Chapter I

Digitalization and environmental sustainability

As the evolving digital economy continues to create both opportunities and challenges for trade and sustainable development, the *Digital Economy Report 2024,* for the first time, turns its attention to the environmental implications of digitalization.

Against a backdrop of multiple environmental crises and the digital solutions leveraged to tackle them, it is increasingly important to consider how to reduce the environmental footprint of digitalization itself.

This chapter outlines the importance of exploring the implications that arise at the nexus of digitalization and environmental sustainability, and stresses the need to consider the entire life cycle of digital products.

The chapter also notes that many developing countries face a particular challenge, as they are less equipped to harness digitalization to mitigate environmental risks while also being exposed to many of the potential environmental costs associated with digitalization.

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A. The digitalization and environmental sustainability nexus

1. An area in need of more attention

Sustainable development is a vital priority for the United Nations and the global community, articulated in successive United Nations summits and in the 2030 Agenda for Sustainable Development. Sustainable development implies economic and social development that is consistent with the protection of planetary boundaries – avoiding irreversible impacts on the environment – and with intergenerational equity, the idea that today's development should not jeopardize the opportunities of future generations (World Commission on Environment and Development, 1987).[1] In this context, three issues have become critical: the consumption of natural resources, the impact of climate change (especially resulting from fossil fuel consumption) and pollution. The cost of failure in these three areas threatens all aspects of sustainability and the future health of planet Earth.

The Rio Declaration from the first Earth Summit urged all stakeholders – Governments, businesses and civil society – to recognize that "environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it" (United Nations, 1993: Principle 4). Consequently, economic development that is not environmentally sustainable will also prove to be unsustainable economically.

Recent editions of the Digital Economy Report have looked in depth at the implications of the rapid growth of electronic commerce (e-commerce) and the digital economy on inclusive and sustainable development. They covered in particular the increasing significance of new digital technologies, platformization and digital data (UNCTAD, 2019a, 2021a). These reports highlighted the accelerated pace of digitalization, leading to a continuously changing nature of the digital economy, accompanied by widening digital and data divides and important environmental implications. They emphasized that bridging these divides and developing balanced frameworks for global governance of data and digital platforms are essential for ensuring inclusive and sustainable development outcomes.

Digital transformation of the world economy and society is taking place in parallel with growing concerns related to the depletion of raw materials, water use, air quality, pollution and waste generation, which are all linked to planetary boundaries, including climate change. Managing digital transformation will greatly influence the future of humanity and the health of the planet. This report explores the interconnectedness of rapid digitalization and the urgent need to foster environmental sustainability against a backdrop of growing inequality and vulnerabilities, such as increasing socioeconomic disparity, environmental degradation and geopolitical tensions. It explores ways to achieve economic prosperity that are compatible with planetary boundaries and intergenerational equity.

The topic is timely, not to say long overdue, as policy discussions on the environment and digitalization in the context of

> Sustainable development implies economic and social development consistent with **planetary boundaries**

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[1] The concept of planetary boundaries assesses human impact on nine dimensions of the planet relative to the time of pre-industrialization. This helps to determine the stability of the Earth system, which should support the well-being of people and the planet. Recent research has shown that globally, six out of nine boundaries have already been crossed (Richardson et al., 2023).

sustainable development have evolved separately for too long. Soon after the second Earth Summit in Rio de Janeiro in 2012, critical voices emerged, suggesting that the Summit had failed to recognize the relationship between information and communications technologies (ICTs), the Internet and sustainability, all of which are crucial elements of sustainable development policy (Souter and MacLean, 2012). The 2030 Agenda for Sustainable Development, which was adopted in 2015, did not take a cross-cutting view of the role attributed to digitalization. The word "digital" is in fact mentioned only in reference to the "digital divide".

To date, shifts towards **low-carbon** and **digital technologies** were considered in parallel, yet they **are closely intertwined** within the broader economic transition

In the Paris Agreement, adopted in the same year as the 2030 Agenda, ICTs were primarily highlighted as a means to share information, knowledge and good practices among countries and stakeholders; to enable the development of low carbon energy technologies; to improve energy efficiency and support various adaptation efforts, such as early warning systems (United Nations Framework Convention on Climate Change (UNFCCC), 2016). Similarly, the 2023 outcome document of the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change recognizes the importance of digital transformation and increased access to technologies to achieve the goals set out in the Paris Agreement (UNFCCC, 2023) – without taking into consideration its direct environmental impact.

Digitalization has continued to evolve at a high speed and, from an environmental perspective, is offering new solutions but also obstacles to sustainability (box I.1). The relationship between digitalization and environmental sustainability in all its dimensions is starting to receive more attention in policy debates with a view to maximizing potential gains from digitalization, while mitigating environmental harms and facilitating sustainability. In the Bridgetown Covenant, the outcome document of the fifteenth session of the United Nations Conference on Trade and Development in 2021, member States included climate change, environmental degradation and the digital divide among the most important development questions (UNCTAD, 2021b). This evolution of the mandate is illustrative of the changing landscape of challenges faced by countries today, as well as their ever-increasing interconnectedness beyond trade, which requires a policy approach that breaks out of regulatory silos.

