Nationally Determined Contributions[51]. To ensure compliance with this obligation remote sensing can help. First of all, states can rely upon the remote sensing to verify their own GHG emissions measurements. By doing so, they contribute to overall transparency, accuracy and completeness of global GHG emissions data. Secondly, the data provided by states will become verifiable by independent-non state, and es-

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[46] https://ec.europa.eu/transparency/regdoc/rep/1/2018/EN/COM-2018-232-F1-EN-MAIN-PART-1.PDF.

[47] See above, Section 2.5.1.

[48] See below, Section 2.5.6.

[49] Cf. the „Concept for city-friendly and sustainable Berlin-tourism 2018+" (Berlin 2018, p. 31).

[50] Paris Agreement, Art. 13(1)

[51] Paris Agreement, Art. 13(5)

pecially in cases where the reports are not reviewed on domestic level (Aganaba-Jeanty & Huggins, 2019).

- Another type of monitoring for which the use and potential of remote sensing is being explored is **monitoring of sites and areas where environmental offences have been known to occur** (Gargiulo, Angelino, Cicala, Persechino, & Lega, 2016). In some cases it has been identified that fines for environmental offences often do not provide a sufficient deterrent and offences occur repeatedly or sites where criminal offences occur continue to operate. In such cases remote sensing could play a significant role because it would allow regulators to, under certain conditions, monitor repeated offenders or to monitor those sites where environmental offences occur on repeated basis (Purdy, 2010). For example, Big Data analytics and applications of a sensor-based Internet of Things can also be used to implement and control ecological obligations across complex value chains.[52] In agriculture, remote sensing and digital land parcel identification systems allow countries to grant direct subsidies to farmers and to enforce other regulatory measures related to the sustainability of agriculture. (OECD, 2019).Until now, however, the use of remote sensing in this type of monitoring has been somewhat limited due to the lack of empirical evidence demonstrating its significance and added value for regulatory bodies. (Purdy, Harris, Carver, & Slater, 2017) Nevertheless, even from the (limited) application it can already be concluded that this type of monitoring of environmental crime has the potential to detect more offences than conventional inspections (Purdy et al., 2017).

A technology that might be used for the implementation of environmental legislation is **blockchain technology**. The World Economic Forum (2018) issued a report according to which over 60 different uses of blockchain currently exist which can have a positive impact on the environment. With regards to implementation of environmental law, two uses of the blockchain technology are particularly relevant:

- For example, blockchain technology allows for **verification of submitted environmental data**. The technology can accelerate and computerise exchanges of, for example, information and values concerning natural resources (Le Sève, Mason, & Nassiry, 2018). Furthermore, it can also allow for checks to ensure that the environmental data submitted are complete, accurate and submitted on time (Allena, 2018). This is possible due to the fact that blockchain can serve as a basis for smart contracts, which will "embed the contract terms in computer code, allowing negotiation or performance of the contract to be automatically facilitated, verified and/or enforced" (Le Sève et al., 2018), which means that no other intermediaries, such as lawyers, will need to be involved in the process.

2.5.4. Access to environmental data to increase transparency of and trust in environmental policy-making

Access for citizens and civil society to data about the environment is considered to be a crucial condition for civic engagement in and public deliberation on environmental policies. Information is an important *political* resource in the fight for a sustainable future. If information – e.g. regarding air pollution, nitrate levels in groundwater or traffic in cities – is missing in the media, there will be a lack of factual arguments in public discourse. Political action accordingly would be incomprehensible, and misinformation by various interest groups cannot be countered. Citizens need to trust information they receive from the media, and journalists, in turn, need to invest a lot of time in querying and researching data that is only available to the state and its institutions as a result of their

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[52] Cf. https://www.weforum.org/agenda/2018/09/why-the-circular-economy-needs-to-link-up-the-whole-supply-chain/;
https://www.weforum.org/agenda/2018/10/how-big-data-can-help-us-fight-climate-change-faster/.

authority (Krüger & Peters). Accordingly data on air and water quality, soil and marine pollution or the ecological condition of forests support evidence-based policy decisions and can make the effects of administrative action more transparent (WBGU, 2019a).

- Civil society actors request open government data and open access to scientific information specifically with respect to environmental policy goals (Semsrott; WBGU, 2019a). Digital technologies can help to display and disseminate information regarding the condition of local environments or other sustainability data and thereby contribute to transparency and trust in fact-based policy decisions.[53] As described,[54] blockchain technology allows for the verification of submitted environmental data. As a consequence of this possibility, blockchain can also result in a **greater involvement of the public and regulatory bodies**. During the verification process, it would allow for interested parties to request and obtain environmental data and information. In practice that would mean that, for example, environmental organisations would be able to carry out their own controls and checks on the basis of the data submitted (Allena, 2018).

- Data-driven applications can also be used to calculate and illustrate the environmental impact of economic activities and economic actors and thereby establish a transparent basis for environmental strategies and policies: For example, the XDC ("Klimametrik X-Degree Compatibility") of the German start-up "right. based on science" quantifies the contribution of an economic unit, e.g. of a company, to climate change. If a company has an XDC of 2.7°C, that would mean that the earth would warm up to 2.7°C if every company were to be as emission-intensive as the company under consideration. A company's contribution to global warming is thus calculated as a function of its economic performance.[55]

2.5.5.   Digital applications to encourage responsible consumer behaviour

According to WBGU (2019a) information about supply chains, environmental costs of products (e.g. provided by QR codes), services or investment flows might help consumers to make sustainable decisions. Digital applications, e.g. interactivity, gaming, virtual nature experience or transnationally networked citizen science Projects (Citizen Science) accordingly offer new opportunities for environmental awareness and to understand global interdependencies. This could, in the long run, help to raise awareness for the need for global environmental cooperation and policy.

UNEP (2019) not only identifies ecological potentials of a SDG-oriented digital ecosystem with respect to enhancing the exchange of knowledge,[56] but also to inform consumer awareness and choice through new techniques to stimulate engagement with data and insights and to increase citizen awareness and engagement. Data-based applications to incentivize behavior on the basis of automated data analysis thus might have great instrumental potentials for effective administration and governance (Djeffal, 2017).[57] Big Data-driven "nudging" technologies are promoted as "soft tools" for environmental policy (Michalek, Meran, Schwarze, & Yildiz, 2015): starting from behavioral, cognitive and neuroscience, psychology and other disciplines, such technologies allow to influence individuals' behavior in a minimally invasive but effective manner (Ekardt & Wieding; Ekardt & Wieding; Grafenstein, Hölzel, Irgmaier, & Pohle, 2018). Potential applications of nudging in the field of environmental policy are sometimes considered as potentially effective complements of existing instruments. For example, these technologies might be used to avoid and overcome

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[53] For example, see https://urban.jrc.ec.europa.eu/#/en.
[54] See Section 2.5.3 above.
[55] https://www.right-basedonscience.de/xdc/.
[56] See Section 2.5.2.
[57] See Section 2.5.3.

ecologically harmful decision-making contexts, perception patterns or behavioral structures and, for example, lead to sustainable decisions of consumers regarding products to be acquired or the use of means of transport (Michalek et al. 2015; Ekardt & Wieding; Ekardt & Wieding; Grafenstein et al., 2018). Nudging technologies also raise serious ethical and legal questions and political issues which remain to be resolved.

2.5.6. Digital applications for inclusive, participatory and cooperative governance

In addition to providing information, digital technologies can also facilitate active participation in policymaking and can thus increase its input legitimacy (WBGU, 2019a). The potentials of digital technologies specifically are seen in the context of (smart) cities which should create an atmosphere where citizens, companies and government together build a vital and sustainable city (Effing & Groot, 2016).The use of digital technologies might focus on instruments for participation in administrative or parliamentary decisions.[58] Popular ideas about the participatory and "empowering" potentials of digital technologies however are not only supposed to enable citizens to participate in environmental governance within the formal framework of a participatory budget (WBGU, 2019a) or in planning, but also to contribute to collaboration by other means. For example, digital applications might include opportunities for citizens to collect and contribute individual data or "crowd-source" environmental data in citizen science-projects and at same time provide for technologies enabling citizens to decide what happens with their data. Civic data production in the context of municipal projects or "citizen science" for example are supposed to provide for the collaborative design of cities and public spaces (Couldry & Powell, 2014; Gabrys, 2014; Schwerk, Thoms, Rabl, & Markl, 2018). Ideas regarding the cooperative generation, use and exploitation of data pursue the goal of civic empowerment (Zuccardi Merli & Bonollo, 2014) and the political and economic inclusion of citizens.

The EU "Horizon 2020" project "DECODE" experiments with three different use cases regarding these empowering potentials of digital technologies: collaborative economy, participatory citizen sensing, and open democracy, with a specific focus on how this relates to user communities in two European cities – Amsterdam and Barcelona.[59] The project develops a technological, peer-to-peer infrastructure which gives the municipality relevant rights and administrative sovereignty regarding digital data. Behavioural or preference data, sensor or machine-generated data shall be collected under the control of the citizens who generate the data or other data producers and made accessible to local enterprises and public interest actors. It is also supposed to enable a participatory process in order to deliberate and decide upon the constitution of a 'data commons' (i.e. a collectively devised and managed socio-technical and legal system that permits the production, governance, and use of different types of data to solve societal challenges). Environmental sustainability is supposed to form one of the central dimensions of a "commons collaborative economy" (Calleja-López, 2018).

The "Horizon 2020" project "smarticipate" is supposed to give citizens access to data about their city in an easy to understand way, enabling them to better support the decision-making process. Residents can also play an active role in verifying and contributing to data. Conversely, local governments shall be enabled to tap into the ingenuity of their residents, gaining valuable ideas. This two-way feedback makes cities more democratic and dynamic.[60]

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[58] https://democracy-app.de.

[59] https://decodeproject.eu/publications/pilot-scenarios-and-requirements

[60] https://www.smarticipate.eu/about/.

3. Environmental pressures related to the digital transformation

The following Section gives an overview on findings in the literature on environmental impacts related to the digital transformation, giving special consideration to impacts on biodiversity (including ecosystems), soil, air- and water pollution, resources and waste (i.e., not on energy/GHG emissions – as these are comparatively well understood). We follow the conceptual distinction between direct, indirect and systemic impacts outlined above.

Preliminary remark: Due to limited time, we do not compile evidence the environmental impacts of **e-commerce** and online shopping. Nevertheless, e-commerce as an activity causes both direct and indirect environmental impacts as well as rebound effects (for the latter, see Section 3.3). Eurostat statistics show that e-shopping is growing steadily in the EU, with the biggest increase among young internet users[61]. E-commerce has a huge influence on retailer sector infrastructure including transportation, packaging and warehousing. A number of studies investigating the sustainability impacts of e-commerce exist which can be considered in future policy-making (Abukhader & Jönson, 2004; Allen et al., 2018; Bertram & Chi, 2017; Dost & Maier, 2017; Hidayatno, Destyanto, & Fadhil, 2019; Mangiaracina, Riccardo, Marchet, Perotti, & Tumino, 2015; Postpischil & Jacob, 2019; Schöder, Ding, & Campos, 2016).

3.1. Direct impacts

The production and use of ICT goods impact the environment in different ways. Typically, the environmental impacts of ICTs are assessed and described by means of a few well-known indicators, particularly energy consumption and climate change impacts (expressed by GWP). Beyond climate change, ICT causes other direct environmental impacts which need to be considered too. In particular, resource consumption (abiotic and biotic), water consumption, land use and biodiversity impacts are relevant. The following sectors describe environmental impacts other than climate change.

3.1.1. Hardware I: ICT final goods

Figure 3-1 shows worldwide sales of stationary desktop computers, mobile PCs (laptops) and tablets from 2010 and estimates to 2023. Generally, the total sales of PCs and tablets have been declining since 2014. The desktop PCs and laptops market had been declining since 2012, while the tablet market was booming. The decline of the PC market coincided with the emerging market growth of tablets starting around 2010 (Statista, 2019e). However, the boom did not last long. Since 2015, the worldwide tablets market has been shrinking.

In 2018, total sales of desktop PCs, laptops and tablets were estimated at 423 million worldwide.

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[61] https://ec.europa.eu/eurostat/statistics-explained/index.php/E-commerce_statistics_for_individuals#General_overview

Figure 3-1: **History and forecast of worldwide shipments of laptops, desktop PCs and tablets from 2010 to 2023 (in million units)**

Source: Statista (2019e)

Figure 3-2 shows the growth of the smartphone market from 2008 to 2022. The global smartphone market reached a plateau in 2017, with annual shipments of 1.46 billion devices. Compared to 2014 and 2015, the market volume has stabilised and is projected to decline slightly in the next two years. The IDC expects the global smartphone market could return to modest growth in 2019 through the introduction of 5G devices. IDC expects the first 5G smartphones to arrive in late 2019 and projects 5G devices to reach a market share of 7 percent in 2020 and 18 percent of global shipments by 2022 (Statista, 2018).

It is estimated that 3.3 billion smartphones are used worldwide in 2019 (Statista, 2019a), which means that 43% of the world population use a smartphone.

Figure 3-2:   **The smartphone market worldwide**

The Smartphone Market Is in a Pre-5G Slump
Estimated worldwide smartphone shipments and year-over-year shipment growth

Source: IDC, cited in Statista (2018)

3.1.1.1.   Resource depletion

A review of numerous studies gives the following insights:

- Electronic devices are very resource intensive. Life cycle assessments of notebooks (Ciroth & Franze, 2011; Grezesik-Wojtysiak, RZESIK-WOJTYSIAK, & KUKLIŃSKI, 2013), smartphones (Ercan, Malmodin, Bergmark, Kimfalk, & Nilsson, 2016; Proske, Clemm, & Richter, 2016) and tablets (Andrae & Vaija, 2017) show that **the production phase, including the acquisition of raw materials** for the manufacturing of final ICT goods, dominates the resource depletion impact (more than 85% of the results) throughout the products' whole life cycle (including distribution, use, end-of-life).

- As for stationary computers, the use phase is the most significant in terms of abiotic resource depletion (Song, Wang, Li, & Yuan, 2013) (s. 6.1.7). It should be stressed that the share of the results of different life phases is directly related to the assumed product life time (assumptions vary in the different studies). With a typical assumption of an 8-year life time, the environmental impacts of the use phase are almost completely dominated by the impacts attributed to electricity consumption, notably greenhouse gas emissions but also the depletion of fossil fuels, and land use (associated with electricity generation).

- Bhakar, Agur, Digalwar, and Sangwan (2015) conducted a comparative life cycle assessment on CRT[62] monitors, LCD monitors and LED monitors. The manufacturing phase dominates in abiotic resource depletion for LED monitors, while for CRT and LCD monitors the use phase is more significant. Since LED monitors consume less power, the effect of the use phase is comparably low. Results demonstrate that the environmental burden of the different technologies depends largely on the devices' power consumption during the use phase. Thus, the impact caused by CRT monitors is almost three times that of LED monitors. It is worth noting however, that the

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[62]   CRT (Cathode Ray Tube) monitors are the most prevalent in developing countries. LCD (Liquid Crystal Display) monitors and LED (Light Emitting Diode) monitors are widely used in developed countries.

abiotic resources considered in this life cycle assessment are not distinguished with regard to their raw material criticality or their associated environmental burdens.

- The parts and components with the most significant environmental impacts in production (André, Söderman, & Nordelöf, 2019b; Bhakar et al., 2015; Clemm, Mählitz, Schlösser, Rotter, & Lang, 2016; Ercan et al., 2016; Liu, Prakash, Schischke, & & Stobbe, 2011; Proske et al., 2016; Song et al., 2013; Teehan & Kandlikar, 2013) are:

  – **ICs (integrated circuits), especially CPU and memory chips**

  – **Display**

  – **PWBs (printed wiring boards)**

  – **Battery**

  – **Power supply**

- Electronic devices contain a variety of materials, including many elemental substances that are widely regarded as critical and that are mined only in small quantities. The analysis by (Manhart et al., 2017) suggests that **smartphones and tablets** are particularly resource consuming types of ICT due to three factors: 1) their relatively high content of critical raw materials, 2) their large number of global shipments, and 3) their quite short lifetime (which necessitates frequent re-placements). The product types generate quite a significant share of the demand for **cobalt** (~ 9.4% of global primary production) and **palladium** (~ 8.9% of global primary production). The production of these two product groups is also a relevant factor in the global demand for **tantalum, silver, gold, indium and magnesium** (between 1% and 3% of global primary production).

- The total **material inventory** of all currently used smartphones and tablets sums up to **1 million tons** (the worldwide stock of actively used smartphones is 3.3 billion (as of 2019) according to (Statista, 2019a) and for tablets 1.14 billion (as of 2017) (Statista, 2019b) (see Annex 6.1.1). (For more data and information on current practices of collection and recycling of small electronic devices, cf. Handke et al. (2019)).

- Jardim and Cook (2017) estimate that more than **30 kilos of rock** have to be dug up to obtain a little over **100 grams** of the metals that are contained in a typical smartphone.

- Discarded ICT consumer products (WEEE), such as phones, tablets, laptops, desktops, and HDDs contain valuable materials as well as hazardous substances. The latter pose considerable environmental and health risks if inadequately treated during disposal. Baldé, Forti, Gray, Kuehr, and Stegmann (2017) estimate that by 2016 **44.7 million metric tons** (Mt) of WEEE were generated. This is an equivalent of **6.1 kilograms per capita** and year, compared to 5.8 kg generated in 2014. WEEE are further expected to **increase to 52.2 million metric tons or 6.8 kg** per capita by 2021. Jardim and Cook (2017) assume that amounts of WEEE generated are even higher and estimated 65.4 million metric tons in 2017.

- Although 66% of the world's population is subject to e-waste legislation, and despite the fact that precious materials contained within e-waste are worth an estimated **55 billion euros**, only **15% - 20%** are recycled through appropriate methods (Jardim & Cook, 2017). Much of the rest goes to informal disassembly in developing countries, primarily in Africa and Asia. This has already led to severe water and air pollution, soil contamination, and adverse health impacts for workers and the local population.

- (Van Eygen, De Meester, Tran, & Dewulf, 2016) and (André et al., 2019b) investigate the environmental benefits of reusing ICT products. The comparison with new laptops shows a clear en-

vironmental[63] advantage of using second-hand laptops. The studies show that reuse leads to an extension of a laptop's service life, reducing the demand to produce new laptops. This saves primary raw materials and energy. The recycling of broken laptops allows for the recovery of metals, also reducing the demand for primary raw materials, with a reduction in demand for abiotic resources (41%). Recycling also entails a reduction in demand (1–9%) for abiotic resources. Both approaches together (first reuse of ICT and then recycling of broken devices) result in a total reduction in resource demand by 42–50% (André et al., 2019b).

- (Van Eygen et al., 2016)) evaluated the performance of WEEE recycling for desktop and laptop computers in Belgium in 2013. The results show that the consumption of primary natural resources is much smaller if ICT products are recycled than in the case of landfilling WEEE: Recycling desktop and laptop computers reduces resource consumption by **80 and 87%**, including significant amounts of primary raw materials. However, improvements in recovery rates for precious metals could still be made (current recycling rates are **below 1%**).

- In the European Union, the collection rate of WEEE was below **49%** in 2016, according to (Eurostat, 2019b). Several EU countries did not achieve the 45% collection target in 2016, as illustrated in Figure 6-15. In general, the collection rates are often below 60%. Since begin of 2019, WEEE collection targets are increased. Member states shall either collect 65% by weight of total EEE put on the market or 85% of WEEE generated on the territory of that member state. However, the WEEE collection targets for ICT and telecommunications equipment (categories 6) are 75% by weight for recovery and 55% by weight for recycling according to Directive 2012/19/EC (Annex V). Thus, recycling targets for digital equipment remain on a lower level as compared to more bulky household products (categories 1 … 4).

3.1.1.2.   Water consumption

Environmental impact assessments of ICT barely address water consumption or water scarcity. The aspect is under-investigated in comparison to energy consumption or global warming potential.

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[63]   The investigated environmental impact categories are: climate change, human toxicity, abiotic resource depletion, freshwater and terrestrial acidification, freshwater ecotoxicity, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, ionising radiation - ecosystem quality, Ionising radiation - human health, carcinogenic effects, non-carcinogenic effects, ozone layer depletion, photochemical ozone creation, respiratory effects – inorganics, land use (André, Söderman, and Nordelöf (2019a))

Table 3-1 (overleaf) gives a summary of findings concerning water consumption of ICT as derived from various environmental impact assessment studies.

Table 3-1: **Summary of literature findings regarding water consumption of ICT**

Object investigated	Source	Freshwater depletion	Dominating life phase
Smartphone	(Ercan et al., 2016): using GaBi database as secondary data	3 m^3 / smartphone (use over three years)	Production (≈ 90%)
	(Ercan et al., 2016): using eco-invent data as secondary data	50 m^3 / smartphone (use over three years)	Production (≈ 80%-90%)
	(Proske et al., 2016)	Water consumption is not covered in this study	
Tablet	(Wilke, 2013)	7,769 litres / tablet in the production phase	
E-reader	(Wilke, 2013)	2,878 litres / e-reader in the production phase	
Laptop	(Ciroth & Franze, 2011)	Water consumption is not covered in this study. However, a water shortage problem caused by Chilean copper mines is mentioned, since copper mines consume high volumes of water.	
	(Grezesik-Wojtysiak et al., 2013)	Water consumption is not covered in this study	
Desktop and monitors	(Song et al., 2013); (Bhakar et al., 2015)	Water consumption is not covered in this study	
Battery as a component in laptops	Calculated based on (Clemm et al., 2016)	2.57 liter / battery in a notebook[64]	Data refers only to the production phase of battery cells (without any upstream processes)
CPU as a component in the electronic devices	Own results based on the ongoing Green Cloud-Computing project[65]	20 liter / one CPU with 4-core (≈ 25 gram) in the production phase including upstream processes	
Water use of the German Electronics Industry along the Value Chain	(Nill, Jungmichel, Schampel, & Weiss, 2017) (2017)	490 Million m^3 per 170 billion EUR of turnover (i.e. 3 litres per EUR of turnover). Distribution of water use along the value chain: • Resource extraction: 23% • Production of inputs: 23% • Direct suppliers: 16% • Electronics industry companies in Germany: 39%	

Source: own compilation of literature data.

As a rule, the production phase of ICT goods has a major influence on water consumption in life cycle assessments. The water consumption is caused by 1) mining of primary raw materials and 2) by semiconductor manufacturing processes. The report by the World Resources Institute (Miranda,

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[64] Clemm et al. (2016): Consumption of water during the production of one cell is 0.6425 kg/cell. A notebook has 4 pcs of cells

[65] Project Title in German: Lebenszyklusbasierte Datenerhebung zu Umweltwirkungen des Cloud-Computing, funded by the German Federal Environment Agency

Sauer, & Shinde, 2010) documented that the **mining sector is a significant water user and producer of wastewater.** Mining requires significant volumes of water, especially in the extraction and processing phases. (Northey, Mudd, Werner, Haque, & Yellishetty, 2019) compiled a database of 8314 data points from 359 mining company reports. Their analysis reveals that the water use required for mining and mineral processing operations depends on the processing conditions required, ore throughput rates, local climate, and water management. Water use varies between **340 and 6,270 litres per tonne ore processed** for 90% of mining operations.

Hayes-Labruto et al. (2013) estimate that the extraction and refining of **one tonne of rare earth elements (REE)** can produce 60,000 m^3 of waste gas that contains hydrofluoric acid, resulting in **200 m^3 of acidic sewage water**. REEs are essential materials used in ICT (s. 6.5) and listed in the 2017 list of critical raw materials for the EU (European Commission, 2017a).

Nill et al. (2017) calculated the groundwater consumption of the German electronics industry along the value chain covering primary resource extraction up to final production sites in Germany. The calculated water consumption is **3 litres per EUR of turnover across the value chain**. Moreover, about 15% of the water is consumed along the supply chain in regions with high water stress, especially in Asia and Africa, where the raw materials are imported from.

The figures referred to above are subject to a large margin of uncertainty due to differences in methodology and data quality. Ercan et al. (2016) argue that results may vary largely depending on the use of primary data or secondary databases for the modelling of mining operations (in their case gold and copper mining) (s. Section 6.1.6).

3.1.1.3.   Land use and land use change

At present, there is no common consensus on best practices for quantifying land use in LCA in general (Fehrenbach, Grahl, Giegrich, & Busch, 2015). Traditionally LCA has focused on two different classes of land use: "occupation" (referring to the coverage of an area for a certain period) and "transformation/conversion" (referring to "land use change", i.e., changing one kind of land cover to another) (Mattila et al., 2011). The ILCD handbook, developed by the European Commission's science and knowledge service "Joint Research Centre (JRC)", amends the model for land use impact assessments. The old method was based on soil organic matter (SOM) loss, which relates to the fertility of soils. In the new method, a soil quality index built which aggregates the indicators provided by the LANCA model is implemented (Fazio et al., 2018). The impact category "land use and land use change" has impacts on ecosystems. Hence, the impact of land use on species and habitat diversity is prioritised mostly in biodiversity impact assessments (Winter, Lehmann, Finogenova, & Finkbeiner, 2017).

The calculation of land use impacts caused by ICT is very difficult due to a lack of data and also for methodological reasons (since it is largely dependent on assumptions and allocations).

Figure 3-3 (overleaf) gives an overview of findings from various studies.

Figure 3-3: **Summary of literature findings regarding land use of ICT**

Subject of study	Findings	Source
Smartphone	Land use and land use change is not covered in this study	(Ercan et al., 2016)
Smartphone	Land use and land use change is not covered in this study	(Proske et al., 2016)
Tablet, E-reader	Land use and land use change is not covered in this study	(Wilke, 2013)
Laptop	Land use and land use change is not covered in this study. However, it is mentioned that deforestation, soil erosion, and land use are also connected to mining activities	(Ciroth & Franze, 2011)
Laptop	Land use is evaluated to obtain the endpoint[66] results biodiversity losses (s. 3.1.1.4)	(Grezesik-Wojtysiak et al., 2013)
Desktop and Monitors	Land use and land use change is not covered in this study	(Song et al., 2013); (Bhakar et al., 2015)
Value chain of the German electronics industry	1 Million hectares per 170 billion EUR of turnover (i.e. 0.1 m^2 per EUR of turnover). Distribution of land use along the value chain: • **Resource extraction: 89%** • Production of inputs: 4% • Direct suppliers: 4% • Electronics industry companies in Germany: 3%	(Nill et al., 2017)

Source: own compilation of literature data.

Nill et al. (2017) calculated the land use of the German electronics industry along the value chain from resource extraction to companies' own sites in Germany. **0.1 m^2 per EUR of turnover are consumed across the value chain**. Moreover, nearly 90% of land use is related to raw material extraction, of which China accounts for the largest share.

3.1.1.4. Biodiversity

Biodiversity impacts of ICT are extremely hard to assess because the cause – impact relationship is very heterogeneous and indirect. ICT affects biodiversity in several ways. Most of them are related to the extraction of natural resources needed for the production of hardware. Another relevant biodiversity impact relates to the releases of hazardous materials (such as heavy metals, toxic fumes, acidic leachates) from raw material extraction processes as well as the inappropriate recycling and disposal of WEEE. Also, the environmental impacts related to power generation (e.g. greenhouse gas emissions) can be linked to biodiversity impacts. However, the methodological challenges to calculating the biodiversity impacts of ICT are immense.

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[66] Midpoint categories are defined as problem-oriented (e.g. global warming potential), whereas endpoint categories are defined as damage-oriented (e.g. human health) (Winter et al. (2017))

Biodiversity is influenced by a variety of aspects on micro, meso and macro levels (Croezen, Head, Bergsma,, Odegard, & de Bie, 2014). The evaluation of biodiversity impacts falls under the end-point[67] impact category in LCA. Research on quantifying biodiversity in the assessment of environmental impacts is ongoing. The „Biodiversity Benchmark" project conducted by CE Delft examines 60 methods and indicators for quantifying biodiversity. It indicates that **land use and climate change** are the most import drivers of biodiversity loss and concluded that ReCiPe (see below) together with the '**water stress** methodology' developed by Pfister are currently the most suitable methods for measuring and possibly benchmarking the biodiversity impacts of individual companies. These methods translate pressures on biodiversity into a quantitative indicators of biodiversity impacts (Croezen et al., 2014). In general, assessing biodiversity impacts is challenging since the impacts of pressures on biodiversity indicators are often not easily attributable to known cause-response chains (Winter et al., 2017).

In LCA practice, there are different life cycle impact assessment methodologies addressing (and at least trying to calculate) biodiversity losses. Examples can be given from Eco-Indicator 99; Impact 2002+ and ReCiPe. The ReCiPe methodology (Huijbregts et al., 2016) considers the following midpoint impact categories in assessing biodiversity losses:

- Climate change
- Water use
- Freshwater ecotoxicity
- Freshwater eutrophication
- Ozone depletion
- Terrestrial ecotoxicity
- Terrestrial acidification
- Land use/transformation
- Marine ecotoxicity

The indicator for biodiversity is expressed as time-integrated species loss. The unit is PDF*yr (potentially disappeared fraction (PDF) of species during a year). "The PDF is the rate of species loss (or in ecological terms the extinction rate) in a particular area of land or volume of water during a particular time due to unfavourable conditions associated with land conversion, land occupation, toxicity, increase in average global temperature, or eutrophication" (Slay, n.Y).

ReCiPe is just one example showing the relevant midpoint impact categories affecting biodiversity losses. Although there is **no harmonised method to assess impacts of anthropogenic activities on biodiversity** to date, and few studies on ICT goods have taken into account biodiversity losses, the following main results of the midpoint environmental impact derived from diverse studies can contribute to determining the hotspots associated with ICT goods:

- Grezesik-Wojtysiak et al. (2013) used the Eco-Indicator 99 Method[68] to assess the biodiversity loss of a laptop. The potentially disappeared fraction (PDF) accounts for 5.65 PDF·(m^2·yr). The production phase including raw material extraction contributes almost exclusively at 97% to biodiversity loss.

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[67] Midpoint categories are defined as problem-oriented (e.g. global warming potential), whereas endpoint categories are defined as damage-oriented (e.g. human health) (Winter et al. (2017))

[68] The Eco-Indicator 99 is a damage approach proceeding from the identification of areas of concern (damage categories) to the determination of what causes damage to endpoints. The method considers three damage categories: human health, ecosystem quality and resources.

- Ciroth & Franze (2011) conclude that the analysis of the entire life cycle of a notebook regarding the endpoint impact categories **human health, ecosystem, and resources** (see Section 6.1.8) suggests that **the production** of the laptop is indeed the main cause of the environmental impacts with rounded **90%,** while use plays a role with a rounded average contribution of 10%.

- Most of the environmental impact categories such as ozone depletion, terrestrial acidification, freshwater ecotoxicity, or natural land transformation are of little importance, while impact categories with a direct connection to **humans (climate change human health and human toxicity) and fossil depletion** belong to the most relevant categories.

- Ercan et al. (2016): The analysis of a smartphone shows that the production stage dominates the impacts for GWP, particulate matter, photo-oxidant creation potential, acidification potential and eutrophication of fresh water. Biodiversity loss for water is dominated by the production stage, if the Ecoinvent data set is applied for modelling. For ozone depletion, the main contributor is electricity consumed in the use phase, which causes about 50% of the impact.

As a result, there is no quantitative evidence on biodiversity losses due to the existence (production, use, and end-of-life) of the ICT final goods. LCA studies or environmental impact analyses can only provide either results of certain midpoint impact categories leading to potential biodiversity losses, or an endpoint indicator such as potentially disappeared fraction (PDF) which can be used as a very coarse hotspot analysis for improvements within a product's life cycle with caution (Slay, n.Y). Nevertheless, there is overwhelming evidence of biodiversity losses on the global level. The current IPBES Global Assessment Report on Biodiversity and Ecosystem Services **finds that** *"around 1 million animal and plant species are now threatened with extinction, many within decades, more than ever before in human history[69]."* However, it cannot be directly attributed to the digital transformation.

Despite insufficient evidence regarding the concrete cause-effect relationship, we believe that **ICT products cause substantial pressures on natural habitats and species.** Adverse environmental impacts can be associated to various life cycle phases of ICT, particularly through mining raw materials, refining metals, semiconductor manufacturing and the disposal of WEEE. It is known that these activities are often highly polluting and cause the release of hazardous substances and nutrients to natural habitats, such as air, soil and water bodies. Moreover, land occupation and land transformation occur as a result of these activities. All the aforementioned environmental impacts are likely to affect bio-diversity, depending on the respective circumstances and location. Hence, regardless of prevailing knowledge gaps, there is confidence suffices to associate digitalisation with biodiversity risks.

3.1.2.   Hardware II: Data centres

A data centre consists of two main components: 1) servers, which carry out the data processing and storage, and 2) support systems, such as power supply and cooling systems. Both components contribute significantly to the energy consumption as well as to the resource consumption of data centres. Data processing in data centres is carried out by servers. Servers are special computers that are usually mounted in racks and connected to the data network. A computer server is primarily accessed via network connections, and not through direct user inputs devices, such as a keyboard or a mouse. In addition to storage systems and network devices, servers represent the

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[69]   https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/

A summary for policymakers of the global assessment report on biodiversity and ecosystem services can be found at
https://www.ipbes.net/system/tdf/ipbes_7_10_add.1_en_1.pdf?file=1&type=node&id=35329

functional core of a data centre. The market development of servers can therefore be used as a proxy for the development of data centres. It should be stressed that the hardware configuration and performance of servers depend on the technology generations, like almost all other ICT goods. Hence, the pure number of servers is only indirectly related to the computing performance of a data centre.

Statista (2019c) estimates that the shipments of servers worldwide amounted to about **11 million units in 2018** compared to 7.1 million units in 2017. It is predicted that about **15 million units** will be shipped worldwide on the server market **in 2022** (+36% compared to 2018).

Data centres encompass:

- ICT equipment such as servers, networking devices and data storage systems
- Infrastructure equipment such as heating, ventilation and air conditioning (HVAC), uninterruptable power supply (UPS), lighting, etc.

The power consumption of ICT equipment and support systems is expressed as power usage effectiveness (PUE), which means that each kWh of electricity consumed by servers (and converted to heat in the process) requires another kWh and more for cooling. The best available technology for data centre cooling has a PUE factor of 1.2 while conventional cooling systems usually run at a PUE of 1.9. Older cooling systems are still found in many data centres and run at higher PUE factors, which means that more than twice as much electricity is needed for cooling than for active data processing.

In terms of resource consumption, the situation is different: While the support systems are usually much heavier in weight than the server equipment, they consist mostly of commoditised metals such as steel, aluminium and copper to some extent as well as building materials (i.e. concrete). The service life of support systems is usually measured in decades. In contrast, the servers consist of typical ICT materials, including semiconductors, copper, precious metals and rare earth elements. Server ICT is replaced in intervals of a few years, up to 10 years maximum (depending on performance requirements). This means, regarding the depletion of natural resources, that the active ICT components in data centres are far more relevant than the support systems.

The sections below summarise the main findings regarding resource impacts derived from a broad review of recent studies.

3.1.2.1.   Resource depletion

The main results from the studies are summarised below:

- Schödwell et al. (2018) analyse the environmental impact of three German data centres by using a self-developed calculation tool. The results indicate that the production phase of IT equipment and support infrastructure equipment[70] dominates the impact category for abiotic resource depletion, contributing **45% to 65%** of the impact of the whole life cycle. Within the production phase, the support infrastructure accounts for **14% to 32%.** The manufacturing phase of servers has the largest impacts on abiotic resource depletion compared to that of networking devices and storage systems (Peiró & Ardente, 2015; Schödwell et al., 2018). However, an LCA study by (Whitehead, Andrews, & Shah, 2015) shows contradictory results in a life cycle assessment of a UK data centre (IT performance) over a 60-year lifetime, which consumes 13 MW (actual total

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[70]   IT equipment considered includes servers, networking devices and data storage systems. The infrastructure equipment considered in the manufacturing phase is UPS (Uninterruptible Power Supply) with batteries.

power) of IT. Server replacements are included in the study[71]. **The use phase has the largest impact for all categories, with the exception of ecotoxicity** (use phase: 26%) (s. Sector 6.2.2 Figure 6-14). Regarding mineral resource depletion, the **production phase accounts only for 15%** of the impact. Nevertheless, the sensitivity analysis shows that the results in the impact category "minerals in the manufacturing phase" increase by 34% if the number of servers is increased. This is due to their **shorter lifetime or more frequent replacements** compared to the base case.

- Three parameters identified by Whitehead et al. (2015) are sensitive to design changes that influence the overall environmental impact: **operational energy for the IT equipment, cooling and power supply; the energy mix; and the amount of IT equipment across the facility's lifetime.**

- The potential savings achieved by recycling on abiotic resource depletion can range between **20% and 60%**. The higher saving rate is due to the higher recovery rates of metals in small amounts, such as **gold, palladium and silver** (Peiró & Ardente, 2015).

- The parts and components with high abiotic resource depletion in the production stage are, according to Peiró & Ardente (2015) and Schödwell et al. (2018):

– ICs (integrated circuits), especially CPU and memory chips,

– HDDs (hard disk drivers), as well as the more recent technology SSD (solid state data storage), which is even more resource consuming,

– PWBs (printed wiring boards): Mainboards and expansion cards,

– Chassis,

– Power supplies with grid connections and large lithium-ion batteries as UPS.

- Although energy consumption and carbon footprints are not the main focus of this issue paper, it is worth noting that **waste heat from data centres is considerable and continuously increasing**. The total amount of industrial waste heat in the EU is estimated to be 3,140 TWh. Waste heat from data centres is 56 TWh (2%) (Pärssinen, Wahlroos, Manner, & Syri, 2019). As one of the essential components of digitalisation, DCs require more and more energy along with the increasing data flow. "The annual increase in energy consumption is estimated to reach 15% - 20%" (Pärssinen et al., 2019). Consequently, **the utilisation of waste heat from DCs becomes more and more important from both environmental and economic perspectives** (Pärssinen et al., 2019). Transforming the unused waste heat from data centres into a useful energy source by for instance using residual heat to heat a swimming pool would fit the zero-pollution strategy. Experiments in practice should be encouraged by policy makers in the industry and have already been taking place, generating estimates such as those stating that the waste heat of a 10-megawatt data centre could heat about 700 homes.[72]

3.1.2.2.   Water consumption

In terms of water consumption and water efficiency of DCs, very little has been published. Shehabi et al. (2016) and Ristic, Madani, and Makuch (2015) analysed the water consumption of data centres covering direct water usage and indirect water usage. IT equipment in DCs releases a lot of waste heat, which must be removed from the ICT components to prevent overheating and damage. Cooling systems use water in the form of closed loop heat exchangers and open loop evapo-

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[71]   IT equipment is refreshed every 3 years and batteries every 10 years during this 60-year lifetime

[72]   https://www.technologyreview.com/s/425858/greenhouse-effect-5-ideas-for-reusing-data-centres-waste-heat/

rators. Direct water usage refers to the water used in HVAC systems[73] of DCs to cool the IT equipment. Indirect water usage refers to the water used for the electricity generation at power plants. The Green Grid has developed the Water Use Effectiveness (WUE_{source}) metric which includes direct and indirect water usage.

The main results are summarised below:

- The indirect water footprint is much larger than the direct water footprint due to the very high energy use in DCs (Ristic et al., 2015; Schödwell et al., 2018). The geographic location of DC can also greatly impact its water footprint because ambient temperature affects the cooling demand. Free cooling with outside air is considered a water-saving technology option (Ristic et al., 2015).

- The water footprint of DCs is estimated to be between **1,047 and 151,061 m³/TJ (≈ 4 Liter and 544 Liter/kWh)**. Outbound DC data traffic generates a WF of **1–205 litres per gigabyte** (Ristic et al., 2015).

- Based on the above results, the calculated water footprint of global data centres with an estimated power consumption of 198 TWh[74] in 2018 was in the range of **740 – 106,822 million m³** of water consumed annually. This equals to **2 – 292 million m³ of water per day** consumed **by the world's DCs.** It should be stressed that the calculated figures are only indicative.

- Ristic et al. (2015) also concluded that indirect water footprint (WF of electricity) is typically much larger than the direct WF, depending on the technology of power generation. The different energy sources used by DCs vary in terms of their cooling water consumption. Therefore, the first focus for reducing the water footprint of DC should be on increasing their energy efficiency. Attention should also be given to the choice of HVAC technology combined with the relative performance of adequate cooling system designs depending on the ambient climate.

- Shehabi et al. (2016) reported that data centres that have 15 MW of IT capacity consume between 80 – 130 million gallons (≈ 300 - 500 million litres) annually, which is nearly equal to 0.8 – 1.3 million litres per day.

- The platform "water footprint calculator[75]" reported that "Facebook's and Apple's data centres in Prineville, Oregon **compete for freshwater with farmers** and the local population. Google is looking to draw 1.5 million gallons (≈ 5.7 million litres) per day from a South Carolina aquifer in addition to the 4 million gallons (≈ 15 million litres) of surface water it already uses per day. The request is part of what the Post and Courier called "**water wars"** between new industries, corporate farms and an influx of new residents."

- Google is now planning to build new data centre in Luxembourg which raises concerns about its impact on the environment and society, especially with regard to water consumption. It is estimated that **10 million litres of water per day** would be needed to run the data centre, which is about 10% of the country's overall water consumption.[76]

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[73] HVAC includes all the technologies monitoring and maintaining temperature and humidity within the DC at levels deemed appropriate to the functioning of the IT equipment (Ristic et al. 2015).

[74] https://www.iea.org/tcep/buildings/datacentres/

[75] https://www.watercalculator.org/water-use/data-centers-water-use/

[76] https://luxtimes.lu/luxembourg/39098-village-worries-about-environment-in-first-google-face-off

3.1.2.3. Land use and land use change

The worldwide land coverage of data centres is expected to increase continuously, growing from ≈ **147 km²** in 2013 to ≈ **180 km²** in 2018. That is approximately comparable to the Brussels-Capital region with 161 km². These figures only refer to the land area of data centres themselves without considering any land use associated with the upstream processes, such as mining and metal production.

3.1.2.4. Biodiversity

Similar to the description in Section 3.1.1.4, the midpoint impact categories potentially leading to biodiversity losses are described below. No quantitative evidence could be established from the literature review in the context of LCA studies on the biodiversity losses related to the DCs (including production of ICT components and support equipment; use and maintenance; end-of-life)

The weighted single-score results based on the Eco-Indicator method for data centres shows that the biggest overall impact is on **human health (63.5%), which is twice that of resources (32.0%)** and an order of magnitude greater than that of the impact on **ecosystem quality (4.5%)** (Whitehead et al., 2015). The authors conclude: "The largest process contribution to human health is from carcinogenic waterborne arsenic and cadmium and emissions to air of carbon dioxide, nitrogen oxides, PM-2.5 and sulphur dioxide from **the disposal of sulphidic tailings.**" Sulphidic tailings are a by-product of the mining and **refining of gold and copper** used to manufacture ICT equipment. If they are not disposed of responsibly, they can leach into surrounding water and soil. Furthermore, **the disposal of tailings results in intensive land use**. Hence, the use of gold and copper and the complex disposal of their waste, therefore, represents a significant environmental concern.

3.1.3. Hardware III: Data transmission networks

Global digital data traffic is rising at an exponential rate. The global IP traffic forecast is presented by the Cisco VNI™ (Visual Networking Index) (Cisco, 2019):

Global traffic projections:

"Annual global IP traffic will reach **4.8 ZB (zettabytes) per year by 2022**, or **396 EB (Exabytes)[77] per month, or 150,700 GB (gigabytes) per second**. In 2017, the annual run rate for global IP traffic was 1.5 ZB per year, or 122 EB per month, or 2,000 GB per second."

Global application trends:

- "Globally, **IP video traffic** will be 82 percent of all IP traffic (both business and consumer) by 2022, up from 75 percent in 2017.
- **Internet video surveillance traffic** will increase sevenfold between 2017 to 2022.
- **Virtual Reality (VR) and Augmented Reality (AR) traffic** will increase 12-fold between 2017 and 2022 globally, a CAGR of 65 percent.
- **Internet video to TV** will increase threefold between 2017 to 2022.
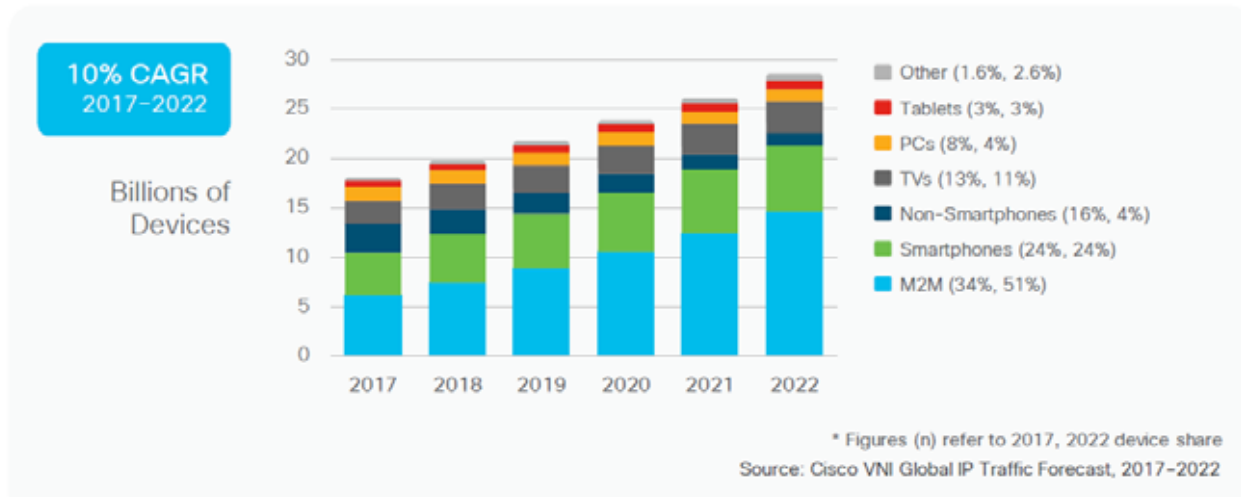- **Consumer Video-on-Demand (VoD)** traffic will nearly double by 2022.

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[77]   1 ZB=1000 EB; 1 EB=1000 PB (petabytes); 1 PB = 1000 TB (terabytes); 1 TB = 1000 GB (gigabytes)

- **Internet gaming traffic** will grow ninefold from 2017 to 2022, a CAGR of 55 percent. Globally, internet gaming traffic will be 4 percent of global IP traffic by 2022, up from 1 percent in 2017."