There are growing references to the "twin transitions", alluding to the need to enable, on the one hand, the transition to a more digital economy and, on the other, the transition to a low-carbon economy (Muench et al., 2022; UNCTAD, 2023a). To date, shifts towards low-carbon and digital technologies have been considered as parallel processes. In reality, they are closely intertwined within the broader transition of the global economy. Moving towards more environmentally sustainable economic activities needs digital tools to become more efficient and resilient in the long term. At the same time, while digitalization is a means to an end, it will need to be as environmentally sustainable as possible to avoid adding to environmental risks. Moreover, the minerals and metal inputs needed for digitalization and the expansion of renewable energy sources are largely the same, creating competing demands and significantly influencing international trade and geopolitical dynamics.

It is important to work towards ensuring that no one is left behind as the world transitions towards a more digital and environmentally sustainable future. A just, low-carbon and digital technology transition requires an integrated approach to sustainable development, which brings together social progress, environmental protection and economic success into a framework of democratic governance. This extends to the human rights context.

Box I.1
The rapidly evolving nature of digitalization

When assessing the trade and development interface between digitalization and environmental sustainability, it is essential to acknowledge the dynamic nature of digital technologies and their applications (German Advisory Council on Global Change, 2019; UNCTAD, 2019a; Global Enabling Sustainability Initiative and Deloitte, 2019). Continuing digitalization creates many new opportunities for harnessing data and digital technologies to foster trade and development and mitigate adverse development and environmental impacts. At the same time, the importance of ensuring that the digital ecosystem is as environmentally sustainable as possible increases further.

Higher speed. The increased use of the Internet and online services partly reflects the recent accelerated progress in high-speed online transmissions. This opens up opportunities for developing new digital applications, such as digital government and financial services, social media and online purchases. The digital delivery of services, both domestically and internationally, relies on greater bandwidth to support high-quality video calls or streaming. The extent to which different parts of the world can seize such opportunities still varies greatly.

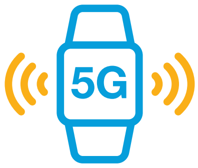
Shift to the cloud. Cloud computing is a key element of the evolving digital landscape (UNCTAD, 2013). It enables users to access scalable and flexible data storage and computing resources as well as to stream video and music. The imagery of the intangible "cloud" can be misleading; cloud computing is well anchored on the ground through hardware, networks, storage and services needed to deliver computing as a service. A defining feature of cloud storage is the transfer of large volumes of data to third party-owned data centres, often controlled by a small number of very large companies (UNCTAD, 2021a).

Platformization. Digital platforms, acting as intermediaries and infrastructure of the digital economy, are uniquely placed to capture and extract extensive data from online actions and interactions on the platforms. The expansion of digital platforms is directly linked to their capacity to collect, analyse and monetize digital data, with businesses ranging from Internet search and social media to cloud storage and e-commerce (UNCTAD, 2019a). The growing role of platforms has led to strong market concentration, dominated by a small number of global digital platforms from the United States and China (UNCTAD, 2021a). Platforms increasingly control all parts of the global data value chain, including data collection, data transmission (installing and owning cables and satellites), data storage (cloud and hyperscale data centres) and data analysis (machine learning and artificial intelligence (AI)). This pivotal role in the digital economy requires high levels of responsibility and better platform governance.

Exponential data growth and real-time sensing. The surge in Internet use, improved cloud infrastructure and the growth of global platforms have significantly boosted interconnectedness among people, machines and the planet. Data generated in real time from improved interconnectedness can help to address various development challenges, including in agriculture, energy, health, home appliances and transportation by analysing (near) real-time data. For instance, the "Internet of things" (IoT), through sensing, automation and cloud computing, is expected to expand from 13 billion connections in 2022 to over 35 billion by 2028, particularly in Asia and the Pacific, and will employ various devices (sensors, meters, etc.) to collect and transmit timely data (Global System for Mobile Communications Association (GSMA), 2023a). At the same time, this increasing connectivity spurs the demand for digital devices, digital networks and services that support the IoT. This translates into more demand for natural resources, more use of water and energy, more greenhouse gas emissions from the production and use of the devices, and more waste to handle at the end of life.

Cognitive changes. The exponential increase in data generation is amplifying the importance of big data analytics, machine learning and AI. Global corporate investment in AI (including private investment, mergers and acquisitions, public offerings, and minority stakes) surged from an estimated $15 billion in 2013 to $189 billion in 2023.[a] Concerns are mounting that powerful AI systems may be evolving too fast and too far, as labs compete to develop ever more sophisticated

Internet of things connections to grow to **35 billion** by 2028, mainly in Asia-Pacific



solutions, with unknown consequences and limited regulation.[b] New generative AI solutions – such as Bing, ChatGPT, Dall-e, Ernie, Gemini (formerly Bard), Gigachat, Midjourney, SenseChat and Tongyi Qianwen – have been met with strong interest, although long-term user numbers remain uncertain.[c] While offering new experiences and value to users, AI applications are computationally costly, energy- and equipment-intensive and generate large quantities of waste (Strubell et al., 2019).