Number of global connected devices

Figure 3-4:   **Global devices and connections growth**

Figure 3. Global devices and connections growth

* Figures (n) refer to 2017, 2022 device share
Source: Cisco VNI Global IP Traffic Forecast, 2017–2022

Source: (Cisco, 2019)

- "Globally, **devices and connections are growing faster** (10 percent CAGR) **than both the population** (1.0 percent CAGR) **and Internet users** (7 percent CAGR). This trend is accelerating the increase in the average number of devices and connections per household and per capita. Each year, various new devices in different form factors with increased capabilities and intelligence are introduced and adopted in the market.

- The number of devices connected to IP networks will be more than three times the global population by 2022. There will be **3.6 networked devices per capita by 2022, up from 2.4 networked devices per capita in 2017**. There will be **28.5 billion networked devices** by 2022, up from **18 billion in 2017**.

- **M2M connections** will be the fastest-growing category. A growing number of **M2M applications, such as smart meters, video surveillance, healthcare monitoring, transportation, and package or asset tracking**, are contributing in a major way to the growth of devices and connections. By 2022, **M2M connections will be 51 percent of the total devices and connections**. The share of M2M connections will grow from 34 percent in 2017 to 51 percent by 2022. There will be **14.6 billion M2M connections** by 2022.

- **Smartphones will grow the second fastest**, at a 9 percent CAGR (increasing by a factor of 1.6). **Connected TVs** (which include flat-panel TVs, set-top boxes, digital media adapters [DMAs], Blu-ray disc players, and gaming consoles) will grow next fastest at 7 percent CAGR, to 3.2 billion by 2022. **PCs will continue to decline** (a 2.5 percent decline) over the forecast period. However, there will more PCs than tablets throughout the forecast period and by the end of 2022 (**1.2 billion PCs vs. 790 million tablets**). **Smartphone traffic** will exceed PC traffic. In 2018, PCs accounted for 41 percent of total IP traffic, but by 2022 PCs will account for only 19 percent of IP traffic. Smartphones **will account for 44 percent of total IP traffic by 2022**, up from 18 percent in 2017."

Global 5G mobile highlights

- **"5G devices and connections will be over 3 percent of global mobile devices and connections by 2022.** By 2022, global mobile devices will grow from 8.6 billion in 2017 to 12.3 billion by 2022 - over 422 million of those will be 5G capable.

- Nearly twelve percent of global mobile traffic will be on 5G cellular connectivity by 2022. Globally, the average 5G connection will generate 21 GB of traffic per month by 2022."

The above statistics indicate that the global growth trend in the volume of data processed in data centres and data transmission infrastructures will continue. This will also result in a further increase in IT equipment used in data centres and data transmission networks, as well as the necessary infrastructure equipment (e.g. power supply, cooling). As a consequence, a further increase in the global resource requirement for the establishment of these ICT and infrastructure equipment and the energy consumption for their operation is expected, followed by an increasing in e-waste volume.

The more data we create, the more ecologically important data centres and networks become.

3.1.3.1.   Resource depletion

Fixed Networks

Transmission networks represent the infrastructure for the transmission of data from terminal devices to data centres and back again. The transmission network is divided into different hierarchy levels, which can be easily divided into the three network levels *access network*, *aggregation network* and *backbone network* (core network) (see Figure 3-5). In addition to the respective cables, technical components are always assigned to the respective network levels as network nodes, distributors and amplifiers.

Figure 3-5:   **Infrastructure components in fixed communication networks (indicative)**

Fixed network hierarchy	explanation	Hardware needed
Access networks	Connecting the end users to their service provider	• Mainly copper cables[78] • Terminating boxes (point of entry), • ONU (optical network units), • Outdoor DSLAM[79], • Cooling systems • Power and emergency power supply
Aggregation networks / metro networks	Grouping data flows from the access networks to backbone networks	• Copper or optical fibre cables • DSLAM • Broadband remote access server (BRAS) • Aggregation switches

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[78]   Depends on the type of connection: DSL (digital subscriber line) use copper cables. VDSL (very high speed DSL) uses copper lines to connect between end users and DSLAM which couples with optical fibre cables further to aggregation networks. PON (passive optical network) uses optical fibre cables.

[79]   DSLAM stands for Digital Subscriber Line Access Multiplexer, which combines multiple signals from subscribers into on aggregate internet connection.

Fixed network hierarchy	explanation	Hardware needed
		• Cooling systems, • Power and emergency power supply
Backbone networks / core networks	Connecting local providers to one another	• Optical fibre cables, • Routers • Switches • Cooling systems • Power and emergency power supply

Source: own representation

We have not found any publications on life cycle assessment of fixed networks. The production, use and end of life of these above listed devices (not exhaustive) have a direct impact on the environment. They expend energy, metal and mineral raw materials, use chemicals and release pollutants during their production. Furthermore, the maintenance they require, and the way in which they are treated at the end of their life are straightforwardly linked with an environmental burden. The knowledge gap regarding these aspects should be closed.

Mobile networks: Core network

The mobile network infrastructure is split into the access network and the core network. The access network is that directly connected to the user equipment. The core network "consists of infrastructure entities providing support for the network features and telecommunication services covering functions such as the management of user location information, control of network features and services, the transfer mechanisms for signalling (switching and transmission) and for user generated information" (PINO, 2018).

(PINO, 2018) investigated the environmental **impacts of the core network for mobile telecommunications** based on the LCA methodology (s. 6.3.2). The study titled "Material Stock and Material Flows of ICT Infrastructures" (Scharp, 2011) conducted in the context of the joint research project "Material Efficiency and Resource Protection" (MaRess) funded by the BMU Federal Ministry of Environment examines **the material composition of components of the mobile network in Germany** and finds that the data basis is very limited and only rough estimates can be made.

Regarding abiotic resource depletion, the key findings include:

- **The core network for mobile telecommunications**: **raw materials acquisition** has the highest contribution to abiotic resource depletion at 95% of the total life cycle. The **acquisition of silver** contributes to **54%** of the total abiotic resource depletion potential of the raw materials phase, followed by **gold contributing 18% and antimony 17%** (PINO, 2018).

- **The material composition of components of the mobile network in Germany** (Scharp 2011):

– The materials and components used in the mobile communications network in Germany were estimated for the year 2008 for 2G (GSM) and 3G (UMTS) technologies. Overall, it is estimated that **136,000 tons of metals and other materials are bound in the German mobile network**. **Steel** accounts for the largest share with approx. **63,000 tons**, which is mainly used in mast constructions, rack housings and installation materials. The quantity of **aluminium** was estimated at around **18,000 tons**, **copper** at around 17,000 tons. The **electronics** are about **9,000**

tons. This includes the infrastructure for cells, the control system and the network controlling system. The other resources required to manufacture the respective materials or components have not yet been taken into account. The secondary infrastructure (customer support, selling points, logistics) was not considered.

– The **annual material flow for maintenance** is relatively low at around **5,000 to 12,000 t** per year. Between 50 and 70% of this material flow refers to construction and electronic components. But **significant uncertainties exist regarding the service life** of infrastructure components.

– Upgrading the existing infrastructure for the fast UMTS network by around 40% (ca. 14,000 new base stations, 140 controller stations as well as some new control centres) could induce **an additional material flow of about 13,000 t**."

– The mass balance of Scharp, 2011) is subject to considerable uncertainty based on the author himself. Besides, the inventory in Scharp's study refers to the old technology (2G and 3G), which should only be regarded as a magnitude.

Undersea cables

Nearly **750,000 miles (≈ 1,207,005 km) of cable** already connect the continents to support internet connectivity. The technology and telecommunications companies that have laid most of the cable include Amazon, Facebook, Google and Microsoft[80].

"**If the world's underwater cables were laid out end-to-end, the cables could extend from here to the moon and back again, and then wrap around the earth's widest point almost three times.**"[81]

Figure 3-6:   **Internet cables in the ocean**

Source: https://www.nytimes.com/interactive/2019/03/10/technology/internet-cables-oceans.html

Donovan (2009)[82] conducted a life cycle assessment of the fibre optic submarine cable system. The environmental impacts refer to ten thousand gigabit kilometres. The results (s. 6.3.1) show

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80   https://www.nytimes.com/interactive/2019/03/10/technology/internet-cables-oceans.html

81   https://www.sciencealert.com/these-rarely-seen-images-show-what-the-internet-actually-looks-like

82   No recent research studies can be found within the time frame.

that **the use and maintenance phase clearly dominates all impact categories at an average of 66%,** with the exception of the ozone depletion potential (ODP) contributing only 6% of the total potential impact. The prominence of the use and maintenance phase is due to **large amounts of electricity and fuel oil** consumed during the **13-year use and maintenance of the cable**. The end-of-life modelled shows that 90% of the virgin materials input are recycled, so that the environmental impacts associated with the raw materials extraction is compensated. **Ozone depletion** is significantly higher for the **raw materials phase** due to the release of halogenated organic emissions during material processing.

By extending the 13 year commercial lifetime to the documented technical lifetime of **25 years**, the results show that all impacts, excluding ozone depletion, were **reduced by between 4% and 23%. Ozone depletion** was affected by **39 percent** due to the high influence of raw material production on this impact category. **The results clearly highlight the potential reduction of environmental impacts by increasing the in-service lifetime of the cable.**

3.1.3.2. Water consumption

Core networks for mobile telecommunications

The LCA study on core networks for mobile telecommunications by PINO (2018) shows that the production stage (excluding raw material extraction), which includes production activities, transport and Ericsson assembly and activities, dominates the **water consumption at 87%.** This is mainly due to the applied Chinese electricity mix corresponding to the location of most suppliers in the modelling. The results of the sensitivity analysis show that a reduction of the microchips area by 30% can lead to a reduction of the overall impact of production activities by an average of 11%. Water depletion associated with the production stage can be reduced by 16%.

3.1.3.3. Land use and land use change

There is less data on land use and land use change associated with data transmission networks. Eurostat land use statistics[83] indicate that land uses related to transport, **communication networks**, storage and protective works account for 2.5% of the EU-28's territory in 2015[84]. A further breakdown only referring to communication networks is not possible due to a lack of data. Generally speaking, land is needed to accommodate infrastructure of data transmission networks including mobile towers, mast, antenna, duct, tunnel, cable lines, base stations and so on.

3.1.3.4. Biodiversity

Underwater cables

The infrastructure of underwater cables has rested upon international treaties since 1884 and was reflected in universally accepted provisions of the 1982 United Nations Convention on the Law of the Sea (UNCLOS). UNCLOS provides for freedoms to lay and maintain international submarine cables. However, "calls have mounted in the context of **marine biodiversity** beyond national jurisdiction (BBNJ) for centralized control of submarine cables and for express or de facto diminishment of the freedoms" (Burnett & Carter, 2017). Burnett and Carter (2017) thus published a monograph

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[83]   https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_use_statistics

[84]   Self-calculated (=3.3%*74.3%) based on the fact that "Land uses related to heavy environmental impact occupied 3.3 % of the EU-28's territory in 2015. By far the most common land use within this category was for transport, communication networks, storage and protective works, which accounted for almost three quarters (74.3 %) of the total area, while 8.2 % of the total for heavy environmental impact was accounted for by mining and quarrying, 5.3 % by industry, 4.9 % by energy production, 4.5 % by water and waste treatment, leaving 2.9 % of the total for construction uses." (Eurostat (2019a))

examining the largely peer reviewed research on **the environmental interaction of submarine cables with high seas environments** and the current submarine cable issues in the context of the BBNJ debates. They conclude that "It would therefore be recommendable that the BBNJ process does not change or condition the existing provisions in UNCLOS that deal with submarine cables and **does not impose any new and additional EIA (environmental impact assessment) and MPA (Marine Protected Areas) requirements for cables** in any new implementing agreement... Submarine cables, with their small footprint, positive contribution to reducing greenhouse gases, and well-studied neutral to minor environmental impact, stand uniquely apart from high impact uses that are of concern to the area beyond the limits of national jurisdiction such as shipping, deep seabed mining, fishing, pipelines and energy. The knowledge presented in this monograph is unequivocal in concluding that **submarine cables should be expressly excluded from any new BBNJ implementing agreement.**"

As opposed to the results of Burnett and Carter (2017), Moll (2018) indicates that "undersea cables are **far from being harmless** to the undersea habitats that they colonize". Transmission losses, noise emission, heat dissipation, occurrence of electromagnetic fields, contamination and disturbance have been identified as five critical potential environmental issues derived from the installation, operation and maintenance of submarine cables. Sea animals, e.g. whales, rely on sound to communicate and navigate and monitor their surroundings. Also, a large quantity of submarine species relies on the earth's magnetic fields to orientate. Magnetic fields generated by the cables can potentially affect the orientation of marine fish and mammals during their migrations or even redirect the migration, causing devastating effects to the survival of several species (Moll, 2018).

It is worth mentioning that an international joint task force (JTF) of three United Nations agencies (ITU/WMO/UNESCO-IOC) is working to incorporate environmental monitoring sensors into transoceanic submarine cable systems[85]. The sensors would measure temperature, pressure, and seismic acceleration, in order to address the potential threats including climate change, sea level rise, ocean warming, tsunamis, and earthquakes. We think the collected data can be used to contribute to assessing the underwater biodiversity.

As a result, we think that there is no robust evidence to prove that cables under the ocean are absolutely safe for the submarine ecosystem and species.

<u>**Core network for mobile telecommunications**</u>

In addition, there are no studies assessing the biodiversity losses associated with IT hardware and infrastructure of data transmission networks above ground in the LCA context. The results of midpoint metrics of human health ecosystem damage from the LCA studies can be used as an estimation of local species losses.

PINO (2018) states that "**The raw materials acquisition stage prevails** in following impact categories: **freshwater eutrophication** (99%), **freshwater ecotoxicity** (95%), **abiotic resource depletion** (95%), ozone depletion (50%), **human toxicity potential** (non-cancer effects 88%, cancer effects 46%), marine eutrophication (21%), acidification potential (12%)."

The **production stage**, which includes production activities, transport and Ericsson assembly and activities, dominates in the **water depletion** impact category by **87%**. It also contributes to about **32% of the ozone depletion potential** of the system and to about 19% of its potential impact on

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[85]   http://www.ocean-partners.org/smart-cables-could-turn-future-telecommunications-cables-ocean-spanning-observation-network

terrestrial eutrophication. It also accounts for 17% of the photochemical ozone formation, for 13% of the total marine eutrophication and ionising radiation potentials, and for 12% in the acidification and particulate matter impact categories.

The **use stage** which accounts for **the electricity consumed** throughout the operation of the system dominates in a number of impact categories: acidification (76%), climate change and climate change with biogenic carbon (92%), marine (65%) and terrestrial (74%) eutrophication, ionising radiation (70%), particulate matter (81%) and photochemical ozone formation (76%). It also contributes to approximately half of the impact potential of human toxicity with cancer effects, to 20% of the ozone depletion potential and to 11% of both water depletion and human toxicity with non-cancer effects.

3.1.4.   Software

There are no LCA studies investigating the environmental impacts throughout the whole life cycle of software. But the importance of software is pointed out by studies. For instance, Hilty et al. (2015) mention that, "Although software products are immaterial goods, their use can bring about significant materials and energy flows. Software characteristics determine which hardware capacities are made available and how much electric energy is used by end-user devices, networks, and data centres". Sikdar (2015) indicates that, "software can do amazing things these days that were not imaginable a decade or two ago", and posed the question of whether a part of the environmental impacts of hardware should be attributed to software.

Hilty et al. (2015) conclude that "software solutions for dynamic predictive load management in data centers promise energy saving potentials of 25% to 30%. Improving average capacity utilization also means that significantly less hardware is required, which in turn entails high potentials for improving materials efficiency".

Furthermore, it is worth noting that **software-induced hardware obsolescence** is becoming more relevant for analysing the environmental impacts of hardware, which was pointed out by several publications, e.g. (Kern et al., 2018); greenspector[86]. Hardware could very quickly get obsolescent, if the update of software demands faster processors, or larger memory capacity.

The German Federal Environment Agency (UBA) is now developing the ecolabel "blue angel" as a criteria for software (Gröger, Köhn, Albers, Lohmann, & Naumann, 2015). The results from the current phase show that "Software has a significant impact on the resource efficiency of IT hardware and on how long it is used. Programs which execute the same functions can have very different levels of energy consumption depending on how they are programmed." Two text processing software are tested regarding the energy consumption. Results of this example demonstrated: "**the energy consumption** of program 1 run on the same hardware to execute the standard usage scenario was nearly **four times higher** and **processor utilization more than four times greater than** with the comparable program 2". [87]

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[86]   https://greenspector.com/en/articles/2017-08-16-obsolescence-programmee-des-logiciels/

[87]   https://www.umweltbundesamt.de/en/press/pressinformation/environmental-impact-of-software-is-now-measurable

3.2. Indirect impacts

The following sections compile the key findings of case studies that evaluate direct and indirect environmental impacts. The focus is on environmental impacts beyond energy and GHG aspects. The case studies were chosen based on 1) sectors focused policy makers and 2) existence of LCA or similar environmental impact assessment studies.

It should be stressed that there are more case studies assessing the indirect impact of ICT goods, e.g. related to telecommuting. Due to lack of time, they cannot all be evaluated in detail in this issue paper. However, possible rebound effects are shortly described in Section 0. The aim is to raise awareness on these possible issues so that further evidence gathering can be initiated if deemed necessary.

3.2.1. Dematerialisation and substitution

In general, dematerialisation and substitution mean to convert physical products into digital goods. Dematerialisation through replacement of physical products with virtual goods is seen as one of the possibilities to abate the environmental impacts through ICT applications, e.g. videostreaming vs. DVD watching, e-books vs. paperbooks. Strictly speaking, dematerialisation is not the proper expression, since switching to digital goods or digital services still need materials, e.g. tablets to read a digital book instead of paper books. It is not the case that these digital products and services are provided without any materials.

3.2.1.1. Case study: E-books vs. Paper books

One trivial example of substitution has already occurred in our daily life, namely the decline of printed media as it is replaced by e-readers, tablets and smartphones. Moberg, Finnveden, and Borggren (2011) assess the life cycle impacts of e-book readers versus paper books.

The results show that for several impact categories (**climate change, abiotic resource depletion, eutrophication, human toxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity), the break-even point is in this study around 30 books.** That means that only after more than 30 books can e-book readers be justified from the perspective of these impact categories. However, if paper books were assumed to be read twice (e.g. lending to friends) the break-even point for e-readers is around 60–70 books. For the other impact categories studied, **the break-even point regarding acidification is higher, at about 200 books.** For the cumulative energy demand, the lowest break-even point was less than 20 books. The Greenpress Initiative (n.Y.) confirms that the break-even points between e-books and paper books are different depending on which environmental impacts are investigated, the lifetime of e-book readers, how often the books are read, etc. For greenhouse gas emissions this number is probably between 20 and 35 books, while for measures of human health impacts the number is probably closer to 70 books.

Moberg et al. (2011) summarises that *"The results indicate that there is **no single answer as to which book is better from an environmental perspective**. The environmental benefit of e-books compared with paper books **depends on parameters that vary for each book and user**. To improve the e-book results, an e-book reader should be used by frequent readers, and if possible, for different purposes such as reading books, newspapers, journals and other documents, thus lowering the impact per functional unit. The lifetime of the device should be prolonged as far as possible, and when no longer in use, the device should be disposed of in a proper way, making material recycling possible."*

This case study shows that the environmental impacts of **both types of read media have the potential to be improved**. **Clear instructions for consumers associated with their individual needs and behaviours are essential in order to help them to make a right decision.**

3.2.1.2.   Case study: Video streaming vs. DVDs

As described in Section 3.1.3, **video traffic** will account for **82 percent of all IP traffic** (both business and consumer) by 2022. Within the framework of the Shift project, a case study of an online video titled "**Climate crisis: the unsustainable use of online video**" regarding CO_2e is conducted (Efoui-Hess, 2019). Figure 3-7 shows that online video has the largest share of data flows, with 60% of global flows in 2018. We are aware that energy and GHG emissions are not the focus of this issue paper. The key result of the study is still worth noting, namely that "the **greenhouse gas emissions of VoD (video on demand) services (e.g. Netflix and Amazon Prime) are equivalent to those of a country like Chile** (more than 100 $MtCO_2e$/year)".

Figure 3-7:   **Distribution of online data flows between different uses**

Source: (Efoui-Hess, 2019)

It should be stressed that due to time constraints we did not review the method applied for the calculation. However, the rapidly increasing data volume of online video streaming does burden the environment and is changing the pattern of network infrastructure and data centres. The author Efoui-Hess "points out that it would indeed be better to watch something on a **standard TV broadcast — analogue broadcasting also consumes electricity, but the data is only transmitted over a limited geographical area, rather than halfway around the world, as is the case with streaming video**."[88]

Furthermore, video streaming through mobile networks via mobile devices is also increasing. Mobile data transfer uses the most electricity[88]. Efoui-Hess states that watching high-definition videos on a smartphone is not really necessary. Streaming **standard-definition video uses around 0.7 GB** per hour, compared to streaming **high-definition around 3 GB per hour** according to Netflix[89], which can lead to a 77% reduction of in data volume.

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88   https://www.dw.com/en/is-netflix-bad-for-the-environment-how-streaming-video-contributes-to-climate-change/a-49556716

89   https://www.infisim.com/streaming-video-data-use/

Regarding a comparison scenario, namely **video streaming vs. DVD**, a recent comparative LCA (Nair, Auerbach, & Skerlos, 2019) shows that **watching a movie on a streaming service outperformed the physical distribution model (watching the same movie on Blu-ray/DVD) across environmental categories investigated[90], under the condition of one-to-one replacement** (one time watching movie via video steaming and one time watching movie on DVD). The **sensitivity analysis shows** that the global warming potential and acidification of digital distribution are ultimately higher if the digital distribution leads to more than 4x the amount of movie viewing.

It should be stressed that the results of this study are based on the assumptions applied (e.g. a server with 3-year lifetime, a Blu-ray player or a Roku[91] with a 5-year lifetime; viewing behaviour). Furthermore, it is unclear whether the upstream processes (manufacturing of servers, routers, switchers, networking devices) and downstream processes (e-waste arising from this hardware) associated with digital distribution have already been considered in this study. The video data volume for streaming is also not mentioned in the paper. As shown previously, the **data volume between SD videos and HD videos is quite different, which has a direct influence on the burden of networking devices and data centres**. In addition, the devices (whether video streamed by smartphones, tablets, laptops and desktops) and network types as well as technology behind them (mobile network, fixed network) also impact the results, which has already been identified as a further research field in this paper.

3.2.2. Optimisation and Innovation

- Applying ICT goods in applications can optimise processes, e.g. by reducing energy and resource consumption or by increasing the material efficiency, which could lead to reduce environmental impact of the applications. Furthermore, innovations or new impetus for new business model are emerging by through digital technologies and processes, e.g. 3D-printing.

3.2.2.1. Case Study: Smart Farming

The agricultural industry is undergoing a fundamental transformation due to advanced ICT technology. Smart farming is widely expected to benefit the environment. ICT-enabled solutions in farming practices and management can be applied to alleviate problems and promote environmental sustainability in reducing energy and GHG emissions, saving water withdraws, reducing chemical use and remotely monitoring and diagnosing the status of crops.

Precision farming (PF) as a technology that allows a farmer to apply the right amount of inputs in the right place, at the right time, in the right way can benefit crops, plants, soils and groundwater (Finger et al., 2019; Mietzsch et al., 2012). The efficient management of fertilizers and pesticides leads to reduced direct N_2O emissions from fields and also reduced indirect emissions resulting from the production phase by saving such inputs.

Although many studies mention the environmental aspects in more or less details, few studies take into account the holistic environmental assessment method, i.e. direct and indirect environmental impacts associated with the applications of the ICT equipment. Most of these studies tend to be qualitative rather than quantitative due to limited data on actual enabled effects (Yuan, 2019).

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[90]   Acidification, ecotoxicity, eutrophication, GWP, ozone depletion, photochemical oxidation, non-carcinogen, carcinogen, respiratory

[91]   A Roku is used for streaming Netflix.

A "smart farming" project[92] funded by the Federal Ministry for Economic Affairs and Energy (BMWi) developed four use cases for different parts of the agricultural value chain with a focus on agricultural machinery. However, environmental benefit or burden along with the ICT impacts is not investigated.

The SmartAgriFood Project [93] conducted two Smart-Farming pilots: "SmartGreenhouse" and "SmartSpraying". The qualitative conclusion regarding the environmental aspects is that SmartFarming can be beneficial by improving irrigation, site-specific pesticide and nutrient application and lower energy consumption (Mietzsch et al., 2012).

Additional effort from an IT hardware and infrastructure perspective

- **Increased ICT devices**: The number of agricultural devices for gathering data worldwide was estimated at **30 million in 2015 and is expected to rise to 75 million by 2020**. The adoption rate of precision farming (PF) in the United States is higher than that in Europe. However, PF technologies also play a vital role in European agriculture (Finger et al., 2019).

- **Increased data transmission**: Arable farming would then **generate 754 Tbyte (754*10^{12} Byte) for Germany and 3.8 Petabyte (3.8 *10^{15} Byte) for the EU-27 per year**. However, these figures dramatically increase when image data are also considered. If each tractor was equipped with a camera and uploaded its data to the cloud, 1**.7 Exabyte (1.7 * 10^{18} Byte)** would be generated **each year for Germany and 8.7 Exabyte (8.7*10^{18} Byte) for the EU** (Mietzsch et al., 2012).

- **Increased resource demands and other environmental impact of applied ICT equipment** (e.g. sensors and drones) associated with the production phase, maintenance phase and end-of-life. It is unclear how long these devices would be used and how frequently / intensively repairs, tests, and inspections should be performed regarding maintenance. Statista states that global sensor unit shipments amounted to 18.8 billion in 2016 and are forecast to reach 32.8 billion in 2021 (Statista, 2019d).

- **Increased e-waste**.

As a result, much of the literature qualitatively states that while smart farming has positive environmental effects (see Section 2.2.1), there is some uncertainty with respect to their magnitude. Moreover, such statements on a positive environmental benefit focus primarily on the direct impacts in the application stage (e.g. saving water, pesticides and fuel; increasing yields). No holistic environmental assessment perspective, in terms of resource depletion, e.g. in the production sensors or drones, big data-relevant transmission networks and therefore datacentres as well as the e-waste afterlife, is considered. The figures listed above only show the magnitudes of effects and are case-dependent. Therefore, additional research into the environmental effects of smart farming is thus required to better assess the sustainable policy measurement.

3.2.2.2. Case Study: Autonomous driving – connected and automated vehicles (CAV[94])

While the energy consumption of a car is not directly affected by whether it is driven by a human or not, automation[95] and connectivity[96] technologies are expected to lay the ground for changes in

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[92] Smart Farming World - Cross-manufacturer networking of machines in agricultural crop production with the help of a service platform. https://smart-farming-welt.de/

[93] The SmartAgriFood project is funded in the scope of the Future Internet Public Private Partnership Programme (FI-PPP), as part of the 7th Framework Programme of the European Commission. The key objective is to elaborate on requirements that shall be fulfilled by a "Future Internet" to drastically improve the production and delivery of safe & healthy food.

[94] Definition: Vehicles equipped with connectivity features and a high level of automation technology (Taiebat et al. 2018).

vehicles and the transport system, leading to potentially significant impacts on the environment. Connected automated vehicles may for example alter the energy intensity of vehicles, lower perceived costs of transport and hence increase travel demand, favour a mode shift, change travel behaviour and improve road safety, just to name a few direct and indirect effects (Wadud, MacKenzie, & Leiby, 2016). This case study will focus on fully automated vehicles, also referred to as self-driving vehicles, for which connectivity is a prerequisite.

Views on when fully automated or autonomous vehicles will replace most human drivers (in any driving mode and any roadway or environmental condition) range from the year 2030 (optimistic) to after 2070 (Fox-Penner, Gorman, & Hatch, 2018). Still, whether unconstrained autonomy will ever be technically possible and financially viable remains an open question and also depends on regulatory and legal frameworks. Real world testing in urban traffic has been underway since 2018, and some countries (e.g. Norway, France, Japan and Singapore) are working on necessary legislation to incentivise and regulate fully automated vehicles (KPMG, 2019). In the agricultural and mining sector self-driving vehicles are already in operation, e.g. autonomous trucks for mining (Caterpillar, 2019), autonomous tractors and other farm vehicles. In 2018, the European Commission set out its approach to prepare the EU legal and policy framework for the deployment of automated mobility while at the same time addressing societal and environmental concerns (European Commission, 2018).

Taiebat et al. (2018) propose a framework of different scales and levels of complexity to analyse the interaction of connected automated vehicle (CAV) technology with the environment. From the lowest to highest levels of complexity and influence, the model analyses the following system levels: vehicles, the transportation system, the urban system and society. (Taiebat et al.)'s extensive literature review contains examples for how potential positive impacts of CAVs on the environment (i.e. a reduction in resource consumption and emissions) can be offset by potentially negative impacts at each of these scales and systems levels.

At the vehicle level, changes in operation are expected to directly influence environmental impact. Analyses indicate that CAVs can be **more energy efficient and less emissions intensive** because they facilitate operations that improve fuel economy (less braking and accelerating, intelligent speed adaptation, reducing cold starts, optimal route selection) thereby reducing energy consumption and exhaust emissions. It is important to note, that CAVs can either be powered by internal combustion engines or batteries and electricity. Electrification is generally assumed to improve environmental outcomes, but this depends on the source of power generation and charging infrastructure (Taiebat et al., 2018). However, higher fuel consumption may result from driving above optimal speed level, if **improved safety of CAVs induces higher driving speeds at which energy efficiency gains are offset**. **Energy intensity on highways** could increase by **20-40%** if cars were to drive at an average speed of 140 km/h instead of between 105-113 km/h (Wadud et al., 2016). Also, **the sensory technology** to allow connectivity and automation (e.g. cameras, radar, sonar, GPS, LIDAR[97] and computing equipment) entails an additional energy and resource demand. (Gawron, Keoleian, Kleine, Wallington, & Kim, 2018) conducted a life cycle assessment of a

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[95] Definition of Automation: When the human role in performing the dynamic driving task is performed by an assisting (automated) system. A widely used taxonomy for levels of automation (0, no automation to 5, full automation) has been proposed by the Society of Automotive Engineers.[95] Examples of automation technology include advanced driving assistance, navigation systems, safety controls (SAE, 2014)

[96] Definition of Connectivity: Capacity to exchange information with other vehicles (vehicle-to-vehicle V2V) and infrastructure (vehicle-to-infrastructure, V2I). Connectivity technology enables automation (Taiebat et al. 2018)

[97] LIDAR: light detection and ranging: a 360-degree sensor that uses light beams to determine the distance between obstacles and the sensor.

RADAR: Radio detection and ranging: a sensor that uses radio waves to determine the distance between obstacles and the sensor.

CAV regarding energy and GHG. The results indicate that "CAV subsystems could **increase vehicle primary energy use and GHG emissions by 3−20%** due to increases in power consumption, weight, drag, and data transmission. However, when potential operational effects of CAVs are included (e.g., eco-driving, platooning, and intersection connectivity), **the net result is up to a 9%[98] reduction in energy and GHG emissions in the base case**. Overall, this study highlights opportunities where CAVs can improve net energy and environmental performance". There is **no analysis on raw material depletion associated with the sensory and computing systems**. **Information on air pollution or water consumption from the production** of connectivity and automation technology for CAVs **is limited** (Gawron, 2019).

Inevitably, this technology will produce and process significant amounts of data, and large computing powers are required to analyse and interpret this quantity of data and translate it into driving commands in real time, making low-latency wireless connectivity a prerequisite[99]. **According to Intel, each fully automated car will be generating around 4000 GB (or 4 Terabytes) per day** (Miller 2017, see Figure 3-8). Based on the global IP traffic in 2019 with 201 Exabytes (EB) per month (Cisco, 2019), 1.7[100] million autonomous cars on the way would generate the same data volume as the present global IP traffic. Compared to the estimated global total number of cars on the road (over 1 billion cars), 1.7 million cars would make up less than 0.2%. This data would be processed in the cars as well as in data centres, and the industry is already investing in the necessary computing technology (Miller, 2017). Both network technology and the data processing infrastructure required for fully automated driving will cause negative life cycle environment impacts, although specific estimates are to date not available.

Figure 3-8:   **Illustration data in autonomous vehicles**

Source: Miller (2017)

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[98]   It is worth noting that Gawron (2019)) allocates PWB, power supply, IC package, and IC based on the weight of electronic components. Allocation based on weight is not correct for ICs, because the production effort associated with technology innovation of the semiconductor industry (multi-chip packages, where several thinned dies are stacked, increasing the total silicon area significantly without increasing the absolute silicon weight in the package) is not reflected by the weight of ICs. Even the original source used by Gawron (2019,) provided the GHG emission factor of ICs referring to die area, not to weight. We do think that Gawron (2019)) underestimated the GHG of ICs production.

[99]   https://www.daimler.com/innovation/case/autonomous/pilot-city-for-automated-driving.html

[100] 1 EB = 10^6 TB. 201*10^6 TB/(4*30d/month) ≈ 1.7 million

Whether a transportation system encompassing CAVs has **positive or negative environmental impacts will depend on** how they alter travel costs (margin of cost savings and effects on mobility), changes in mobility services (up-take of shared and pooled mobility and the interaction with mass transit (possible mode shift away from mass transit)), effects on roadway utilisation (reduction of traffic and congestion) and whether efficiency gains at the vehicle level can offset the expected increase in vehicle kilometres travelled (Taiebat et al., 2018).The greatest uncertainty lies in whether CAVs (especially electric) would induce a shift from a system reliant on privately owned vehicles to a system of shared and on-demand mobility, without weakening mass transit. In a best case scenario, this could result in efficiency improvements, congestion reduction, energy saving and ultimately reduced emissions. **The impacts on noise pollution are expected to be positive** (Patella, Aletta, & Mannini, 2019) (s. 6.7). Environmental impacts at higher levels of analysis, i.e. the urban system and society are even more uncertain. As Taiebat et al. review, CAV-related changes in infrastructure are largely unknown, and as Innamaa et al. (2018) write, it is a particular challenge to distinguish the effects from automation from other factors contributing to long-term land use change. They propose three performance indicators for future analysis (number and location of parking slots, density of housing, location of employment).

3.2.2.3.   Case study: Smart Textile and Wearables

Wearable technology is an emerging trend that integrates electronics to the daily activities and fits into the changing lifestyles. The "wearables" devices can be worn on one's wrist, foot, eyes, and neck depending on their functional requirements. Smart textiles are penetrating in the healthcare and sportswear as well as fashion sectors. The news[101] on 21 June 2019 reported: "The wearable market is expected to reach global shipments of **222.9 million units in 2019 with earwear and watches** accounting for more than 70 percent of all wearable shipments by 2023, a report by the International Data Corporation (IDC) suggests."

Electronic textiles with digital functions are also called wearable computers. Examples of electronic assemblies embedded in textiles are sensors, actuators, lighting elements, electronic processing units and components for power generation and storage. Figure 3-9 gives an overview (informative) of textile-integrated electronic components and their intended applications.

Figure 3-9:   **Examples of components and materials integrated in e-textiles**

Components and application purpose	Examples of materials used
Electrically conductive fibres: - electrostatic dissipation, electro-magnetic shielding, electric wiring and contacting, sensor and actuator elements, power distribution, light-emitting device, wireless communication for healthcare	Stainless Steel, Copper, silver, gold, Nickel, titanium
	Intrinsically conductive fabric or polymers (polypyrrole, polyaniline or Poly (3,4-Ethylenedioxythiophene)); Reduced Graphene Oxide
	Conductive polymer composites containing Nano-particles (e.g. silver-NP; carbon nanotubes)
Contacting and bonding elements	Solder alloys: tin, silver, copper, antimony, bismuth
	Conductive adhesives: silver particles

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[101]   https://gadgets.ndtv.com/wearables/news/wearable-devices-market-to-hit-223-million-units-in-2019-idc-2057047

Components and application purpose	Examples of materials used
Embedded circuit boards: - mounting and interconnecting of electronic components, mechanical fixation and protection within the textile	Flexible substrata (e.g. silicon elastomers or polyimide film), metals (copper, silver, gold), fire retardants, lacquer
Electronically active devices: - providing ICT functionality (smartness)	ICT devices such as mp3-player, micro-controller and embedded periphery, antenna, RFID-tags, flexible displays and LEDs, etc.
Energy harvesting devices	Solar cells, photoadaptive polymers, piezoelectric materials, thermoelectric generators, (containing e.g. silicon, zinc-oxide, nanoparticles, nanowires)
Power storage	Rechargeable batteries (Li-ion)

source: (Köhler, Hilty, & Bakker, 2011);(Köhler, Gröger, & Liu, 2018); (Wilson & Laing, 2019)

No LCA studies or environmental impact assessment regarding the whole life cycle or other environmental impacts besides GHG on smart wearables have been available at the time of writing this report. ICT devices embedded in non-ICT products (in this case: textiles) create difficulties for local waste management processes and often require specific recycling procedures.

Potential risks for human health and ecosystems could be (van der Velden, Kuusk, & Köhler, 2015; Wilson & Laing, 2019):

- **Chemicals and hazardous substances** are close to the body. Although the electronic components are encapsulated, long-term safety of the exposure has not yet been proven. Additionally, there is also a concern regarding the potential dispersion of electrically-conductive substances into the environment in the end-of-life phase.

- **Electromagnetic radiation** in wireless networking is close to the body, putting users at risk of exposure.

- The production of electronic components needs **critical raw materials**. The widespread application of wearables could lead to more abiotic resource depletion and water depletion. In addition, the added complexity of diverse chemical compositions of substances used to functionalise fabrics could heighten the risks associated with increased production of chemicals along with the energy consumption, substance consumption and pollution. Negative effects on human health and ecosystems may be attributed to substances being released into the environment.

- There is currently not enough information on the **lifetime of smart textiles**. The potential risk could exist that after a short life time the additional functionalized "smart" components are obsolete which increase the amount of e-waste.

- Although legislation for the disposal of electrical equipment (WEEE directive) exists in the EU, the applicability of these textiles with electronic components is vague. The embedded electronic components make the recycling process difficulty. If the smart textiles are disposal by the incineration, there are unknown effects of emission in the air from the additional electronic components. Wilson and Laing (2019) point out that "**Effective disposal of fabric sensors of wearable technologies** is a necessity to manage the increasing demand".

3.2.2.4. Case Study: Supply chain management (including with blockchain technologies)

ICT is adopted quickly in supply chain management. The supply chain is transforming from traditional linear supply chain nodes to a dynamic and connected supply network.

It has been recognised that blockchain technology or distributed ledger has other potential applications which can benefit from a decentralised verification of transactions, for example, tracing the raw material supply chain (Svemin, 2019).

Potential environmental pressures:

- To our knowledge, there are no environmental impact assessments on blockchain technologies used in certain cases in terms of abiotic resource depletion, water depletion, biodiversity losses. Few studies assess the energy consumption and GHG emissions related to Bitcoins, a blockchain-based application. We think that blockchain and Bitcoin should be assessed differently, although blockchain technologies originate from Bitcoins. However, the current estimation and calculation of the energy consumption and GHG of Bitcoins can be regarded as proxies for understanding impacts of blockchain technology.

- It is well established that Bitcoin requires a huge amount of electricity, used by miners around the world running the computer hardware[102]. The estimated **average annual energy consumption** by the CBECI's[103] is **71.44 TWh.** The range of annual energy consumption is between **32 TWh to 128 TWh** (as of 05.11.2019). The carbon footprint of Bitcoin analysed by Stoll, Klaaßen, and Gallersdörfer (2019) shows that Bitcoin's annual electricity consumption adds up to 45.8 TWh. The corresponding annual carbon emissions range from 22.0 to 22.9 $MtCO_2$. Whether blockchain used in tracing the raw materials value chain would consume as much energy as Bitcoin is unclear. It depends on the number and size of transactions. Hence, indirect environmental pressure to adopt blockchain technology should be investigated for different use cases.

- The environmental impacts associated with the embedded systems remain unclear. Intelligent communication among different supply chain nodes needs **intelligent networks and infrastructure** including, e.g. huge storage capacity on the device, RAM, fast access to the internet, sensor technology. In the case of bitcoin, mining hardware has been switched over time from the first generation using conventional computers with CPUs (central processing units), to the second-generation using GPUs (graphic processing units), to the third generation with field-programmable gate array (FPGA) and currently to application-specific integrated circuit (ASIC)-based mining systems. It remains unclear whether **hardware** enabling the application of blockchain technology to the raw material value chain also needs specific configurations. It is clear that blockchain will further **increase data transmission and in turn IT as well as the infrastructure equipment in data centres.** The calculation by IBM (2018) shows that data storage could amount to 406 TB per year based on transactions per second (TPS) of 1000. If the TPS reaches to 30 000, storage would 8535 TB per year. The storage data volume is based on the total size of the ledger and total number of transactions stored (IBM, 2018).

- The technical protocol associated with the **software** needs to be developed which in turn leads to environmental pressures.

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[102] https://digiconomist.net/bitcoin-energy-consumption
https://www.theverge.com/2019/7/4/20682109/bitcoin-energy-consumption-annual-calculation-cambridge-index-cbeci-country-comparison

[103] https://www.cbeci.org/

As blockchain-based applications are emerging, understanding the technology and management become increasingly important for policy makers. For this reason, the EU has created the "**European Blockchain Partnership**"[104] in 2018. European Member States will work together towards developing blockchain-based services and a European Blockchain Services Infrastructure (EBSI)[105] to deliver EU-wide cross-border public services using blockchain technology.

One pertinent question for policy-making is whether there is a more environmentally sound and better digital alternative to trace supply chains than blockchain technology, which is associated with intensive energy consumption.

Additionally, it remains unclear whether blockchain technology is **as reliable as** is claimed. What if the power of quantum computers unsettles this technology? On 22 September 2019, Google pronounced the achievement of quantum supremacy, referring to a quantum computer outperforming traditional computers in solving certain computation problems. This news sparked a lively discussion on the Internet, e.g. "Google's quantum supremacy could mean it is able to perform in 200 seconds what would take a powerful computer 10,000 years and potentially mean bitcoin, and the encryption that underpins it, could be broken."[106]

3.2.2.5. Case Study: Monitoring of biodiversity and ecosystem services

Biodiversity research addresses the complexity and dynamics of the living world. ICT is fundamental for data collection and the analysing, managing, simulating and monitoring of biodiversity research. Hardware (e.g. computing system, remote sensing, GPS) and software (databases, dynamic modelling) are already being applied in biodiversity research. ICT application enables an enormous amount of extensive data-related analysis to be conducted more efficiently and can optimize work processes. It is clear that application of the hardware and software as well as the data transmission via networks and DCs are associated with negative environmental impacts to some extent. However, we do think this negative environmental pressure could be compensated by positive environmental impacts, since all human activities, businesses, and industries have some degree of impact on biodiversity either directly or indirectly. Still, for protecting biodiversity it is important to understand and monitor species and habitat linked to the health of ecosystems on which we as humans strongly depend.

It should be stressed that the sectors conducting biodiversity research should raise awareness that ICT monitoring devices themselves can harm ecosystems (through mining and the spreading e-waste in sensitive ecosystems); choose more energy efficient and environmentally sound ICT products; extend their lifespan, for instance, through repair; and treat e-wastes through appropriate recycling chains.

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[104] https://ec.europa.eu/digital-single-market/en/blockchain-technologies
[105] https://ec.europa.eu/cefdigital/wiki/display/CEFDIGITAL/ebsi
[106] https://www.forbes.com/sites/billybambrough/2019/10/02/could-google-be-about-to-break-bitcoin/#47b7b3ae3329

3.3.   Systemic impacts

Coroama and Mattern (2019) point out: *"While relatively well-known in economics, rebound effects have not yet been thoroughly investigated for digital goods and services, and even less so for the broad digitalisation of whole industrial and economic sectors."*

Rebound effects can occur if digitalisation increases consumption or triggers growth effects. One typical example is the optimisation of logistics. Bieser and Hilty (2018b) describe: "The optimisation of logistics has decreased the cost of logistic services, so retailers can afford to offer free delivery and return to consumers, which has dramatically changed consumer online shopping behaviour (e.g. the online retailer **Zalando had an order return rate of roughly 50% in 2013)**".

Kallis et al. (2015) point out that "One reason **dematerialization** is very difficult is because the more efficient an economy becomes, the more resources it might consume. Technological advancements lead to a more efficient use of resources, reducing their cost, but raising the demand for them, making new uses more affordable."

Table 3-2:   **Possible rebound effects related to different digital applications**

Examples	Possible rebound effects
Teleworking, telecommuting	Telecommuting could increase the number of weekend trips to compensate for the activities not performed during the week, such as shopping.
	(A study by Abreue Silvaa and Melo (2017) confirms for locations in England and Wales that home-based telework does not contribute to reducing travel but rather tends to increase travel - in particular travel by more polluting modes and especially in the case of one-worker households.)
	One could easily imagine scenarios wherein the family car is happily used by other family members for their yet unmet demands, rather than staying in the garage when the main income earner does not commute to work.
	On the relation between teleworking and a potential reversal of the urbanisation trend, a systematic review by Salemink et al. (2017) confirms persistent and growing differences in data infrastructure quality between urban and rural areas ('digital divide', see Townsend, Sathiaseelan, Fairhurst, & Wallace, 2013). While public policies to promote the availability or improvement of data infrastructure are essentially responsive, they are rapidly outdated by market developments. At the same time, the hampered diffusion of technologies, and the lower average levels of education and skills in rural areas have a negative impact on adoption and use of ICT. Other overview studies confirm that the vast majority of teleworkers still live in cities (Moriset, 2019). This evidence presently seems to contradict the assumption that teleworking could reverse the trend towards urbanisation.
E-commerce; online shopping	This effect is probably more prominent for clothes ordering, customers often order more models and several sizes of each, and then take advantage of return policies.
	Increased return rate: the online retailer Zalando had an order return rate of roughly 50% in 2013 (Bieser and Hilty 2018b)
	Consumers shift their spare time and cost savings to other energy-intensive activities.
	Consumers tend to buy more than they really need.