Towards virtuality. Another new feature driven by digitalization, higher computing power and speed is increased "virtuality", seen in the growing use of augmented reality and virtual reality. Virtual reality offers a three-dimensional online environment that can be entered by using a dedicated headset connected to a computer or game console. Augmented reality shows the real world enhanced by computer-generated items, such as graphics, enhancing the real world by superimposing computer-generated information (Shen and Shirmohammadi, 2008). Such technologies can enable users to access objects and experiences regardless of their physical location. Increased adoption of virtual reality may have both positive and negative environmental impacts, depending on the inputs required and whether it replaces or complements existing polluting behaviour.

Distributed ledger technology. Blockchain and other distributed ledger technologies allow multiple parties to engage in secure transactions without any intermediary. The technology underpins cryptocurrencies and holds potential for many domains relevant to developing countries, such as digital identification, securing property rights and disbursing aid.[d] Blockchain technology, specifically cryptocurrencies that rely on proof-of-work as their mechanism to validate transactions, demands significant resources, notably electricity and processing power. The International Energy Agency (IEA) estimates blockchain energy demand to increase by nearly 50 per cent between 2022 and 2026 (IEA, 2024). How growth in adoption of distributed ledger technology is handled will have environmental implications in the future, and will depend on adoption rates and efficiency improvements.

Source: UNCTAD.

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[a] See https://aiindex.stanford.edu/report/.

[b] See https://futureoflife.org/open-letter/pause-giant-ai-experiments/.

[c] See https://www.washingtonpost.com/technology/2023/07/07/chatgpt-users-decline-future-ai-openai/.

[d] See UNCTAD (2021c) for blockchain applications in support of the Sustainable Development Goals.

United Nations General Assembly resolution 76/300, on the human right to a clean, healthy and sustainable environment, adopted in July 2022, recognizes that this right is "related to other rights and existing international law" (paragraph 2) and affirms that its promotion "requires the full implementation of the multilateral environmental agreements under the principles of international environmental law" (paragraph 3).

The digitalization and environmental sustainability nexus is to some extent reflected in the report by the United Nations Secretary-General, *Our Common Agenda*, and its proposal for a global digital compact and the Inter-Agency Task Team for the Global Accelerator on Jobs and Social Protection for Just Transitions (United Nations, 2021a). All this is expected to feature prominently in the Summit for the Future in September 2024.[2] As part of these broader efforts, new initiatives have been launched. In particular, in 2022, the Coalition for Digital Environmental Sustainability (CODES) developed an "Action Plan for a Sustainable Planet in the Digital Age" at the Stockholm+50 Conference (CODES, 2022). Nonetheless, considerably more attention

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[2] See https://www.un.org/en/common-agenda/summit-of-the-future.

needs to be given to the intersection between the rapidly evolving digital economy and environmental sustainability, and its implications for trade and development. The processes involved are all complex and difficult to regulate.

2. Comprehensive life cycle assessments

The relationship between digitalization and environmental sustainability is multifaceted and can be explored from various perspectives. There is a need to consider the extent to which digitalization complies with the "planetary guardrails" (Haum and Loose, 2015), related to the climate, nature, soils and oceans. Key environmental impacts are linked to energy use and greenhouse gas (GHG) emissions, protecting habitats, soil and water resources and reducing air pollution and waste. All of these are closely linked to the concept of the Anthropocene age which reflects how human activity has a long-lasting impact on the environment (*The Economist*, 2023).

Digital solutions are often seen as key for achieving Sustainable Development Goal 12 which relates to sustainable consumption and production. For example, they can reduce the environmental impacts of consumption and economic development through the use of smart devices and by enhancing production efficiency (World Economic Forum (WEF) and PwC, 2020; Technopolis and Institut für ökologische Wirtschaftsforschung, 2024). This raises a critical question of how to better leverage digitalization to achieve sustainability, for which improved data and measuring approaches are needed. Hence, the main focus of this report is how to make digitalization and activities related to the ICT sector more sustainable. Unless adequately addressed, their negative impacts are likely to increase as digitalization expands across all sectors.

Discussions of sustainable consumption and production have increasingly focused on the desirability of a more circular economy to reduce environmental impacts. Most goods today are produced in an essentially linear model that begins with the extraction of raw materials and passes from processing, design, manufacturing, distribution and use to disposal. As will be discussed later in this report, the digital economy still remains highly linear. A more circular digital economy would seek to reduce, reuse and recycle digital devices and infrastructure, including by extending their lifespan. This can be achieved through sharing, rental or donation; maintenance and repair; resale and redistribution; as well as remanufacturing and refurbishing. These activities can help reduce emissions caused by mineral extraction and processing, manufacturing or final disposal. Ideally, transitioning to a more circular digital economy would help achieve at least equivalent levels of economic growth and business profitability to those in the linear economy but with greater environmental sustainability.

The ability to identify significant environmental opportunities and risks arising from digitalization is hampered by a lack of agreement on what specifically constitutes the ICT sector (typically, end-user devices, network infrastructure and data centres; figure I.1) and associated services and what needs to be included when measuring environmental impact. This together with a lack of relevant data makes it challenging to develop targeted policy responses to minimize the environmental impacts of digitalization.