Examples	Possible rebound effects
Autonomous vehicles	Better inclusion of the elderly or disabled means they will also be able to ride autonomous vehicles instead of public transport, worsening the environmental impact of their mobility.
	Autonomous vehicles can induce a substantial number of empty runs.
	The time spent in an autonomous vehicle is likely to be more enjoyable or productive than when driving one's self. The time while riding an autonomous vehicle free of stress or attention can be used for socialising or work.
	Shared autonomous vehicles might indeed displace almost exclusively public transport, not private car ownership.

Source: Coroama and Mattern (2019), if not otherwise indicated.

Coroama and Mattern (2019) provide interesting examples of minimal rebound effects accompanying reduced environmental impacts:

- The first World Resources Forum (WRF) in 2009 was organised simultaneously in Davos (Switzerland) and Nagoya (Japan). The two venues were connected by videoconferencing. The intention of this conference format on two different continents was to reduce intercontinental flights. The number of participants was increased compared to the traditional single-site conference format, namely either Davos or Nagoya. That means, there is indeed a rebound in the number of participants. But the travel-related carbon footprint impact is lower than that of the traditional one. This distributed organization format is more efficient (possible trains or intra-continental flights instead of intercontinental flights) than the traditional one and consequently induced more participants. But this new organisation format implied a substantial reduction of intercontinental flight. That means, the **rebound activities should inherently have a lower negative environmental impact than the original activities (Coroama & Mattern, 2019). Hence, promoting digital strategies in sectors with high negative environmental impacts could be more resistant to rebound effects.**

- Vending machines in Japan were so popular in the early 1990s, that the energy consumption became a political issue. The efficiency of Japanese vending machines improved by 52% from 1991 to 2007 by introducing energy efficiency measures. The number of machines increased over this time frame only slightly from 5.4 to 5.5 million. The high efficiency measurement did not induce large rebound effects, since space in Japan is limited. It is unaffordable to sacrifice more space to install additional machines. "**A different (financial or physical) limiting factor than the energy or resources undergoing efficiency gains may thus be likely to lead to only modest rebound effects**" (Coroama & Mattern, 2019). **This knowledge contributes to assessing the potential intensity of rebound effects induced by certain digital strategies.**

- An experiment in New Jersey in which several Google street view cars were fitted with methane sensors shows that CH_4 leaks from natural gas transmission and distribution networks can be efficiently identified and pipes quickly fixed compared to traditional methods. The yearly saving of CH_4 leaks through this measurement do not cause more need for heating gas. This is most likely because an upper threshold to the comfort temperature in homes has already been reached. (Coroama & Mattern, 2019) concluded: "**When a market is saturated and there is no additional demand for a product, naturally there will be no direct rebound effects** (although indirect rebound, e.g. income effects, may still occur)".

- Cleantech or circular economy processes displace the wrong kind.

Potential systemic impacts related to the use of digital technologies for **smart farming** and **tracing information in agriculture and food supply chains** (cf. Section 2.3) include the following: an estranged changed relationship between humans and animals / plants (WBGU, 2019c); increased dependence of farmers on technological service providers; a widening of the gap between large (viable) and small (vulnerable) farms; a dilemma between privacy and transparency; unclear ownership of data; valuable data might get priced; common pool issues for companies in a supply network in setting up data exchanges (Poppe et al., 2013); increasing likelihood of corporate concentration (the more a major agribusiness company is able to amass data and understand the food system, the more it will be able to fend off competitors; cf. Mooney, 2018). Mooney also points out that "Beyond ownership (data accumulation), gaining control includes the ability to manipulate the information via proprietary (including trade secrets and conventional intellectual property systems) algorithms and distributed networks (blockchains); (…) those controlling the industrial food chain apply market information, climate projections, and soil and crop disease data in order to tweak fertilizer compositions, seed coatings and crop traits for the next growing season." In the fishing sector, ICT solutions may increase overfishing (e.g., aqua-drones can drive target species into the nets untraceable by monitors or fishing regulators) (Mooney, 2018).

In the field of **energy consumption**, a Fraunhofer ISI study which assessed the potential for energy savings by 2050 under three different scenarios shows how **systemic effects could significantly diminish techno-economic potentials for final energy demand** – for instance, though energy consumption related to 'network enabled' household appliances. If techno-economic potentials are not realised, new societal trends (including digitalisation), if not counteracted by strong energy efficiency policies, could even increase energy consumption up to 42% compared to the study's baseline (Fraunhofer ISI, 2019). While energy and GHG impacts are not in the focus of this paper, **lessons** from this study **for the field of resource consumption** include that systemic effects can be pervasive; that there is an urgent need for similar research into the relation between resource efficiency and digitalisation; and that **the digital transformation cannot be sustainable if it is not regulated in a way that mitigates its negative environmental effects** (WBGU, 2019c).

Methodological challenges in the assessment of systemic impacts still remain, including the definition of scope and baseline, prediction of the possible future adoption of use cases, estimation of rebound effects or extrapolation from one single use case to society-wide impacts. Many studies have estimated the direct and indirect ICT impacts of individual ICT use cases (e.g. telecommuting; online shopping) by aggregating impacts of individual use cases, which often neglect the interaction among use cases (Bieser & Hilty, 2018a), as shown in Table 3-2. Bieser and Hilty (2018a) propose a new approach to assessing systemic effects of digitalisation based on **a time-use perspective**. The time-use approach focusses on how individuals allocate their time to everyday activities, based on the assumption that time allocation is the key element of individual lifestyle. Time, as a naturally limited resource (each person has 24 hours on any given day), can help us understand human behaviour and decision-making in a social context as well as its environmental implications.

4.   Discussion and conclusions

In the following section, we discuss the findings, focussing on several questions defined at the beginning of this project.

4.1.1.   Could the environmental opportunities linked to the digital transformation outweigh its negative environmental impacts?

Bieser and Hilty (2018b) conducted a systemic literature review on the indirect environmental effects of ICT. In their paper, diverse results on GHG emissions were identified. For example, the "SMARTer 2030" study by the Global e-Sustainability Initiative (GeSI), the ICT industry's association for sustainability, **expects that ICT applications could avoid up to 20% of global annual GHG emissions in 2030** (indirect effect), while the ICT sector causes only 2% of global GHG emissions (direct effect). In contrast, another study (Hilty et al., 2006) suggests that by 2020 **the positive and negative effects of GHG emissions will tend to cancel each other out across the application domain.** Bieser and Hilty (2018b) point out that these diverging results can be explained by differences in approaches: The old study by Hilty et al. (2006) is based on a dynamic socio-economic model, whereas the GeSi study uses a static approach, which is based on a much simpler model. Pohl and Finkbeiner (2017) also indicate that the GeSI study offsets actual direct effects of ICT against hypothetically avoided indirect effects in other fields. Further impacts which might lead to differences between potential and actual reduction were not considered. The **inconsistencies in methodological approaches** make it difficult to compare the results and also make it difficult for decision makers to correctly interpret the results. Bieser & Hilty (2018a) point out that "Indirect impacts of ICT are often assessed by estimating the aggregated impact of several individual use cases. Such assessments face **several methodological challenges**, such as defining the baseline, estimating the environmental impact, predicting the future adoption of use cases, estimating rebound effects, or extrapolating from the single use case to society-wide impacts".

It should be stressed that this issue paper only addresses the environmental impacts, excluding energy consumption and global warming, potentially associated with ICT products and their applications. Energy and GHG are nevertheless important issues which require further investigation. For instance, there is still little evidence on data transmission networks concerning the hardware used and their global warming potential along the whole life cycle, not to mention other environmental impacts. Even only from a GHG point-of-view, whether indirect impacts can compensate for the direct impacts in certain applications is still unclear and depends on the frame conditions.

Hence, **a standardised method and guidance** is necessary in order to provide an underlying basis for evaluating the indirect impacts including rebound effects, and subsequently more reliable strategies and measurements on sustainable digitalisation for decision makers.

4.1.2.   Which are the main (non-energy) environmental pressures and opportunities related to digitalisation?

The *main* (non-energy) environmental pressures and opportunities related to digitalisation are as follows:[107]

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[107] Since this endeavour significantly overlaps with the questions "Which ecological risks and potentials are related to digitalised applications" and "What processes and techniques in the context of digitalisation can potentially increase environmental pressures", we have integrated the answers to these three questions in the following text.

Environmental opportunities and potentials

- **Mobilising industry for a clean and circular economy**: The (non-energy) environmental opportunities arising from digitalisation can play an important role in relation to the circular economy, especially with respect to tackling the issue of electronic waste. Most importantly, the technological advancement plays a role in better collection and subsequent recycling of electronic waste and the reuse of the materials used. For example, the advancement in technology, namely the introduction of smartphones and mobile applications encourages consumers to recycle e-waste at official locations in return for financial incentive.

- **Preserving and restoring ecosystems and biodiversity**: Digital technologies may help to alleviate pressures on the natural environment and biodiversity in many respects. ICT-enabled solutions help monitoring biodiversity and ecosystem services. The impact of these technologies and applications on the state of biodiversity and ecosystem services, however, is indirect and uncertain: better information (acquired on the basis of sensor technologies etc.) can help assessing "distance to target" with regard to policy goals on biodiversity protection. ICTs can also help visualise and communicate biological data, thus increasing policy and public awareness. Both are necessary, though not sufficient preconditions for effective policy action. Digitally supported & biodiversity-friendly business models can make business models viable that prevent the degradation of biodiversity or support the provisioning of ecosystem services, for instance through promoting dematerialisation or reduced resource demands through sharing activities.

- **From 'Farm to Fork' (a fair, healthy and environmentally-friendly food system)**: With regard to the environmental effects of smart farming, a number of quantitative assessments have been made. They present evidence on reductions in water use, pesticide use and N_2O emissions. Since these findings stem from trial tests or pilot projects and were made in very different environments, it is not sure whether they can be upscaled and/ or transferred to other locations. As regards potential environmental or sustainability benefits relating to enhanced traceability in agriculture and food supply chains, we could identify very little (qualitative or quantitative) research. There are expectations and claims, but most independent research focusses on economic benefits or benefits relating to risk management and food safety.

- **A zero pollution ambition for a toxic-free environment**: With regards to pollution reduction, non-energy environmental opportunities can also be relevant, especially when addressing reduction of air pollution. The types of technologies most significant in this respect are artificial intelligence and blockchain. AI-based tools have been deployed to monitor and forecast the levels of pollution or for autonomous vehicles and traffic lights. Blockchain technology, on the other hand, can be used for reward-based systems which reward those who reduce pollution with digital rewards, which can be exchanged for daily necessities.

- **Cross-cutting aspects**:

  – Digitization offers major potentials for **improving environmental information and knowledge** which might lead to more sustainable policies and environmental innovation. Digital technologies extend environmental knowledge as they help to create and spread relevant data at high speed and on a massive scale, e.g. by continuously delivering data by remote sensors on Earth observing systems, which can be used for new research approaches and collaborative experiments. Increasing attention is being given to possibilities to generate and exchange knowledge about the environment by citizen science.

– Based on the potential of data for environmental policy and technological innovation, scientists as well as political actors increasingly argue for the need and the environmental potentials for **exchanging knowledge between diverse actors**. This includes open access and open data policies, which traditionally include the provision of governmental data (open data) and scientific data (open access). Recent publications propose the development of data-sharing platforms, or a "digital ecosystem for the environment" to make available data for environmental policies and innovation on a European or global level. In addition, the awareness is increasing that privately held data is of great value for environmental policies in many respects. For instance, such data might be used for public planning, traffic policies or the effective implementation of environmental law. The issue of general or sector-specific obligations for private enterprises to share their data – as well as more general implications of data-governance for environmental policies and innovations – should therefore be further explored.

– New technologies also supposed to provide for new opportunities for **effective implementation and enforcement of environmental standards**. These potentials prominently result from new technological possibilities to improve monitoring capacities – such as remote sensing or blockchain, which allows for (automated) checks to ensure that environmental data submitted have been complete, accurate and submitted on time.

– Open government data as well as access to scientific data about the environment can potentially support **evidence-based policy decisions** and make the effects of administrative action more transparent. Public transparency and trust might also be improved by technological instruments which allow for participation of citizens and public interest actors in public decision making. For example, environmental organisations could be empowered to carry out their own controls and checks on the basis of data submitted by enterprises or government bodies. Digital technologies, more generally, have the potential to improve political and economic inclusion of citizens.

– Better information about supply chains, environmental costs of products (e.g. provided by QR codes), services or investment flows might **help consumers to make more sustainable decisions**. It is also argued that digital applications such as gaming, virtual nature experience or transnationally networked citizen science projects offer new opportunities for environmental awareness and to understand global interdependencies. In addition, data-based nudging is considered to be an effective tool to incentivize behavior and thus to have a great instrumental potential for effective administration and governance. Nudging technologies however also raise serious ethical and legal questions and political issues which remain to be resolved.

Environmental pressures and risks

- **The extraction** of **raw metals** (cobalt, palladium, tantalum, silver, gold, indium and magnesium and other critical raw materials (CRMs)) as well as **the production of microelectronic components especially integrated circuits** are the main contributors to **fossil depletion, abiotic resource depletion, global warming, freshwater eutrophication, human toxicity, freshwater toxicity, marine toxicity, and terrestrial toxicity.**

- **Disposal of waste from metals** (e.g. palladium, gold, copper) extraction and refining are the main causes of **toxicity and land use**.

- The main **water consumption** results from the **mining processes**, and also the production of **microelectronic components, especially integrated circuits.** Furthermore, **cooling water used in data centres is also a concern.** Pollution from wastewater is evaluated in various LCA impact categories such as freshwater eutrophication, freshwater toxicity, marine toxicity.

- **E-waste** contains precious materials and hazardous substances. Much e-waste goes to **informal disassembly** in developing countries, primarily in Africa and Asia.[108] This has already led to **severe water and air pollution, soil contamination, and adverse health impacts for workers and the local population.** According to current estimates based on Rizos et al. (2019), only between 12% and 15% of mobile phones are properly recycled. Furthermore, the authors estimate that the stock of unused, so-called "hibernating" devices in EU households currently amounts to almost 700 million devices in Europe. If these devices could be collected and recycled, approximately 14,920 tons of gold, silver, copper, palladium, cobalt and lithium with a value of over €1 billion could be recovered.

- **Biodiversity and land use** are conjoined issues. Land use and biodiversity are currently neglected aspects in the environmental assessment studies of ICT products. However, based on the midpoint impact categories, which contribute to biodiversity loss, there is definitely **concern about impacts on biodiversity**. Furthermore, it remains unclear to what extent the more than 1 million kilometres of underwater cables impact biodiversity.

4.1.3. What are the entry points of regulation to support ecologically beneficial dynamics and technologies?

The following parameters are "entry points" (along the life cycle) for regulating the digital transformation in a way that minimises its environmental threats and maximises its environmental opportunities. They can be grouped into "entry points" for "ICT for Green" and "Greening ICT":

ICT for Green

Improving product information

- Improving (the availability of) product information and sharing it across the value chain is another entry point. This includes sustainability information as well as information relating to a product's material composition. As an example, manufacturers should provide information on the critical raw materials (CRMs) they use in products – firstly, to support remanufacturers and recyclers to make informed decisions on treating the components or products; and secondly to support policymakers in monitoring the use of CRMs.

Figure 4-1: The 2017 list of Critical Raw Materials for the EU

2017 Critical Raw Materials (26)			
Antimony	Gallium	Magnesium	Scandium
Baryte	Germanium	Natural graphite	Silicon metal
Beryllium	Hafnium	Natural Rubber	Tantalum
Bismuth	Helium	Niobium	Tungsten
Borate	HREEs	PGMs	Vanadium
Cobalt	Indium	Phosphate rock	
Fluorspar	LREEs	Phosphorus	

Source: (European Commission, 2017a) (EU, 2017; European Commission, 2017b)

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[108] See also the CWIT project ("Countering WEEE Illegal Trade") at https://www.cwitproject.eu/

- Finally, the EU should stimulate environmentally sound **collection and recycling of e-waste in developing countries** (e.g., though creating an international recycling fund for e-waste that could make pre-defined premium payments on pre-defined volumes of soundly recycled e-waste) (Bodle et al., 2020).

Sustainable ICT consumption

- Policies should also aim at increasing **environmental information/ consciousness** and social engagement, for instance by guiding consumers to recognize the environmental impacts beyond GHG associated with their behaviours and to choose sustainable solutions (e.g., suitable cloud services fitting their individual demands).

- Strengthening ICT consumption should also include stringent regulations on **advertising** by internet providers, combining the demands of consumers and corresponding cloud services regarding data sufficiency and utilisation sufficiency, which will facilitate sustainability-oriented consumer decisions.

- **Data sufficiency**: The global increasing data volume processed in data centres and data transmission infrastructures leads to a further increase in IT equipment used in data centres and data transmission networks, as well as the necessary infrastructure equipment (e.g. power supply, cooling). The central question of 'data sufficiency' is how much networking speed and data traffic for which purpose is indeed 'necessary'. Any digital measurement on, for instance, smart cities, smart homes, smart farming, smart logistics, smart factories etc. should take this question into consideration. Moreover, the spread of 3D movies or augmented and virtual reality games will significantly increase the volume of data to be transferred through networks and data centres.

- An 'overhaul' of the prevalent **throw-away mentality** would substantially increase the direct environmental impact of the ICT sector (for instance, old ICT goods might not be the latest technical or smartest ones, but they are still working). Hilty and Bieser (Hilty & Bieser, 2017) claim that *"even under conditions of the well-established Swiss recycling system for waste electrical and electronic equipment, resource depletion and the efforts to recover scare materials resources will grow as a consequence."* Options should be explored as to how such a change in societal values could be promoted.

- In addition, consumers should be guided by public environmental **data** provided by manufacturers as well as by **tools** when choosing an ICT product or using cloud services, in order to make more sustainable purchasing decisions.

Improving environmental governance

- Digital technologies imply a wide range of instruments which might be used to improve environmental governance. On the one hand, this is the case due to massively improved means to gather and share all kinds of data about environment, society and the economy. Such information not only can improve environmental policies and might trigger sustainable innovations.

- Data-based technologies also provide for tools to better monitor the environment and control problematic activities and ensure a more effective implementation of environmental law. Better information might help consumers to make sustainable decisions.

- On the other hand, digital technologies might be used for more inclusive, legitimate environmental policies. Scientific data about the environment can support evidence-based policy decisions. New technologies which provide for greater transparency and facilitate civic participation in policymaking could increase legitimacy of environmental decisions.

- These options should be made greater use of, but pilot projects should be supported by research on (social and potentially environmental) side effects.

Greening ICT

Increasing resource efficiency and reducing absolute levels of resource consumption

- An overarching framework is necessary for increasing resource efficiency in the ICT sector and for reducing absolute levels of resource consumption.

- Options include the adoption of quantified targets for (sector- and resource-specific) resource efficiency and for absolute resource consumption in the future EU sustainability strategy; or the introduction of economic instruments providing incentives for greater resource efficiency (Bodle et al., 2020).

Improving the sustainability governance of mining and sourcing

- Since the extraction of critical mineral resources causes a host of impacts on resource depletion, biodiversity and land use (and will cause more in the future), it is important to improve the sustainability regulation and its enforcement in the EU and strengthen respective capacities in non-EU mining countries.

- At the same time, responsible behaviour needs to be promoted among the economic actors sourcing extracted resources, for instance through introducing due diligence obligations on human rights compliance and environmentally responsibility. The sustainability of technical options for supply chain management through, for instance, tracking and tracing of raw materials by blockchain technologies should be further assessed. For blockchain technologies to actually enhance transparency, standards need to be developed on what sustainability impacts matter along specific supply chains.

Expanding the lifetime of ICT goods

- (Baldé et al., 2017) show (s. table below) that the lifetime of smartphones in many countries is less than 2 years, and in Germany was 1.5 years in 2015. In many cases, those final devices are replaced not because they are obsolete, but because they are outdated (e.g. not the latest design, fastest speed, latest technology). André et al. (2019b) indicated that laptops typically have a lifespan of three years, and little more than two thirds can be reused without requiring any spare parts.

Table 3.2: Smartphone life cycles by countries, in months, for 2013 - 2015

	USA	China	EU5	France	Germany	Great Britain	Italy	Spain
2015	21.6	19.5	20.4	21.6	18.8	23.5	17.7	20.0
2014	20.9	21.8	19.5	19.4	18.2	22.0	18.7	18.2
2013	20.5	18.6	18.3	18.0	17.1	20.0	18.6	16.6

Source: Kantar World Panel 2016

- The results of (Prakash, Liu, Schischke, & Stobbe, 2012) show that the production phase of a notebook, accounting for about 56% (214 kg CO_{2e}) of the total life cycle greenhouse gas emissions (lifetime: 5 years), has a significantly higher impact than the use phase. Moreover, the global warming potential of the production phase of a notebook is so high, that it cannot be com-

pensated in realistic time periods by energy efficiency gains in the use phase. Assuming different increases in energy efficiency of a new notebook from 10% to 70% compared to an older one in the life cycle assessment, the replacement of an older notebook can only be justified after 89 years (given 10% increased energy efficiency in the use phase) to 33 years (given 70% increased energy efficiency in the use phase).

The short lifespan entails an increased need for resources to manufacture new products. On the other hand, it increases the volume of electronic scrap and the associated ecological, social and economic problems. The technological innovation trend, such as the Internet of Things (IoT), 5G mobile networks, pervasive computing and wearable computing, will in all probability further exacerbate this problem, because these products should not only be small and inexpensive, but also often combined with other short-lived consumer goods such as textiles or packaging.

A clear environmental benefit of using second-hand laptops compared to new laptops has already been demonstrated by André et al. (2019a).

Improving (the framework conditions for) the circular economy

- Digitalisation and **circular economy (CE)** are closely interlinked. On the one hand and as mentioned above, energy and raw materials used by the ICT sector cause a variety of undesired ecological impacts. On the other hand, data and digitally enabled applications could make significant contributions towards a circular economy, e.g. with the help of interconnected digital tools which may help to improve the use of natural resources, design, production, consumption, re-use, repair remanufacturing, recycling, and waste management.

- An entry point is **Extended Producer Responsibility (EPR)**: The main characteristic of any EPR policy is that it places some responsibility for a product's end-of-life environmental impacts on the original producer and seller of that product. It is understood that EPR will provide incentives for producers to make design changes to products to the effect that waste management costs would decrease. Those changes should include improving product recyclability and reusability, reducing material usage and downsizing products, and engaging in a host of other so-called "design for environment" (DfE) activities. EPR could be facilitated by using digitally-enabled solutions, in particular by information sharing along the value chain and especially between manufacturers and recyclers or re-manufacturers.

- In addition, existing regulatory frameworks and especially the **Ecodesign Directive** should be used and further developed in order to manage both transitions together – digitalisation and the development of a circular economy.

- One option for improving the framework conditions for the **repair of ICT goods** is the certification of reliable and professional repair operators in order to reduce barriers to implementing circular economy. For instance, final consumers have concerns on data privacy which could hamper the second use of devices.

- It is also necessary to **increase the collection rate of ICT goods** once they reach the end of their life.

- A **market for secondary (raw) materials** is a prerequisite for the development of well-functioning secondary material supply chains. In this context, quality standards and exchange of information und material characteristics, deliverable quantities, impurities, costs, etc. play an important role. Digital solutions like online platforms may help to improve information sharing on secondary materials.