Digital solutions are often seen as key for achieving **Sustainable Development Goal 12** on sustainable consumption and production

To better understand these impacts, researchers use life-cycle assessments (LCAs) to evaluate the environmental impacts of a product or a service throughout its entire life span.[3] International standardization for LCA methodology, particularly ISO 14040 and ISO 14044, has laid the foundation for a formalized, robust and reliable approach to measuring environmental impacts. LCA is not limited

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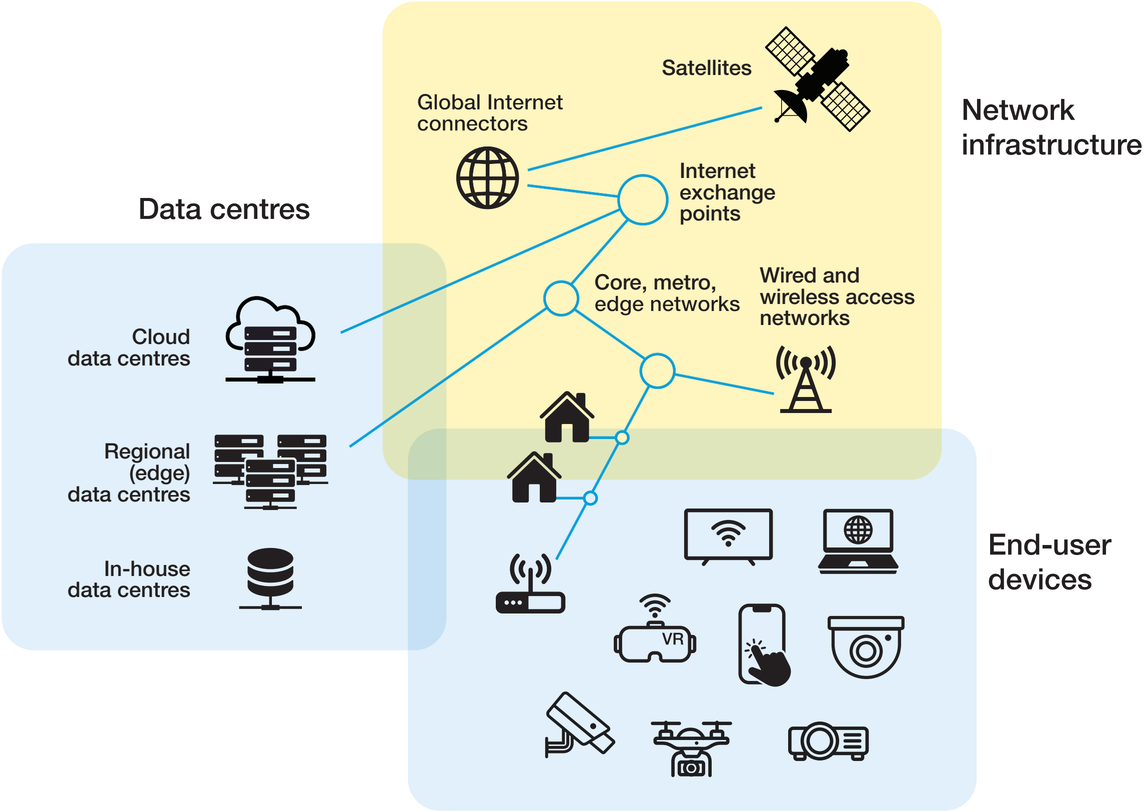
[3] LCA can be applied in different areas and sectors. Recent UNCTAD work has investigated the trade impact from manufacturing (UNCTAD, 2021d) and of plastic substitutes on the environment (UNCTAD, 2023b).

to any single environmental indicator, such as GHG emissions, but can encompass multiple criteria. For instance, the LCA-based product environmental footprint methodology developed by the Joint Research Centre of the European Union identifies 16 environmental impacts that can be assessed through LCA, with a strong link to various Sustainable Development Goals and to planetary boundaries (Joint Research Centre, European Commission et al., 2019).[4]

For digital transformation, LCA can help to identify stages with important environmental impact from end-user devices and ICT infrastructure (networks and data centres), highlight potential environmental trade-offs and assess the sustainability potential of substituting digital for non-digital technologies (Hilty and Aebischer, 2015; Itten et al., 2020).

Given data availability, LCAs in the digital economy typically focus on GHG emissions. However, this focus has limitations. Such partial analysis can lead to production processes that are environmentally suboptimal, potentially leading to

Figure I.1
The ICT sector is made up of three parts: Networks, data centres and end-user devices



Source: UNCTAD, based on Pohl and Hinterholzer (2023).

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[4] The Joint Research Centre suggests the following impact categories for a comprehensive environmental footprint of consumption in relation to Sustainable Development Goals: Goal 3 (good health and well-being): human toxicity, cancer; human toxicity, non-cancer; particulate matter; photochemical ozone formation; ionizing radiation; Goal 6 (clean water and sanitation): impacts due to water use, ecotoxicity, eutrophication; Goal 13 (climate action): climate change; impact due to resource use; Goal 14 (life below water): eutrophication marine and freshwater; ecotoxicity; Goal 15 (life on land): impact due to land use; eutrophication terrestrial; acidification; impact due to mineral and metal resource use; ozone depletion (Joint Research Centre, European Commission et al., 2019).