- **Remanufacturing of Critical Raw Material (CRM)**: Peck and Jansson (Peck & Jansson, 2015) reveal a gap between policy and practice: "policy makers see a significant opportunity in remanufacturing in securing raw materials supply and this is seen in the EU Circular Economy Package expected in December 2015. The academia (CRM publishers), companies and other RTOs do not see the role for remanufacturing. All CRMs are 'accessible' via remanufacturing as long as the component or sub-assembly is not scrapped." The remanufacturers` awareness and knowledge on embedded CRMs is necessary to facilitate informed planning for the recovery of CRMs on component level.

- **E-waste** volume is rapidly increasing year by year and has been an emerging threat to the environment. On the other side, e-waste is also raw material. Currently, huge amounts of such raw materials are wasted. Baldé et al. (2017) indicate: "The value of secondary raw materials after waste management is just a fraction of the value of its components or the price of used appliances. **Circular economy models need to be adopted to encourage closing the loop of materials through better design of components, recycling, reusing**, etc., while mitigating the environmental pollution. Therefore, the circular economy concept offers huge economic and employment opportunities for e-waste management; the presented **55 Billion Euros of secondary materials** is an underestimate of those economic opportunities. This calls for the development of proper legislation to manage e-waste that's supported by data to show both the environmental and economic benefits the better management of e-waste." Reducing e-waste streams and improving recycling technology are therefore essential for building a more circular economy. More efforts must be made to enforce, implement, and encourage more countries to develop e-waste policies. Considering the 27 critical materials defined by the EU (s. Section 6.5), the ICT goods and infrastructure are recognised as one of the major users of metals, REEs. Peiró & Ardente (2015) suggest a **declaration of critical raw materials**: "Although the recovery of rare earths from electronic waste is not yet fully established, this resource should not be sent to landfill, in line with the objectives of waste policies. An option that would help progress towards the recycling of rare earths and other critical raw materials would be the provision of information about the location of these metals within the product, in this case HDDs and other components in the server."

- Finally, the EU should stimulate the environmentally-sound collection and **recycling of e-waste in developing countries** (e.g. though creating an international recycling fund for e-waste that could make pre-defined premium payments on pre-defined volumes of soundly recycled e-waste).

Increasing transparency on chemicals used in the ICT industry

- The semiconductor industry uses an extensive range of ultrapure chemicals and solvents. Choi et al. (2018) reveal that more than 430 chemical products are used. The transparency of chemicals used in the ICT industry should be increased in order to better evaluate their associated environmental impacts.

Greening data centre operation

- One option to green data center operation include encouraging and promoting the utilisation of waste heat from data centres. The utilisation of waste heat from data centres is becoming more and more important from both environmental and economic perspectives. Transforming the unused waste heat from data centres into a useful energy source by, for instance, using residual heat to heat a swimming pool would fit the zero-pollution strategy. Experiments in practice should be encouraged and promoted by policy makers.

- Also, data centre operators should be obliged to report on their water consumption and disposal routes of obsolete hardware, and to reduce respective impacts over time.

Sustainable software

- Promoting relative sustainable software (e.g. voluntary application of the criteria of German Blue Angel label for resource-efficient software could be a first step but should be made binding in the medium term). Software-induced hardware obsolescence should be prevented through product law.

Complex algorithms

- Complex algorithms that are used in search engines and in all kinds of digital applications etc. determine, for example the choice of routes for autonomous driving or selection options offered for products and services on trading platforms. The criteria – or steering targets – which determine these choices, however are highly intransparent. At the same time, algorithms fulfil their functions and thus determine these choices in a very effective way. They therefore can have potentially wide-ranging negative impacts. This raises the fundamental question of how to prevent unsustainable data biases and how to make the orientation of optimisation and the consideration of environmental and sustainability criteria transparent (Gailhofer, 2019).

Governance of the data economy

- Data are the economic and technological means of production of digital technologies and applications. Access to and rights to use data thus are crucial for the development and operation of environmentally promising applications. At the same time, the factual economic distribution of data – e.g. data-based market-concentration favouring few "data-rich" corporations – can disadvantage sustainable applications or business models and privilege the development and dissemination of detrimental innovations (cf. Gailhofer & Scherf, 2019). Existing debates about adequate regulatory levers to support the usage of data in line with the common good therefore are highly relevant for environmental policies. Given the differentiation and scope of these debates regarding adequate policies and legal arrangements and the complexity of their environmental evaluation, this paper however does not elaborate specifically on regulatory alternatives. The general importance of data as well as particular arguments regarding rights to access data for particular use-cases will be emphasized where needed.

4.1.4. What are the likely consequences of digitalisation for achieving the SDGs, in particular the environmental SDGs 6, 11, 12, 14 and 15?

The following table indicates how digitalisation can contribute to or undermine (synergy vs. conflict) the achievement of selected of the UN Sustainable Development Goals (SDGs).

Beyond our own findings from above, the table includes analysis conducted by GeSI and partners (GeSI & accenture, 2016; GeSI & Deloitte, 2019) as well as by the German Advisory Council on Global Change (WBGU, 2019c). GeSI finds that "Of the 169 SDG targets, 103 are directly influenced by these technologies, with established examples of deployment that provide insight into their potential to make an impact. Analysis of 20 targets and their indicators across the SDGs shows that the expected deployment of existing digital technologies will, on average, help accelerate progress by 22% and mitigate downward trends by 23%" (GeSI & Deloitte, 2019, p. 7). WBGU (2019c, 314, Table 8.2.1-1) emphasises the ambivalence of digital change's influence on the

sustainability goals which, according to them, demonstrates the great need for giving direction to the digital transformation.

Table 4-1: Potential ecological effects of digitalisation on selected SDGs (based on WBGU 2019)

SDG	Potential synergies	Potential conflicts
SDG 6: Clean water and sanitation	• Increased reliable data for water monitoring and waste water control • Improved and, where appropriate, more cost-effective and efficient management of water-supply and disposal systems • Improved irrigation systems and rainwater harvesting • Better seasonal water management through early detection of droughts or the risk of torrential rain. • Better quality management of drinking water	• Direct impacts: Mining of increased metal and mineral raw resources for producing hardware; production of semiconductor industry; cooling water used in data centres • Digitalization cannot have an effect without good analogue and common-good-oriented management • Fragility and maintenance deficits of pipeline systems • Vulnerability to cyber attacks
SDG 9: Industry, innovation and infrastructure	• Dematerialization and resource efficiency by means of Industry 4.0 • Digital innovation for societal and ecological challenges • Resource-conserving IT infrastructures (Green IT)	• Increased consumption of resources and electricity by digital technologies • Rebound effects resulting from efficiency improvements by industry
SDG 11: Sustainable cities and communities	• Increased reliable data through real-time monitoring and data collecting • Saving energy and resources, reducing GHG emissions and air pollution through smart city mobility (traffic control and optimization), smart logistics, smart buildings etc. • More efficient supply of drinking water. • Improved municipal administration, including participatory urban planning and management • Easier self-organization of city dwellers via municipal platforms and means of communication	• Increased direct and indirect impact as well as e-waste • Potential rebound effects • Vulnerability of urban infrastructures (e.g. waterworks) to cyber attacks
SDG 12: Responsible consumption and production	• Increased global environmental awareness through more information about the sustainability of products, as well as production and consumption methods • Increased reliable data by real-time monitoring and data collecting; comprehensive monitoring of environmental impacts using 'intelligent' products, sensors and big data, implementation in economic incentives for sustainable corporate action and competitive advantages • More efficient use of resources via smart manufacturing and more complete infor-	• Increased direct and indirect impact, e.g. demand for critical raw materials and natural resources • Increased volumes of e-waste and related pollution • Fewer possibilities of 'eco-sufficient' behaviour because of greater technical dependency and shorter product life cycles of technical devices, displacement of low-tech solutions • Increasing complexity of products reduces reparability • Short-lived software and increasing

SDG	Potential synergies	Potential conflicts
	mation systems, platform-based business models and (virtual) corporate networks; dematerialization via virtualization or the addition of services to production (servitization), e.g. sharing • Improved production and supply-chain management reduces e.g. food losses • Enabling the transformation to the circular economy, e.g. through smart manufacturing; closing cycles by means of a digitally supported circular economy – not only in waste management • Potential of 3D printing for producing spare parts. • Public procurement as a pioneer in the field of green IT (12.7). • E-platforms for sustainable goods to easily get information on sustainable products or instruction on environmentally-sound behaviours for final consumers • Transparent reporting; facilitate the public's access to environmental data • On-demand parts manufacturing • Tracing raw materials or illegal exports of e-waste • Transparent life cycle information of a product for final consumers including end-of-life (e.g. the e-wastes are treated in recycling facilities or transported to Africa)	computing capacities increase product obsolescence • Possible increase in consumption as a result of more comprehensive marketing and greater availability of goods, e.g. through online shopping • Economic growth effects through new business opportunities • 'Smart' labelling that equates digital products with sustainable products dilutes target orientation (greenwashing). • Potential rebound effects
SDG 14: **Life below water**	• Increased reliable data through real-time monitoring and data collecting, e.g. natural systems in oceans, or plastic waste in the oceans • Digital technologies offer long-term prospects for the circular economy and for combating marine garbage • Digital technologies can help to improve themonitoring, surveillance and enforcement of ecosystem protection and to combat overfishing, as well as illegal and destructive fishing • Improved access to digital information systems could help improve market access for small-scale fisheries	• The use of digitally supported technology means that very few shoals of fish escape capture • Digitalization is currently accelerating economic processes based on fossil energy (including offshore oil and gas production) and resource extraction. This drives marine pollution (e.g. plastics) and acidification • Digital technology increases the demand for rare metals and with it incentives for deep-sea mining.
SDG 15: **Life on land**	• Increased reliable data through real-time monitoring and data collecting • Big data analytics for, e.g. biodiversity and land use ('smart conservation')	• Potential rebound effects • New dependencies on the multinational companies that provide digital technologies or improved input

SDG	Potential synergies	Potential conflicts
	- More people could benefit from e-healthcare through better accessibility. - Precision agriculture can improve environmental protection, resource efficiency and productivity - Digitally enhanced monitoring of ecosystems and soil conditions (including forests and wildlife) strengthen the protection of terrestrial ecosystems and biodiversity - By using mobile phones, smallholders can benefit from advice on improvements in production planning and the management of weather-related risks. Other agricultural risks, e.g. pests, plant diseases or soil erosion, can also be identified using mobile phones and digital photographs; advice can be provided and risks thus mitigated or prevented - Securing the land rights of smallholders, e.g. via blockchain technologies as a way of preventing large-scale land grabbing.	Marginalization of poor smallholders by 'land grabbing', among other things.
SDG 17: Partnerships	- ICT can enhance the cooperation on and access to science, technology and innovation, and enhance knowledge sharing - ICT can promote development, transfer, dissemination and diffusion of environmentally sound technologies on favourable terms - Capacity building for data evaluation and monitoring and for the concrete preparation of national implementation plans	- Possible disruptive impact of individual or cumulative digitalization consequences on world trade, macroeconomic stability and – deduced from this – systemic issues in general - Cooperation on technology transfer, the collection of data sets and statistics, or the dissemination of ICT use can lead to (new) dependencies and privacy conflicts. Nor is it a matter of purely 'technological fixes'

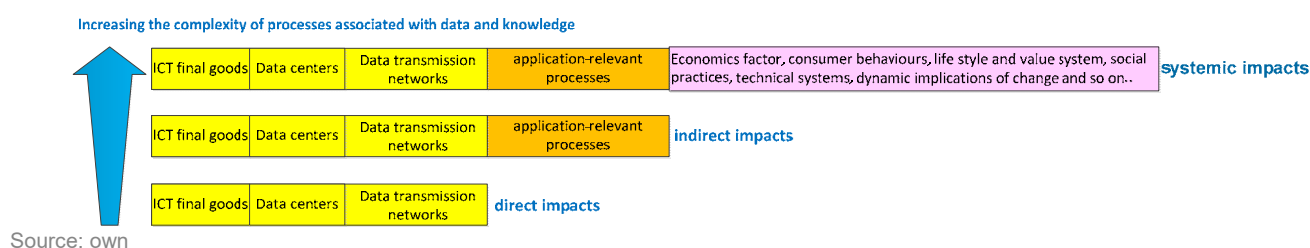Source: WBGU (2019c), complemented by own findings and GeSI & accenture (2016).

4.2. Overarching conclusions

Although much literature addresses the benefits or opportunities resulting from digitalisation, we still think that digitalisation has not been sufficiently explored from an environmental perspective. This partly related to the factor that these opportunities are often not addressed in environmental legislation.

The degree of complexity of processes and data flows associated with digitalisation is followed by gradually increasing direct, indirect and systemic impacts respectively, as shown in Figure 4-2. Evaluating direct impacts associated with the physical existence of ICT goods is the fundamental step for further assessment of indirect impacts resulting from the application of ICT goods in concrete application sectors. However, the environmental assessment of data centres, data transmission networks and emerging innovation technologies such as blockchain, 5G, sensory technology,

semiconductor industry, or edge computing[109] has yet to be sufficiently explored, especially regarding non-energy aspects. This makes the assessment of indirect impacts more challenging. Complexity increases continuously when systemic impacts are taken into account, since the scope is broadened and other interconnected effects (see Figure 4-2) play a role. We therefore suggest that direct impacts associated with ICT goods and corresponding technologies be further investigated, since they are the baseline for assessing indirect and systemic environmental impacts.

Figure 4-2: **Increasing complexity of data flows and processes when accounting for indirect and systemic impacts**

Increasing the complexity of processes associated with data and knowledge

ICT final goods	Data centers	Data transmission networks	application-relevant processes	Economics factor, consumer behaviours, life style and value system, social practices, technical systems, dynamic implications of change and so on..	**systemic impacts**
ICT final goods	Data centers	Data transmission networks	application-relevant processes	**indirect impacts**
ICT final goods	Data centers	Data transmission networks	**direct impacts**

Source: own

The process of digitalisation requires an enormous amount of hardware covering final ICT goods, data centres, networks as well as accompanying infrastructures (e.g. cooling, uninterrupted power supply, etc.). All of these physical products demand energy and resources throughout their life cycles. Hence, one cannot assume that digitalisation will automatically lead to resource, energy or other environmental benefits. A holistic approach is needed to properly understand the impacts and get robust results: that is, not only the use phase should be looked at, but also manufacturing and end-of-life phases; not only IT equipment should be focussed on, but also on the required infrastructures; not only the carbon footprint should be measured, but also other impacts; not only direct but also indirect and systemic effects need to be acknowledged.

To steer the digitalisation into a (more) sustainable direction, the rate of efficiency gains needs to be greater than the rate of economic growth. Hilty & Bieser (2017) assume that "the data traffic, e.g. machine-to-machine communication, autonomous driving, smart city, smart home applications and the corresponding network infrastructure might grow faster than the energy and resource efficiency of the infrastructure itself, resulting in growing negative impacts." So far, these issues have not been discussed let alone sufficiently in the EU environment policy context. However, the European Green Deal could be a turning point for this, as it acknowledges that "Europe needs a digital sector that puts sustainability at its heart" (European Commission, 2019, p. 9)

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[109] Edge computing refers to a distributed computing paradigm according to which the data is computed and stored closer to the locations where it is needed, so that data need not be transferred halfway around the world. Edge computing is estimated to be a good solution to combat resource depletion and protect the environment. However, no LCA-relevant studies were found in the timeframe of writing this issue paper.

5. Recommendations for further work

Based on the literature review, we see need for further research and evidence gathering in the following areas:

5.1. Developing methods and guidance

Methodological challenges are:

- There is no standard method for assessing rebound effects.

- A large number of approaches have been proposed attempting to address the many pressures on biodiversity, but no worldwide applicable model exists (Winter et al., 2017). The same goes for land use and land use change.

- It has been indicated in several LCA studies that secondary databases used for the modelling of environmental impacts can also have an influence on the results. For instance, (Ercan et al., 2016) modelled gold and copper production phases by applying data sets from two different databases[110], creating a large difference in results.

To date, guidance is missing for final consumers on making the right decision based on their needs, e.g.

- Do we really need **Gigabit internet**? (1 gigabit=1000 Mbps (Megabit per second)). Internet providers advertise high-speed internet heavily. However, even if the final users watch movies in ultra HD (4K) quality, the internet download speed per stream recommended by Netflix is 25 Mbps[111], not 1000 Mbps. A video solution with an 8K TV requires a download speed of 50 Mbps[112].

- Can final users distinguish between SD and HD when streaming online video, which causes a different data volume transferred through the networks? Is the difference substantial enough to justify the resulting environmental impacts (see Section 3.2.1.2)?

A centrally regulated law on advertising by internet providers is needed to give consumers clear purchase advice.

5.2. Closing data gaps

- The semiconductor industry uses an extensive range of ultrapure chemicals and solvents. (Choi et al., 2018) reviewed two facilities of integrated circuits in South Korea and found that a total of 428 and 432 chemical products were used in plants A and B, respectively. Moreover, introducing advanced technology, such as multiple patterning and 3-dimensional chips, more ultrapure cleaning chemicals are needed. Also, the introduction of new materials into chips can cause big changes to long-standing cleaning formulas[113]. To our knowledge, there is no available inventory data on amounts used, possibly partly due to trade-secret information.

- There is a significant lack of data about the network infrastructure along with the technology generations. Little research has been conducted on hardware used in the network, covering both

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[110] One is from Ecoinvent, the other is from Gabi. Both of them are well-known databases used in LCA-community.

[111] https://help.netflix.com/en/node/306

[112] http://allinfo.space/2018/12/04/8k-tv-angekommen-ist-hier-ist-was-sie-wissen-mussen/

[113] https://cen.acs.org/articles/95/i40/computer-chips-shrink-cleaning-needs.html

energy and carbon footprints and also other impact categories such as resources, water, toxicity, etc.

5.3. Understanding technologies associated with their resource demands and environmental impact

Assessment of environmental impact should consider technology development and innovations. For instance, if the magnetic storage (HDD: hard disc drivers) were to be replaced by flash storage (SSD) technology, the importance of rare earth elements (e.g. Neodymium, Dysprosium) in HDDs would weaken. Western Digital and Seagate have already shut down their HDD assembly facilities and increased production of SSDs, due to the fact that the total market of hard drives is dropping[114]. Other examples would be 5G, blockchain technology and sensor technology. Sensor technology has evolved quite rapidly in the past few years. Sensors are applied in a wide range of digitalisation sectors, such as smart homes, autonomous driving, smart farming, smart meters, smart monitoring for environment detection, and sensors in the healthcare sector. Sensors with different functions take various forms and use various materials (e.g. nanotechnology is also increasingly applied in sensor technology). The implications of widespread applications of sensors for resource depletion, chemicals and hazardous substances used in production, e-waste flows in the environmental impact context remain unclear. Hence, technology assessments should incorporate aspects of environmental assessment.

5.4. Broadening the scope of the impact categories of environmental assessment studies (beyond the Energy and Carbon Footprint)

There are more studies on energy and CO_{2e} emissions than other impact categories. One reason is that data on energy, especially in the use phase, is more easily accessible than other impact categories (Arushanyan, Ekener-Petersen, & Finnveden, 2014). Another reason is that overall consensus already exists on the method for assessing global warming potential, namely that of the IPCC. Energy and carbon emissions are not the only environmental impacts associated with digitalisation that should be examined. Other environmental impacts, such as abiotic resource depletion, water depletion, eco- and human toxicity should not be ignored, as these environmental consequences might be similarly important as well.

5.5. Integrating systemic impacts into ICT-enabled solutions

(Bieser & Hilty, 2018a): "Increasing diffusion of ICT leads to more complex systemic effects, a trend which implies that there will be a growing error if one tries to predict the overall effect by simply aggregating individual ICT use cases. Selected use cases may fundamentally change our patterns of production and consumption, leading to collateral impacts on other use cases. Therefore, in order to estimate the overall, systemic indirect environmental effect of a given set of ICT solutions, one should take a whole-system approach considering the interaction between use cases." More precise guidance is required for specific economic sectors.

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[114] https://www.anandtech.com/show/13097/western-digital-to-shut-down-hdd-manufacturing-facility-increase-production-of-ssds

5.6. Exploring 'big points' of sustainable ICT consumption and options for educating consumers

Research is necessary to identify the 'big points' – i.e., activities through which individual consumers create substantive environmental impact (Bilharz, 2008) –; to explore the state of knowledge / attitudes of consumers regarding these big points as well as regarding sustainable consumption options in the field of ICT goods and applications; to collate information on effective options for educating consumers and strengthening their capacities with regard to a sustainable digitalisation.

5.7. Policies for making digitalisation and the data economy more sustainable

Policies, legislation and institutions should be identified that can help to shape digitisation in a sustainable way at all levels of governance (EU, Member State, regional, city etc.). For example, cities should be helped to re-design their digitalisation strategies with a view to ambitious environmental targets. While this issue paper did screen some relevant policy options, more in-depth research is required, assessing existing proposals and developing further suggestions.

One relevant aspect is the regulation of Big Data and the **data economy**. While policies and legislation regarding environmental data are appropriate given the potential of data-driven technologies explicated above, environmental policy considerations should not exclusively focus on this kind of data. Given the impact and effectiveness of the new technologies, such regulations thus would affect the distribution of agency between private, public or civil society actors. General rights to access, use or trade many kinds of data – such as data regarding individual transport or consumer behaviour – thus for example can have major consequences for political margins to regulate or control environmentally problematic applications or business models. Despite the prominence of the technologies' environmental impacts, however, environmental policy objectives have yet to be considered in these legal policy debates. For such reasons, there is a need for analysing the environmental implications existing proposals regarding the regulation of the data economy (e.g. by means of dismantling or mitigating data-monopolies). This holds particularly for the question of how these proposals can contribute to achieving environmental policy objectives – such as energy or resource efficiency, sustainable transport or sustainable consumption.

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Annex II: Main results from the literature screening in greater detail

6. ICT final goods

6.1.1. Material basis: Smartphone and Tablet (Manhart et al., 2017)

Electronic devices contain a broad variety of materials, including many elemental substances that are widely regarded as critical and that are mined only in small quantities. Figure 6-1 gives an overview of the material composition of smartphones and Figure 6-2 of those of tablets. The content data of both tables are based on (Manhart et al., 2017), in which authors collected various literature sources and their own selected measurements. The authors indicated that the content data is only indicative and might vary significantly from model to model. It has to be stressed that the compilation of both tables lacks data on various elements. In particular there is no data for the content of **beryllium and lithium**, which are both commonly used in electronic devices. While beryllium is used for bonding wires, amongst other things, lithium is a major material for the Li-Ion batteries that power virtually all mobile phones and tablets. The tables display bills of material on an elementary level, at least in relation to the various metals. As a consequence, compounds such as PVC and flame retardants are not addressed as such. In addition to these shortcomings, the material composition might vary over time, which is not necessarily reflected in the data. Thus, the data and information in these tables should only be used for rough estimates (Manhart et al., 2017).