"greenwashing". For instance, electricity use by data centres can be reduced by upgrading servers more frequently, yet this leads to more electronic waste.

This report examines the three phases of the life cycle of end-user devices and ICT infrastructure and seeks to assess the environmental footprint of digitalization in view of the interconnected global challenges of digitalization, climate change, trade and development. Typically, within such an assessment:

- The *production phase* covers the extraction of raw materials, including minerals and metals, and their complex refining process; the assembly of different components of devices and ICT infrastructure; and their subsequent transportation for global distribution. This phase is discussed in chapter II, with a particular focus on the intensity of mineral and metals use, as well as geopolitical, trade and development considerations of their value chain.
- The *use phase* considers environmental effects generated by operating and using end-user devices, transmission networks and data centres. Particular attention is given to energy use, GHG emissions and water consumption. This is the focus of chapter III. Chapter V looks at a specific use case, namely the environmental impact of e-commerce.
- The *end-of-life phase* at the treatment of digital technologies after use, and the importance of moving towards a more circular economy, is discussed in chapter IV.

3. Direct and indirect effects

The three phases of the life cycle of digitalization have different environmental impacts. In order to assess the overall possible effects, it is important to distinguish between direct and indirect effects.[5]

a. Direct effects

Direct (or first order) effects result from digital devices and ICT infrastructure throughout their life cycle, spanning raw material extraction and processing, manufacturing, transportation for distribution, use and the end-of-life phase (ITU, 2014). The direct effects on resource use, energy use, GHG emissions and water and soil pollution constitute their "environmental footprint" (Hilty and Aebischer, 2015).

As noted above, it is important to consider other direct environmental impacts beyond GHG emissions (Mewes, 2023). For example, extraction of raw materials and handling of waste during production and end-of-life phases can have significant environmental impacts, such as soil contamination and dangers to biodiversity (table I.1). Additionally, in extraction, production and cooling of digital devices and infrastructure significant amounts of water are used throughout the life cycle (Olivié-Paul, 2022).

GHG and water footprints, while interconnected, raise different issues. In one sense they go together: the more ICT devices are built and deployed, the more energy is used, the more GHGs are emitted, and the more water is consumed. There can also be a negative correlation. For example, there is often a trade-off between the energy and the water used for cooling. Moreover, while GHG emissions are particularly relevant for climate change, the water footprint relates to freshwater scarcity (increasingly a consequence of climate change) and possible impacts on biodiversity. Unlike the global impact of GHG emissions, which can be offset in various places, negative impacts on water supply are highly location-specific. Saving water in one area cannot compensate for the local impact in another.

> Focusing only on GHG emissions can result in environmentally **suboptimal production processes,** potentially leading to "greenwashing"

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[5] For more details, see Berkhout and Hertin (2001); Bieser and Hilty (2018); Bremer et al. (2023); Coroamă et al. (2020); Hilty and Aebischer (2015); Horner et al. (2016); Pohl et al. (2019); Williams (2011).

Table I.1
Direct environmental effects of digital devices and infrastructure

Life cycle phase	Type of environmental impact	Digital device example: Smartphone
Production ▲	**Raw materials extraction.** Impacts on GHG emissions and the local environment from extracting and processing raw materials to make digital devices and infrastructure.	Materials, fossil fuels and water needed for transport and processing of raw materials for smartphone production.
	Production and transportation. Impacts on GHG emissions and water use from manufacturing and transporting digital devices and infrastructure.	Energy and water to produce and ship a smartphone to market.
Use ▲	Impacts on GHG emissions and water use from operating digital devices and infrastructure.	Energy needed to use a phone; energy and water needed to power the underlying digital infrastructure such as data centres, mobile or fixed broadband.
End-of-life ▲▼	Impacts on GHG emissions, pollution of water and soil from reuse, recycling and end-of-life treatment of digital devices and infrastructure.	*Negative:* Energy to dispose of the smartphone; impacts on water and soil from recycling and disposal of components. *Positive:* Proper reuse and recycling of devices and components reduces future negative impacts from raw material extraction.

Source: UNCTAD, adapted from Bremer et al. (2023); Pohl et al. (2019); Horner et al. (2016).

Notes: A red upward pointing arrow indicates a negative effect (increasing environmental impact); a green downward pointing arrow indicates a beneficial effect (avoided impact). A red upward pointing arrow next to a green downward pointing arrow means that the net effect can be either positive or negative.

b. Indirect and rebound effects

Indirect (or second and higher order) effects describe other environmental impacts from the use of digital technologies and services in different sectors of the economy, thus going beyond the direct footprint of the ICT sector. These can be both environmentally beneficial and harmful. Positive indirect effects that decrease emissions or other environmental harms are sometimes referred to as “enabling effects”, “abatement” or “avoided emissions” (Bremer et al., 2023).

Data-driven digital technologies can be powerful tools to mitigate negative environmental footprints from economic activities. For instance, they can enable real-time monitoring and adaptation in resource use (“optimization effect”). Substituting physical goods and travel with digital alternatives can enable decarbonization and dematerialization within some production and consumption patterns (“substitution effect”). Various studies highlight the potential for significant GHG emissions reduction through the effective use of digital technologies in different industries (box I.2).

The International Panel of Climate Change (IPCC) acknowledges the potential role of digital technologies, including sensors, IoT and AI to mitigate climate change, improve energy management, boost energy efficiency and promote the adoption of low-emission technologies while creating economic opportunities (IPCC, 2022a). Despite this, take-up of digitally enabled production processes remains limited. Industry estimates suggest that effective use of digital technologies could significantly reduce global GHG emissions (Global Enabling Sustainability Initiative and Deloitte, 2019). The same study optimistically concluded that digitally induced reductions of emissions could be nearly seven times the size of the growth in total carbon emissions from the ICT sector over the same period. Researchers also recognize the potential of supply chain and business model innovations to reduce the environmental impact of the economy (Blanco et al., 2022; Parida et al., 2019; Wang, 2017). Furthermore, machine learning offers mitigation potential by improving monitoring, energy use and optimizing transport and construction (Rolnick et al., 2023).

To date, various studies have been unable to confirm the potential for environmental gains from digitalization through anticipated

Box I.2
Opportunities for digital technologies to mitigate carbon emissions

Digital technologies can be applied across sectors with a view to reducing negative environmental effects. This box provides examples of potential opportunities including in global value chains, transportation, construction, agriculture and energy. However, in most areas, empirical evidence on actual gains realized remains limited.

Digital technologies can be used to make global value chains more environmentally sustainable by enhancing productivity, reducing environmental impacts of current production and consumption modes, introducing new, more environmentally friendly technologies and eco products, and enhancing the diffusion of business models based on circular economies (UNCTAD, 2023c). The use of advanced robotics, three-dimensional printing, sensors and wireless technologies can enable automation and the decentralization of tasks to potentially reduce emissions from transport. Digitalization can also help to better monitor environmental standards, optimize logistics, boost operational efficiency and thereby reduce carbon emissions and energy consumption. Data processing technologies, such as big data analytics, cloud computing and AI, further contribute to environmentally sustainable production processes.

The transport sector accounts for about one-quarter of global energy-related GHG emissions; varying from below 3 per cent in some least developed countries (LDCs) to more than 30 per cent in high-income countries, although growth rates in transport-related emissions have been larger in developing regions in recent years.[a] Smartphone applications can help to optimize routes and vehicle efficiency (GSMA, 2019). However, the effect of circular and shared economy initiatives as well as other aspects of digitalization is uncertain (IPCC, 2022a). Dematerialization could reduce demand for transport services, while an increase in e-commerce with priority delivery may raise demand for freight transport.

Another major contributor to emissions is the buildings and construction sector. In 2021, this sector accounted for 37 per cent of energy and process-related CO_2 emissions.[b] Digital technologies may be leveraged to reap benefits from optimizing energy use through automation in smart buildings and cities (Global Enabling Sustainability Initiative and Deloitte, 2019).

The agricultural sector accounts for 10–12 per cent of global anthropogenic (human-generated) GHG emissions. Precision agriculture, improved weather prediction and the IoT in smart water infrastructure can notably reduce CO_2 emissions and improve irrigation efficiency (Global Enabling Sustainability Initiative and Deloitte, 2019; Technopolis and Institut für ökologische Wirtschaftsforschung, 2024). At the same time, precision farming has been found to only slightly reduce pesticide use (Bovensiepen et al., 2016).

According to the IPCC (2022a), improvements in energy efficiency from digital technologies can help to reduce energy demand in all end-use sectors. This includes material input savings and increased coordination. For example, smart appliances and energy management can effectively reduce energy demand and associated GHG emissions without reducing service levels; similarly, district heat systems can use waste heat from nearby data centres.

Source: UNCTAD, based on cited sources.

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[a] See IPCC (2014, 2022a).

[b] See https://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-and-construction-hit-new-high-leaving-sector.

Empirical evidence on actual environmental gains from digitalization **remains limited**

efficiency and substitution gains from ICT (Clausen et al., 2022; Schultze et al., 2016). In fact, one review found no significant shift towards sustainable energy consumption levels in any sector after introducing digital tools (Lange et al., 2020). Similarly, the IPCC (2022a) stresses that potential gains may be reduced or counterbalanced by "rebound effects", leading to increased demand for and use of goods and services.

Rebound effects in digitalization, where initial positive impacts are offset by increased demand and use, can undermine the benefits of more efficient goods and services (Vickery, 2012; Coroamă and Mattern, 2019; Technopolis and Institut für ökologische Wirtschaftsforschung, 2024). Rebound effects can occur for the same good or service because the efficiency gains made it cheaper or more convenient to consume more of it. The money or time saved through digitally induced efficiency, however, can also lead to the increased consumption of other goods and services, two phenomena often referred to as "income effect" (Coroamă and Mattern, 2019) and "time rebound" (Binswanger, 2001), respectively.