Figure 6-1: **Indicative material composition of smartphones**

Material		Main application	Content per smartphone	Content in worldwide 3.3 billion smartphones used in 2019
Aluminium	Al	Case	22.18 g	73,194 t
Copper	Cu	Wires, alloys, electromagnetic shielding, printed circuit board, speakers, vibration alarm	15.12 g	49,896 t
Plastics	-	Case	9.53 g	31,449 t
Magnesium	Mg	Case	5.54 g	18,282 t
Cobalt	Co	Lithium-ion battery	5.38 g	17,754 t
Tin	Sn	Solder paste	1.21 g	3,993 t
Iron (steel)	Fe	Case	0.88 g	2,904 t
Tungsten	W	Vibration alarm	0.44 g	1,452 t
Silver	Ag	Solder paste, printed circuit board	0.31 g	1,023 t
Neodymium	Nd	Magnets of speakers	0.05 g	165 t
Gold	Au	Electronic components, printed circuit board	0.03 g	99 t
Tantalum	Ta	Capacitors	0.02 g	66 t
Palladium	Pd	Electronic components, printed circuit board	0.01 g	33 t
Praseodymium	Pr	Magnets of speakers	0.01 g	33 t
Indium	In	Display	0.01 g	33 t
Yttrium	Y	LED-backlights	0.0004 g	1.3 t

Gallium	Ga	LED-backlights	0.0004 g	1.3 t
Gadolinium	Gd	LED-backlights	0.0002 g	0.7 t
Europium	Eu	LED-backlights	0.0001 g	0.3 t
Cerium	Ce	LED-backlights	0.00003 g	0.1 t
Others	-	Glass, ceramics, semiconductors….	99.29 g	327,657 t
			160 g	**528,037 t**

Source: (Manhart et al., 2017); own calculation based on (Statista, 2019a)

Figure 6-2:   **Indicative material composition of tablets**

Material		Main application	Content per tablet	Content in worldwide 1.14 billion tablets used is 2017
Glass	-	Display	66.53 g	75,844 t
Aluminium	Al	Case	56.59 g	64,513 t
Copper	Cu	Wires, alloys, electromagnetic shielding, printed circuit board, speakers	40.79 g	46,501 t
Plastics	-	Case	26.49 g	30,199 t
Cobalt	Co	Lithium-ion battery	15.55 g	17,727 t
Magnesium	Mg	Case	13.57 g	15,470 t
Tin	Sn	Solder paste	3.19 g	3,637 t
Iron (steel)	Fe	Case	2.44 g	2,782 t
Neodymium	Nd	Magnets of speakers	0.60 g	684 t
Silver	Ag	Solder paste, printed circuit board	0.31 g	353 t
Tungsten	W	Vibration alarm	0.27 g	308 t
Praseodymium	Pr	Magnets of speakers	0.15 g	171 t
Tantalum	Ta	Capacitors	0.04 g	46 t
Gold	Au	Electronic components, printed circuit board	0.03 g	34 t
Indium	In	Display	0.02 g	23 t
Palladium	Pd	Electronic components, printed circuit board	0.01 g	11 t
Yttrium	Y	LED-backlights	0.002 g	2.3 t
Gallium	Ga	LED-backlights	0.002 g	2.3 t
Gadolinium	Gd	LED-backlights	0.001 g	1.1 t
Europium	Eu	LED-backlights	0.0003 g	0.3 t
Cerium	Ce	LED-backlights	0.0001 g	0.1 t
Others	-	Ceramics, semiconductors….	204.43 g	233,050 t
			431 g	**491,358 t**

Source: (Manhart et al., 2017); own calculation based on (Statista, 2019b)

These material requirements are compared to the total primary (mine) production during the same time period (2014). As the global mining data does not yield a material specific production volume for rare earth elements, the rare earth elements contained in smartphones and tablets (Nd, Pr, Y, Gd, Eu, Ce) were summed-up to one figure for this exercise.

Figure 6-3: **Total material requirements of smartphones and tablets in relation to the world primary production of mineral commodities**

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[115]	> 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[116]	> 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[117]	< 1% & 1-10%	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%

Source: (Manhart et al., 2017)

The analysis yields that smartphones and tablets are quite important applications for **cobalt** (~ 9.4% of world primary production) and **palladium** (~ 8.9% of world primary production). The global production of these two product groups is also a relevant factor in the global demand of **tantalum, silver, gold, indium and magnesium** (between 1% and 3% of world primary production). Nevertheless, the calculated values in Figure 6-3 are based on various assumptions and should not be overstressed. They are only indicative figures and should be carefully reviewed with additional analytic efforts before being used for decision-making. Generally, such industry shares of the global material demand are important indications for the potential influence of a sector on upstream activities.

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[115] Data for magnesium metal.
[116] Data for pig iron.
[117] Data for rare earth oxides (REO).

6.1.2.   Material basis: Desktop computers

Figure 6-4:   **Desktop computer bill of materials**

Table 5 — Desktop-computer bill of materials (BoM) according to Song et al. (2013).
Packaging included.

Categories	Weight (kg)	Percentage
Iron housing	4.95	47.28 %
Plastic housing	0.16	1.53 %
Printed circuit board	0.66	6.30 %
CD-ROM/DVD ROM	0.75	7.16 %
Power-supply unit	1.62	15.47 %
Hard disk	0.55	5.25 %
Cable	0.14	1.34 %
Radiator (Al)	0.57	5.44 %
Fan	0.07	0.67 %
Packaging	1.00	9.55 %
Total mass	**10.47**	**100 %**

Source: (Tecchio et al., 2018)

6.1.3. Material basis: Laptops

Table 7 — BoM for notebooks, modified from Talens Peiró et al. (2016b) with mass of battery as in Clemm et al. (2016)

Components	Materials	[g]
Plastic polymers	Plastic blend with flame ret. (PC+GF20 FR40)	109
	Plastic blend with flame ret. (PC ASA CF10 — FR40)	129
	Poly-methyl methacrylate (PMMA)	105
	Unspecified plastics	103
Metals	Aluminium	189
	Magnesium alloy	177
	Steel (including screws)	77
Display panel	Glass + other (unspecified)	160
Batteries	Prismatic battery: Li-ion	260
	Button battery: lithium manganese dioxide	3
PCBs	Motherboard	167
	RAM cards	17
	CPU	4
	Other PCBs	77
Other components	ODD	212
	Storage system	96
	Fan	10
	Small LCD	5
	Speakers	5
	Lamps	8
	Cables	17
	Total	**1 930**

Source: (Tecchio et al., 2018)

6.1.4. Material basis: Rack server

Figure 6-5: Description of the materials and their quantities in servers (Peiró & Ardente, 2015)

Component/Materials	Mass (g)	Amount in server (g)
Aluminum	- Chassis (249) - ODD (1) - 4HDD (787) - 2PSU (226)	1 263
Brass	- Cables (7)	7
Copper	- Chassis (179) - ODD (7) - Cables (81) - Heat pipe (442) - 4Fan (78) - 4HDD (7) - 2PSU (13)	806.56
Steel	- Chassis (12,265) - ODD (115) - Heat pipes (140) - 4Fan (386) - 4HDD (547) - PSU (1408)	14 861
Ferrous metals	- 4 Fan (55) - 4HDD (152) - 2PSU (9)	216
Zinc	cables (96)	96
ABS	- Chassis (348) - ODD (12)	360
EVA	- 2PSU (75)	75
HDPE	- ODD (28) - Cables (104) - Packaging (78)	210
PBT	- 4 Fan (206) - 2PSU (34)	240
PC	- Chassis (282) - ODD (7)	289
PCABS	- 4Fan (220) - 4HDD (68) -2PSU (36)	324.28
PCFR40	- 2PSU (51)	51
PCGF	- 4HDD (52)	52
PUR	- Cables (2)	2
PVC	- Cables (145)	145
Styrofoam	- Packaging (1026)	1 026
Synthetic rubber	- Cables (35)	35
Other materials		
Cables	- PSU (31)	31
Electronics	PCBs (including capacitors): - Mainboard (1667) - Expansion card (349) - CPU (54) - Memory (135) - 4HDD (68) - 2PSU (1543) - Chassis (131) - ODD (19)	3 966
Paper	- Packaging (3629)	3 629
Others (solder)	- ODD (2)	2
Neodymium magnets	- 4HDD (68)	68
Batteries	- Coin cell CR2032 (1.6) - Li ion prismatic (43)	44.6
Total		**27 799**

ABS: acrylonitrile-butylene-styrene; EVA: ethylene vinyl acetate HDPE: high density polyethylene; PBT: polybutylene terephthalate; PC: polycarbonate; PCABS: polycarbonate acrylonitrile-butylene-styrene; PCFR40: polycarbonate with flame retardant; PCGF: polycarbonate glass fibre; PUR: polyurethane; PVC: polyvinyl acetate

Source: Berwald et al. (2015)

Figure 6-6:   **Description of the materials and their amounts in printed circuit boards contained in a sample server (all amounts are in grams) (Peiró & Ardente, 2015)**

	Amount in server
Printed circuit boards (Total mass)	3 966
Brominated Epoxy Resins	1 176.97
Glass Fibre	1 722.01
Aluminum	333.78
Copper	705.295
Gold	0.9620
Iron	3.5600
Nickel	0.7779
Palladium	0.3971
Silicon	6.5600
Silver	0.4830
Tin	9.4130
Titanium	3.6200
Magnesium	0.0039
Neodymium	0.2100
Lead	0.0032
Other materials	1.9101

Source: Berwald et al. (2015)

6.1.5.   Material basis: Embedded automotive systems

Modern automobiles represent a relevant field of application for embedded electronics worldwide. Although not all electronic control components in vehicles are based on digital technology (some peripheral modules contain analogue components), the extent of digitisation in the automotive sector is steadily increasing. On average, electronic control components embedded in automobiles account for about 30% of total vehicle costs. This share of costs is expected to rise to up to 50% by 2030 (Restrepo et al., 2017). Embedded electronic components consist primarily of printed circuit boards with microelectronic circuits, which typically contain a number of critical materials.

A material flow analysis of the automotive electronics of the entire Swiss car population showed that the vehicle population taken into account in the study (about 4 million cars) contains material in a total mass of about 6.1 Mt (ibid.). There was a direct correlation between the time of manufacture of the vehicles and the number of embedded electronic control systems: The younger the vehicle, the higher the number of electronic components and associated sensors and actuators. A large part of these actuators (these are usually small DC motors with strong permanent magnets) can only be used meaningfully in the vehicle because digital control electronics provide them with an application purpose. As enabling technology, digitisation in this example induces further use of technology, which also requires resources. According to estimates by Restrepo et al. (2017), the quantities of critical materials (KM) used in vehicle electronics are expected to increase dramatically in the coming years.
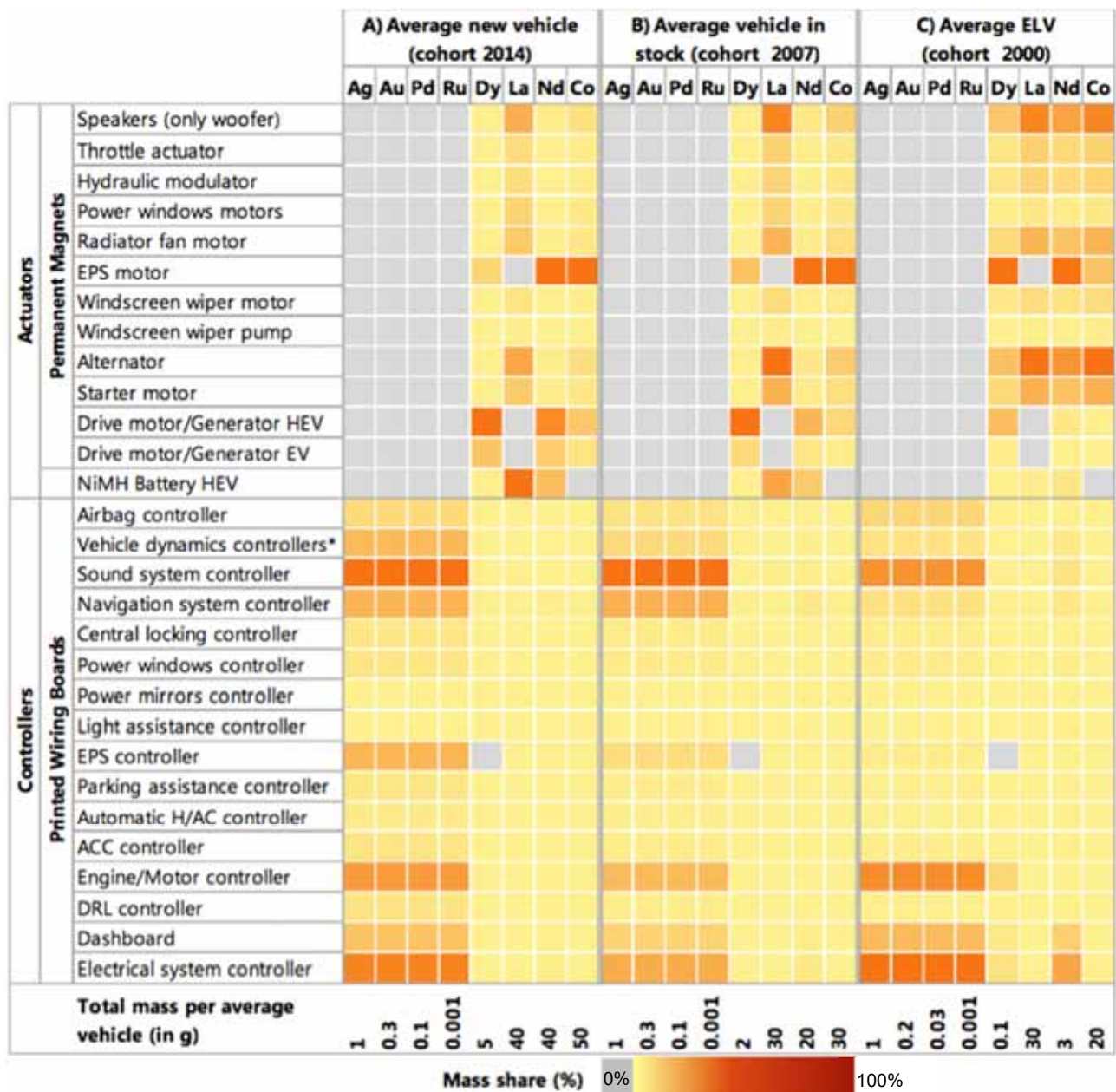
Figure 6-1: **Control electronics in passenger cars (imported from Switzerland in 2014)**

Source: Restrepo et al., 2017

The distribution of critical resources in these electronic control components depends on the type of hardware. Rare earth elements (SEE) are mainly found in non-digital components such as motors and loudspeakers. The largest quantities of SEE mass in new vehicles are embedded electronically controlled actuator motors and generators. Gold, silver and platinum metals are primarily contained in the on-board network controller (fuse box), the sound system controller (radio), the navigation system controller and the motor/engine controllers. This material concentration is similar in most passenger cars regardless of type.

Figure 6-2:   **Occurrence of selected critical materials in passenger car electronics***

Source: Restrepo et al., 2017 (* Data related to 2014 vehicles imported from Switzerland)

The total mass of critical metals in new vehicles (2014) is more than five times higher than that of end-of-life vehicles (ELVs). All new vehicles imported into Switzerland each year, for example, contain 25 tonnes of SEE, while end-of-life vehicles only contain 3 tonnes per year. Approximately half of the mass increase is due to the 3 times larger number of newly imported vehicles (compared to end-of-life cars), while the other half is due to a higher mass of critical metals in new vehicles. It is therefore expected that the amount of critical metals in end-of-life vehicles will increase by a factor of 2 over the next 15 to 20 years.

Figure 6-7 **Mass of critical metals in vehicle electronics of an average vehicle from 2014**

element	Median mass per vehicle in g	Total mass in all worldwide Vehicles produced in 2014 in t
dysprosium	5	338.910
lanthanum	40	2.711.281
neodymium	36	2.440.153
cobalt	50	3.389.102
palladium	0,04	2.711
ruthenium	0,0007	47
silver	0,7	47.447
gold	0,2	13.556

Source: Restrepo et al. 2017, Supporting information   Source: Own extrapolation based on (OICA, 2017)

Figure 6-7 shows an extrapolation of the quantities of critical metals per vehicle determined by (Restrepo et al., 2017) to the worldwide number of passenger vehicles produced in 2014 (67.7 million units) (OICA, 2017). However, this estimate does not yet take into account a possible transition from current passenger car technology with internal combustion engines to computer-controlled electric vehicles. Future self-propelled vehicles would be significantly equipped with more powerful digital control systems than today's passenger cars. This will significantly increase the amount of KM per car.

6.1.6. Life cycle assessment of smartphones

- Fairphone 2 (Proske et al., 2016): the unique character of Fairphone 2 is modularity. The modularity has a positive effect on reparability and recyclability and can thereby reduce the overall life cycle emissions.

Figure 1-1: Relative impacts of the different life cycle phases per impact category

- Sony (models Z3 and Z5) (Ercan et al., 2016):

– Important environmental impacts: Human Toxicity non-Cancer potential effects; Human Toxicity Cancer potential effects; Eco-system Toxicity potential effects; Abiotic Depletion Potential (ecoinvent normalized results)

– when applying the Ecoinvent data set, gold contributes to nearly half of the abiotic resource depletion potential (also cobalt, silver and lithium give significant contributions). These results depend on the amount of gold that is needed to produce a smartphone, the rate of recycled gold that enters the smartphone life cycle, how the EoLT stage is modelled, and the gold recycling rate at EoL.

Fig. 4 Total life cycle result for all impact categories for smartphone Z5 with accessories using Ecoinvent database and adopting a 50/50 recycling approach with 19% recycling of gold assumed.

Fig. 5 Total life cycle result for all impact categories for smartphone Z5 with accessories using GaBi database for gold and energy production and a 50/50 recycling approach with 83% recycling of gold assumed. Note that the figure shows relative results compared to figure 4

– In Figure 5, Ecoinvent gold and copper data and models are replaced by GaBi's own data models, and the results are expressed in percentage of the Ecoinvent-based results indicating a large difference in results due to the two data sets. Neither of the two scenarios presented in Fig. 4 and 5 could be described as the true one, rather they represent a range of possible outcomes.

– the toxic impact potential is dominated by the acquisition of gold, followed by the copper processes.

6.1.7.   Life cycle assessment of desktop computers and monitors

Results from the studies (Bhakar et al., 2015; Song et al., 2013)

The following tables summarise the results from the contribution analysis and differentiates the impacts by life phase and at a component level.

Figure 6-8:   **Comparison of environmental impacts differentiated by life cycle phases**

Sources	Life cycle phases	Environmental impacts of the life cycle phases
Life Cycle Assessment of CRT, LCD and LED Monitors (Bhakar et al., 2015)	Acidification Potential (AP), Climate Change (CC), Eutrophication Potential (EP), Freshwater Aquatic Eco-Toxicity Potential (FAETP), Freshwater Sediment Eco-Toxicity Potential (FSETP), Human Toxicity Potential (HTP), Ionizing Radiation (IR), Malodours air, Marine Aquatic Eco-Toxicity Potential (MAETP), Marine Sediment Eco-Toxicity Potential (MSETP), Photochemical oxidant formation (POCP), Abiotic resource depletion Potential (ADP), Ozone Depletion Potential (ODP), and Terrestrial Eco-toxicity potential (TETP).	 Fig. 6 LCA results of LED monitor across all the phases Fig. 5 LCA results of LCD monitor across all the phases

Fig. 4 LCA results of CRT monitor across all the phases

Life cycle assessment of desktop PCs in Macau (Song et al., 2013)	Manufacturing and use have a clearly higher environmental impact compared to the distribution and end-of-life (EoL).	

Environmental impacts dominating in the manufacturing phase:

- Eutrophication (EP)
- Ozone layer depletion (ODP)
- Human toxicity (HTP)
- Freshwater aquatic ecotoxicity (FAETP)
- Marine aquatic ecotoxicity (MAETP)
- Terrestrial ecotoxicity (TETP)

Environmental impacts dominating in the use phase:

- Abiotic resources (ADP)
- Global warming (GWP)

| | | • Acidification (AP)
• Photochemical oxidation (POCP) |
| | Environmental impacts of the manufacturing phase at component level: The environmental impacts of a desktop PC are clearly dominated by the PWB, which has an impact ranging from 44% (PCOP) up to 77% (MAETP) of the manufacturing phase. The second contributor was the power supply (PS) with an impact between 6% (MAETP) and 32% (PCOP). These are followed by the CD-ROM, the HDD and aluminium components. | |

There is another life cycle assessment paper of an integrated desktop device by (Subramanian & Yung, 2017). The paper is intended to compare desktop computers and all-in-one PCs. All-in-one PCs integrate the electronic components (CPU, RAM, HDD, network ports) behind the monitor so that the entire PC is enclosed all in one unit. This study is not assessed in this issue paper, since we think the comparability of the two PC systems in this paper is fair. First of all, it is not mentioned whether the two comparable types of PCs provide similar technical performance. Secondly, all-in-one PCs have poor upgradability and poor reparability as opposed to desktop PCs. Therefore all-in-one PCs might have shorter lifetime than desktop PCs. These aspects are not discussed in the paper and not reflected in the life cycle assessment. In the study, both types of PCs have the same lifetime. Hence, we think the underlying basis for the comparison is not justifiable.

Figure 5: Consumption of gold, palladium and silver in the notebooks used in the federal administration with two different service life times of notebooks

Source: Prakash et al. (2016)

6.1.8. Life cycle assessment of laptops

Results from the study by (Grezesik-Wojtysiak et al., 2013)

A screening life cycle assessment for a laptop, assembled, used and disposed in Poland was performed by (Grezesik-Wojtysiak et al., 2013). 11 impact categories (see table below) were calculated with the application of the Eco-indicator 99 method, expressing the significance of the burden on the environment.

Damage category	Impact category
Human health	Carcinogenic effects on humans (Carcinogens)
	Respiratory effects caused by organic substances (Respiratory organics)
	Respiratory effects caused by inorganic substances (Respiratory inorganics)
	Damage caused by climate change (Climate change)
	Effects caused by ionising radiation (Radiation)
	Effects caused by ozone layer depletion (Ozone layer)
Ecosystem quality	Damage caused by ecotoxic effects (Ecotoxicity)
	Damage caused by the combined effect of acidification and eutrophication (Acidification/Eutrophication)
	Damage caused by land occupation and land conversion (Land use)
Resources	Damages caused by extraction of minerals (Minerals)
	Damages caused by extraction of fossil fuels (Fossil fuels)

For the whole life cycle of 5 years, the manufacturing of the product dominates 6 among 11 impact categories investigated. The use phase is responsible for the remaining 5 impacts.

Figure 6-9:   **LCA results using the Eco-indicator 99 method, at the step of characterisation**

After the weighting procedure, the results indicated the damage caused by the extraction of fossil fuels (46.7%), respiratory effects caused by inorganic substances (23.6%) and damage caused by climate change (7.95%) as the main impact categories that are highly affected by the laptop life cycle.

Figure 6-10:   **LCA results using the Eco-indicator 99 method after the weighting procedure**

Results from the study by (Ciroth & Franze, 2011)

The results from (Ciroth & Franze, 2011) are only presented in percentages. The following figures are taken directly from their study. The results show that the production of the notebook dominates the environmental impacts throughout all 17 impact categories. The use phase including the reuse phase is the second contributor to the overall environmental burden. This is based on the fact that the notebook investigated is a highly energy-efficiency computer. Besides that, the relatively short

use time and place where the computer is used due to the electricity mix, also influence the shares between the life cycle phases concerning environmental impacts.