Indirect environmental effects could be significantly greater than the direct environmental footprint from digital technologies

Digitalization is also decreasing the skill thresholds needed to perform various activities, thus likely increasing their use ("induction effect") – a phenomenon that may be particularly visible for autonomous vehicles (Coroamă and Pargman, 2020) and the use of data analysis through large language AI models, such as ChatGPT, which previously required specialized training. Additionally, an "obsolescence effect" may arise as certain unconnected products become less useful because they are not connected to newer generations of technology (Hilty and Aebischer, 2015). Even if it is possible to achieve efficiency improvements and substitute physical goods with digital services,[6] behavioural changes due to rebound effects and increased overall consumption may mitigate anticipated beneficial environmental effects (Digitalization for Sustainability, 2022).

In the case of e-commerce, for example, buying a product online can be more energy efficient under certain conditions than driving to a physical store to buy the same product, thereby reducing GHG emissions. But if the convenience of online shopping encourages increased purchasing frequency, volume and returns that are not always resold, any initial emission reductions may be diminished or counterbalanced.

Higher order indirect effects, or societal effects, stem from behavioural changes triggered by the interaction of direct and indirect effects, including rebound effects, as digital technologies are widely adopted, leading to changes in lifestyles and value systems (Hilty and Aebischer, 2015; Horner et al., 2016; Pohl et al., 2019; Williams, 2011). For example, digitally enabled teleworking reduces transport-related energy use but increases energy use in the places in which the telework is performed. It may induce secondary changes such as living locations (for instance, relocating further away from urban centres into larger houses), communication methods (more remote communication through social media) and purchasing habits (online rather than offline) (table I.2).

Challenges in measuring indirect effects often lead to these being excluded when assessing the true environmental impact of digitalization. This underlines the importance of developing better standardized frameworks to more adequately account for indirect and rebound effects to ensure that efficiencies are correctly estimated in the future (Widdicks et al., 2023).

c. Combined effects of digitalization are uncertain

Understanding the cumulative environmental effects is crucial for policymakers, researchers, the private sector and consumers to determine the net impact of

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[6] While this substitution from physical goods to digital services may appear to reduce the need for materials, this is not necessarily the case, as any digital service is enabled by devices, transmission networks and data centres.

digital technologies. The cumulative effect depends on whether ICT is considered part of the problem or solution for environmental sustainability (figure I.2): In terms of direct effects, negative impacts arise from the production, use and end-of-life phases of digital devices and infrastructure. Applying digitalization in other sectors, however, can have both positive indirect effects, limiting environmental impacts through optimization and substitution, or negative impacts by inducing more consumption or making existing devices obsolete. Furthermore, more systemic indirect effects due to behavioural or structural changes can either reduce or increase the impact on the environment.[7]

Indirect environmental effects could be significantly greater than the direct environmental footprint from using digital

Table I.2
Indirect environmental effects from the use of digital devices and infrastructure

Type of indirect effect	Potential environmental impact	Digital device example: Use of maps on a smartphone
Substitution ▲▼	Products are replaced by their digital equivalents (with lower or higher environmental impacts).	Replacement of paper-based maps and dedicated GPS-only devices.
Optimization ▼	Adoption of digital technologies leads to efficiency improvements.	Enhanced traffic and energy efficiency through real-time routing, reducing travel due to optimized routes.
Rebound ▲▼	Time and income effects. Optimization gains from digital technologies enable cost reductions (in terms of money or time), boosting the consumption of the good or service or of other goods or services.	***Same good or service:*** additional use of device compared to traditional paper-based maps, increased data consumption. ***Other good or service:*** energy consumed during time/with resources saved by more efficient travel.
Induced consumption ▲	Digital technologies induce an increase in the consumption or use of a product, process or service.	Increased travel as smartphone-enabled routing eases and aids driving in unfamiliar areas.
Transformational (societal) rebound ▲▼	Introduction of digital technologies causes macroeconomic adjustments across sectors.	Growth in location-based services and advertising; GPS technology in smartphones boosts autonomous vehicles and expands intelligent transportation system manufacturing.
Sustainable lifestyle and practices ▼	Digital technologies enable or encourage more sustainable lifestyles and practices.	Smartphone maps and routing promote sustainable travel methods, such as walking or biking in unfamiliar areas.
Systemic transformation and structural economic change ▲▼	Digital technologies generate systemic society-wide transformations.	Digital maps change transportation consumption boosting demand for car-sharing and ride-sharing such as Uber; long-term, GPS-enabled autonomous vehicles shift living and working location choices. Improved navigation efficiency may enable more private vehicle use over public transportation, and delay structural changes needed to reduce carbon emissions and traffic congestion.

Source: UNCTAD, adapted from Bremer et al. (2023); Pohl et al. (2019); Horner et al. (2016).

Notes: A red upward pointing arrow indicates a negative effect (increasing environmental impact); a green downward pointing arrow indicates a beneficial effect (avoided impact). A red upward pointing arrow next to a green downward pointing one means that the net effect can be either positive or negative.