Figure 6-11:   **Environmental impacts along the life cycle phase of a notebook based on the ReCiPe method**

Furthermore, the environmental hot spots through normalisation based on "World ReCiPe H/H" revealed that the most relevant impact categories are climate change (human health and ecosystems), human toxicity, particulate matter formation, and fossil depletion (see Figure 6-12).

Figure 6-12:   **Normalised environmental impacts along the life cycle phase of a notebook based on the ReCiPe method**

Figure 25: Results of the endpoint assessment single score (in pt)

In summary, the main findings were:

- On the level of overall life cycle phases, production and use of a notebook PC have a large environmental impact.

- On the component level, the production of the display and motherboard of a notebook PC has a rather large environmental impact, followed by battery production.

- the most relevant impact categories are fossil depletion, climate change (human health and ecosystems), human toxicity, particulate matter formation, and respiratory effects caused by inorganic substances

6.1.9. Wearables and smart textile

https://www.statista.com/chart/3370/wearable-device-forecast/

The number of wearable devices shipped worldwide is expected to double from 2019 to 2022.

Figure 6-13:   **Forecast unit shipments of wearable devise worldwide from 2017 to 2019 and in 2022 (in million units), by category**

© Statista 2019

Source: https://www.statista.com/statistics/385658/electronic-wearable-fitness-devices-worldwide-shipments/

6.2.   Data centres

6.2.1.   Material basis: Critical raw materials used in a server (Peiró & Ardente, 2015)

Table 15. Critical raw materials in PCBs included in enterprise servers.

Part	Material	Symbol	Content	Amount per server (g)
Batteries	Cobalt	Co	Li polymer battery (Ansmman, 2011): 5.1783-12.9457 g	9.0620
	Lithium [a]	Li	Coin battery (CR2032): 0.07g (Maxell,2015) Li polymer (Ansmman, 2011): 0.6098 – 1.5246 g	1.1372
HDD	Dysprosium	Dy	Average content in magnets (in mass): 21.2% Nd; 5.3% Pr; 5.3% Dy; 1.1% Tb (Du and Graedel 2011)	3.6040
	Neodymium	Nd		14.4160
	Praseodymium	Pr		3.6040
	Terbium	Tb		0.7480
PCBs [b]	Magnesium	Mg	Chassis: 0.0001g; Expansion card: 0.0004g; Mainboard: 0.0024g; HDD: 0.011g;	0.0040
	Neodymium	Nd	Chassis: 0.0011g; Expansion card: 0.0217g; Memory card: 0.0115g; Mainboard: 0.1354g; HDD: 0.0438g	0.2135
	Palladium	Pd	Chassis: 0.0157g; Expansion card: 0.0389g; Memory card: 0.0207g; Mainboard: 0.2432g; HDD: 0.0786g	0.3971
	Silicon [c]	Si	Chassis: 0.2408g; ODD: 0.0045g; Expansion card: 0.5238g; CPU: 0.0950g; Memory card: 3.7930g; Mainboard: 1.5492g; HDD: 0.4480g	6.6544
Connectors [b]	Antimony	Sb	4.4447 g	4.4361
	Beryllium	Be	0.0348 g	0.0348
	Chromium	Cr	8.5648 g	8.5648
	Cobalt	Co	0.2039 g	0.2039
	Palladium	Pd	0.0002 g	0.0002
	Silicon [d]	Si	4.5726 g	4.5726

[a] Lithium is excluded from the CRM in 2014 [b] Data sources used to estimate the content of CRM are included in table A4 in the annex of this report [c] Silicon in servers is contained in electronic grade (9N) in the die of packages [d] In most cases silicon is contained in stainless steel alloys

Table 16. Estimated amount of critical raw materials in enterprise servers

Material	Symbol	Amount per server (g)	Material	Symbol	Amount per server (g)
Antimony	Sb	4.4361	Silicon [b]	Si	11.2271
Beryllium	Be	0.0348	**Rare earth elements (REEs)**		
Chromium	Cr	8.5648	**Material**	**Symbol**	**Amount per server (g)**
Cobalt	Co	9.2659	Dysprosium	Dy	3.6040
Lithium [a]	Li	1.1372	Neodymium	Nd	14.6295
Magnesium	Mg	0.0040	Praseodymium	Pr	3.6040
Palladium	Pd	0.3973	Terbium	Tb	0.7480

[a] Lithium is excluded from the CRM in 2014 [b] Silicon in servers is contained different grades: electronic grade (9N) in the die of packages, and in stainless steel alloys

Note:

We doubt that the terbium values are actually as high as indicated in the table above. According to our study funded by the German Federal Environmental Agency, no terbium has been used in HDDs (Prakash et al. 2016a).

6.2.2. Life cycle assessment of data centres

Figure 6-14: Impact category single scores (Whitehead et al., 2015)

Impact Category	Single Score Results (Pt) (method: Eco-Indicator-99)		Manufacturing	Operation	End of Life
			Share in %		
Carcinogens	1.62E+02	**26.3%**	20%	80%	0.1%
Respiratory Organics	8.13E-02	0.0%	48%	52%	0.0%
Respiratory Inorganics	1.54E+02	**25.0%**	28%	72%	0.2%
Climate Change	7.27E+01	**11.8%**	13%	87%	0.1%
Radiation	2.91E+00	0.5%	6%	94%	0.1%
Ozone Layer	2.99E-02	0.0%	4%	96%	0.0%
Ecotoxicity	1.75E+01	2.8%	**74%**	26%	0.1%
Acidification/Eutrophication	6.72E+00	1.1%	22%	75%	3.1%
Land Use	3.78E+00	0.6%	7%	92%	0.1%
Minerals	8.36E+00	1.4%	15%	85%	0.1%
Fossil Fuels	1.89E+02	**30.6%**	40%	60%	0.0%
Total	6.17E+02	100%	-	-	-

The greatest impacts are from fossil fuels (189 Pt), carcinogens (162 Pt) and respiratory inorganics (154 Pt), which together account for 82 % of the total impact.

6.3. Data transmission networks

6.3.1. Hardware used in data transmission networks

Mobile networks

In addition to wired access networks, mobile networks also form a direct interface to mobile ICT terminals. According to Scharp, 2011) primary components of the mobile network are divided into four areas: *Base stations*, *base station controllers*, *mobile switching centres* and *operation and maintenance centres* (see Table 6). The digital signals sent by mobile devices are transmitted by radio to the base stations. The base stations then transmit the digital signals to the controller, which decides on the use of the radio channels and power control (Scharp, 2011). The mobile core is the core system that mediates the connections with the other mobile networks or fixed networks and also manages the data or base station controller. The mobile network is controlled by the OMC (operation and maintenance centre)(Scharp, 2011).

In today's digital mobile radio network (depending on the local equipment level), several generations of technology exist side by side: 2G (GSM), 3G (UMTS) and 4G (LTE), each with increasing data transmission speeds. Brodersen, 2017) assumes that the new 5G mobile communications standard will be introduced across the board from around 2020. The 5G networks are seen as the basis for the broad implementation of the Internet of Things.

Table 6:   **Selection of typical ICT and infrastructure components in the mobile network**

Base station	Base station controller	Mobile switching centre	Operation and maintenance centre
• Batteries, • Power supplies, • Inserts, • Cooling, • Fan, • Antennas, • Antenna masts, • Lightning protection, • Amplifier, • Transceiver, • Exchange Terminal, • Core base module, • Cable, • case	• Controller (BSC/RNC), • Racks, • Cooling systems, • Power and emergency power supply	• Router, • TRAU (Transcoding and Rate Adaptation Unit), • Power and emergency power supply, • UPS system, • Broadband Access Unit, • Media gateway, • Radio link networking in racks, • GPS clock, • Cooling system, • Devices for database systems and interface systems (e.g. GGSN devices [Gateway GPRS Support Nodes], SGSN devices [Serving GPRS Support Nodes])	• RGU (Radio Gateway Units), • WS-GU (Work Station Gateway Units), • OMC server, • Protocol server, • Firewall server, • Switches, • PCs, • ACP (Administrative Control Panel), • Power and emergency power supply

Source: Scharp, 2011

6.3.2. Life cycle assessment of Core Networks for Mobile Telecommunications (PINO, 2018)

The studied product system is a configuration of the Blade Server Platform (BSP) by Ericsson. The functional unit is the "use of one representatively equipped BSP 8100 for five years." The system boundary includes all life cycle stages from cradle to grave with all relevant transportation. All significant activities have been modelled and flows of resources, energy, wastes and emissions have been accounted for.
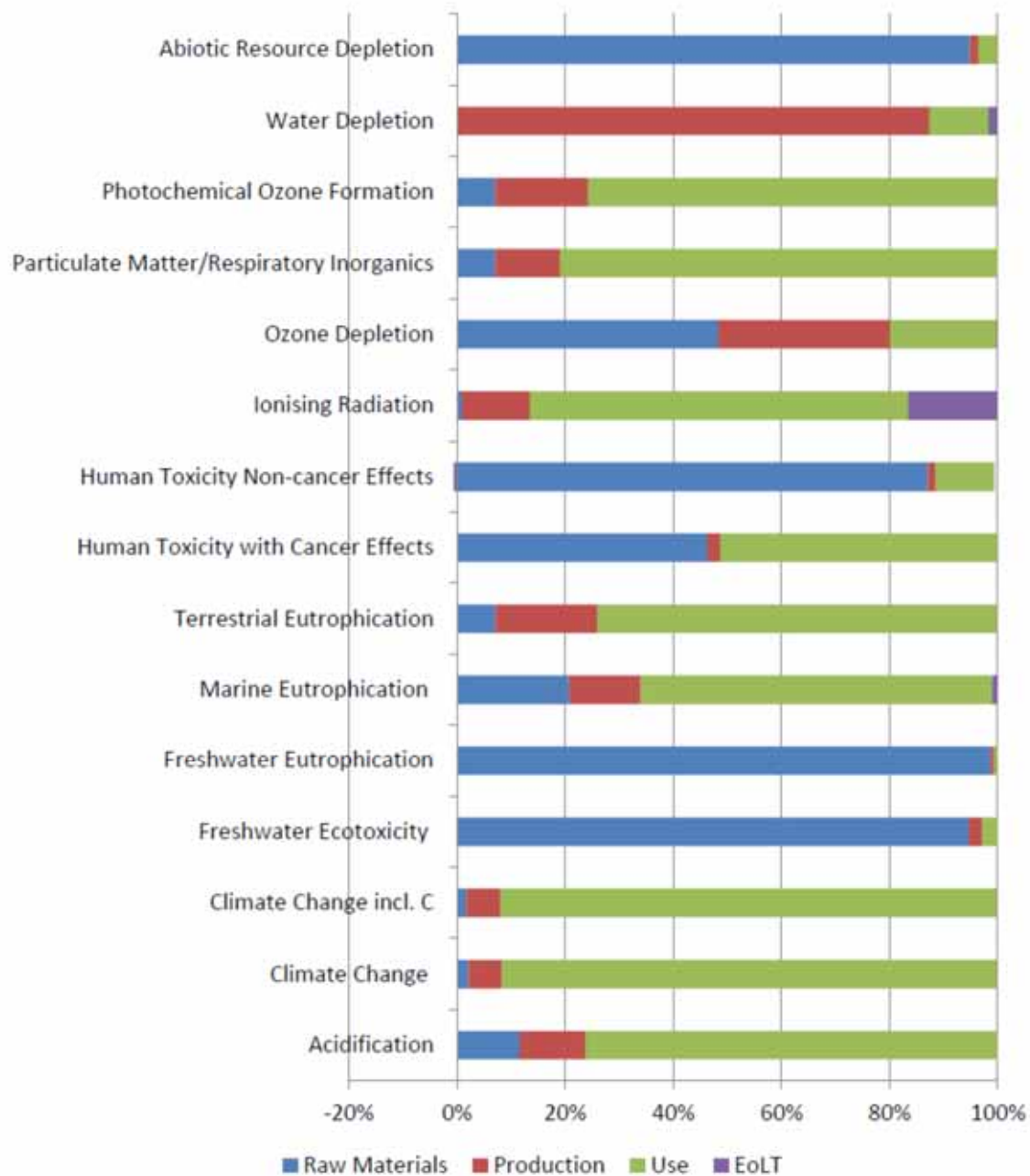

Figure 12. Impact distribution among life cycle stages

Figure 13. Contribution of different materials in the raw materials acquisition stage

6.3.3.   Life cycle assessment of fibre optic submarine cable systems (Donovan, 2009)

Figure 18: Summary of results – per 10,000Gb·km.

6.4. E-books vs. Paper books

Source		Life cycle phases	Environmental impacts of the life cycle phases
Books from an environmental perspective—Part 2: e-books as an alternative to paper books (Moberg et al., 2011)		The results of this study refer to 'one specific book bought and read by one person'. The paper book is a 360-page hardcover novel. The e-book version of the book was a 1.5 MB PDF file downloaded using an average desktop computer.	**Table 1** Life cycle impacts of an e-book read on an e-book reader and a paper book (Borggren et al. 2011) See table below.

Table 1 Life cycle impacts of an e-book read on an e-book reader and a paper book (Borggren et al. 2011)

Impact category	Unit	E-book	Paper book, European wood-free paper
Energy	MJ eq	16	56
GWP	kg CO_2 eq	0.87	1.3
ADP	kg Sb eq	0.0058	0.0085
AP	kg SO_2 eq	0.023	0.0057
EP	kg PO_4 eq	0.0011	0.0018
ODP	kg CFC-11 eq	2.2E-07	1.4E-07
HTP	kg 1,4-DB eq	0.59	0.86
FAEP	kg 1,4-DB eq	0.32	0.074
MAEP	kg 1,4-DB eq	352	526
TEP	kg 1,4-DB eq	0.0069	0.012
POCP	kg C2H4	0.0010	5.2E-04

Energy: cumulative energy demand; *GWP* global warming potential; *ADP* abiotic depletion; *AP* acidification potential; *EP* eutrophication potential; *ODP* ozone depletion potential; *HTP* human toxicity potential; *FAEP* freshwater aquatic ecotoxicity potential; *MAEP* marine aquatic ecotoxicity potential; *TEP* terrestrial ecotoxicity potential; *POCP* photochemical ozone creation potential

6.5.   Critical raw materials (CRMs)

(Mancheri, Tukker, Brown, Petavratzi, & Espinoza, 2017)

Figure 2. Shares of critical raw material use in Europe. The bar-chart above shows the shares of critical raw material use as reported in Table 2, based on the entire Annex 1.
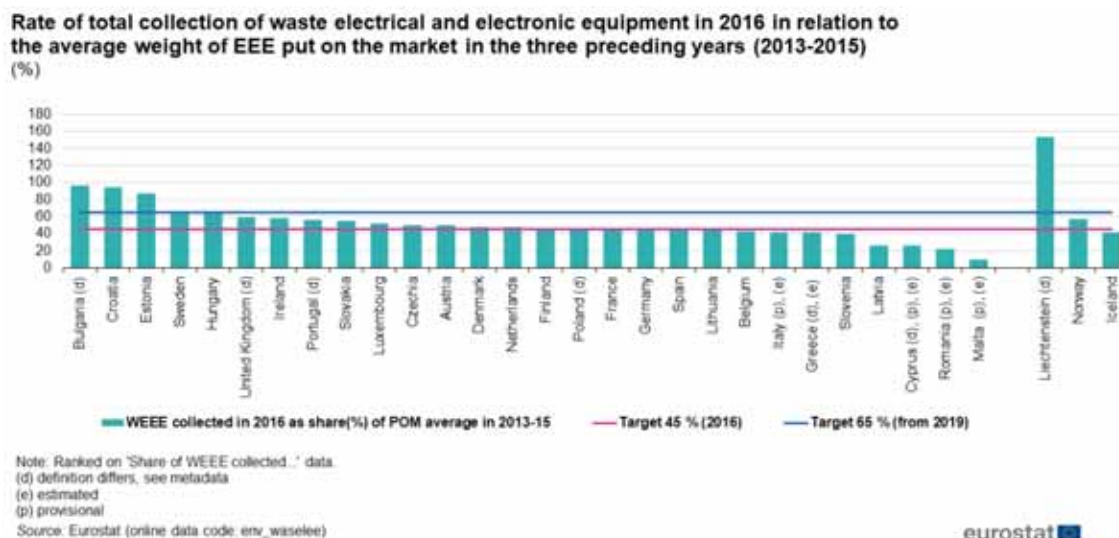
(Peck & Jansson, 2015)

Table 6: CRMs in the supply chain of the ICT + electronics sector

Sector and its production value (2011)	Application	CRM-Use (EU-14 CRM)	EU economic importance			Progress to full supply chain analysis
			Value (2012) in € million	Share of prod. >25%	Share of products in sector >0.2%	
Manufacture of electrical equipment €270,000 M	Washing machines	Nd, Dy	4,600	82%	1.7%	Yes
	Dishwasher	Nd, Dy	2,200	85%	0.8%	No*
	Cooling appliances	Nd, Dy	2,400	59%	0.9%	No*
	Air conditioners	Nd, Dy	2,800	63%	0.5%	No*
	Optical fibres	Ge	1,400	69%	0.5%	Yes
	Displays and screens	Ce, Er, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pr, Ru, Ta, Tb, Tm, Sb, Y	15,200	63%	5.6%	Yes
	LED lighting	Ce, Eu, Ga, Gd, Ho, In, La, Ta, Tb, Tm, Sb, Y	7,300	79 %	2.7%	Yes
Manufacture of computer, electronic and optical products €260,000 M	Laptops	Br, Dy, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pt, Pr, Rh, Ru, Ta, Sb, Y	2,300	8%		No
	Mobile (Smart) phones	Br, Dy, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pt, Pr, Rh, Ru, Ta, Sb, Y	3,000	10%		No
	Video cameras	Ce, Er, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pr, Ru, Ta, Tb, Tm, Sb, Y	320	17%		No
	Cameras	Ce, Er, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pr, Ru, Ta, Tb, Tm, Sb, Y	320	8%		No
	Radio sets	Ga, Ge, Nd, Pd, Pr, Ru, Ta, Sb	170	14%		No
	Loudspeakers	Nd, Dy	450	59%	0.18%	No
	MRIs	Dy, Gd, Nb, Nd, Pr, Tb	3,300	81%	1.3%	Yes

Note: Data from 2011, except sector values from 2012

6.6. E-wastes

Figure 6-15: **Collection rate for WEEE in the EU in 2016**

Source: (Eurostat, 2019b)

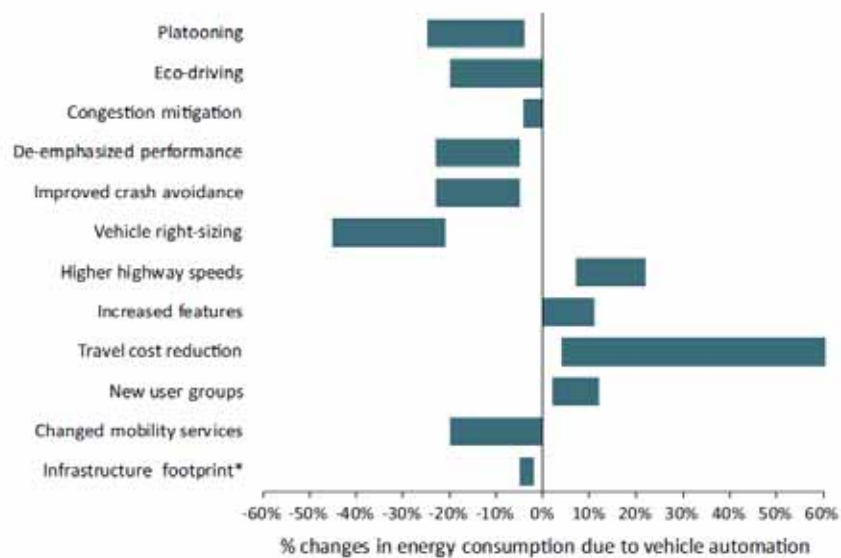## 6.7. Autonomous driving

Vehicle level energy impacts

Fig. 1. Summary of estimated ranges of operational energy impacts of vehicle automation through different mechanisms (*please see Appendix A for lifecycle infrastructure impacts, which has not been considered in later calculations due to our focus on operational impacts).
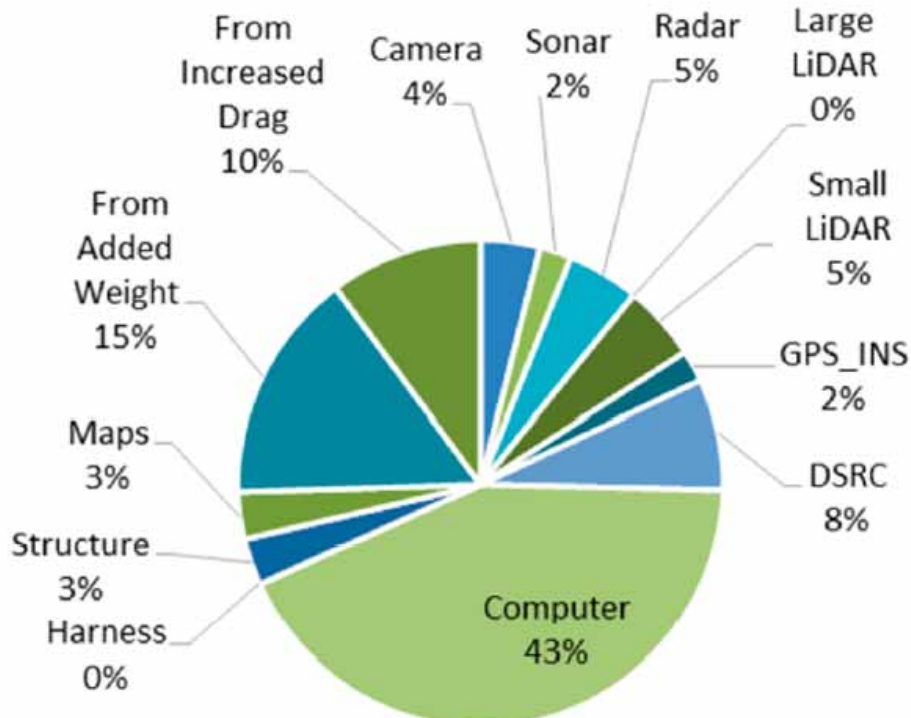
(Wadud et al., 2016)

CAV component emissions

Figure 3. Medium CAV subsystem GHG emission (1,300 kg CO_2-eq) breakdown by component.

Gawron et al. (2018) provide a comparative analysis between level 4 CAVs and non-CAVs in the US in the near to medium term. The analysis is conducted around six scenarios which result from pairing two types of vehicles (an internal combustion engine vehicle and a battery electric vehicle) with three types of connectivity and automation technology (small, big and large CAV subsystem). The figure depicts the life cycle GHG emissions of a medium CAV subsystem on a battery electric vehicle. Life cycle assessment in this study included material production, manufacturing and assembly.

Noise pollution

Table 3: Noise emissions comparison: 100% AV and current scenarios

	NOISE EMISSIONS (dBA)		
	INTRA-URBAN ROADS	HIGHWAYS	ENTIRE ROAD NETWORK
CURRENT (C)	349,275	77,016	426,291
100% AV (AV)	264,967	72,601	337,567
(AV-C)/C	−24%	−6%	−21%

Source: Patella et al. (2019)