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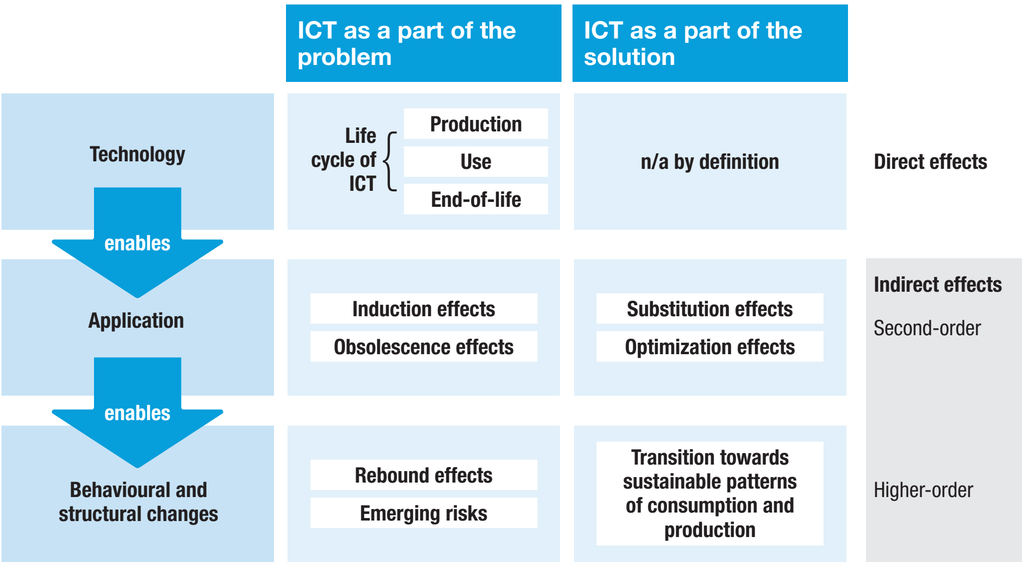
[7] For more information, see IEA (2017); Bergmark et al. (2020); Coroamă et al. (2020); Global Enabling Sustainability Initiative (2020); The Royal Society (2020); Bieser et al. (2023); Bremer et al. (2023); Kaack et al. (2022); Technopolis and Institut für ökologische Wirtschaftsforschung (2024).

technologies.[8] For example, direct life cycle GHG emissions ("ICT footprint" in the figure) from teleworking using a computer, data transmission networks and data centres are likely to be less than 0.4 kg carbon dioxide equivalent emissions (CO_2e)[9] when a global average electricity grid mix is used.[10] This is roughly one tenth of the emissions arising from a 20 kilometre commute to work by car.[11] Hence, using digital technologies can lead to a positive indirect effect of avoiding a commute equivalent to 4 kg of CO_2e emissions ("applications of digital technology" in the figure). Longer-term behavioural and lifestyle changes ("structural effects and economic changes" and "systemic and societal-level effects and transformation" in the figure) can have larger, albeit uncertain, positive or negative indirect impacts, depending on how policy, technology and behaviour interact and evolve. However, to date, options to comprehensively measure indirect effects remain limited, though the International Telecommunication Union (ITU, 2022) has put forward a first recommendation (L.1480) on assessing the impact of ICT on GHG emissions in other sectors.

This report thus focuses primarily on the direct environmental effects of digital devices and infrastructure, encompassing the entire life cycle. Chapter V is an exception as it looks at a specific use case of digitalization,

Figure I.2
Digitalization as a problem or a solution for promoting environmental sustainability



Source: UNCTAD, based on Hilty and Aebischer (2015).

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[8] Indirect effects are also considered when categorizing scope 1, scope 2 and scope 3 emissions. Scope 1 covers direct GHG emissions owned or controlled by a producing entity; scope 2 covers indirect GHG emissions from electricity, heating or cooling used; and scope 3 are indirect emissions linked to all other indirect effects, e.g., from mining, production, inputs, transportation and end-of-life treatment (Allwood et al., 2014). Scope 3 is understood to have the largest emissions impact, and is the most complex to measure.

[9] CO_2 equivalent emissions serve as a proxy measure that allows emissions from various GHGs to be compared in terms of their potential for global warming. For this, an amount of a GHG is converted to an amount of CO_2 which has the same global warming potential as the original GHG (Eurostat, 2023; IPCC, 2023).

[10] Based on an eight-hour workday using a laptop (30W), 24-inch LED monitor (30W), 50 per cent allocation of a router (5W), fixed access and core networks (<5W), data centre services (<2W) and associated embodied emissions.

[11] Based on the life cycle GHG emissions for an average new vehicle in 2017 including raw material extraction, production, use (fuels included), based on IEA (2019).

namely e-commerce. E-commerce has both positive and negative direct and potential indirect environmental impacts, and these can be influenced by policymaking.

Regardless of indirect environmental impacts of digitalization, including societal effects, minimizing the direct footprint of the digital economy remains essential.

B. Assessing the overall direct environmental footprint of digitalization

As noted above, accurately assessing the direct environmental impacts of the ICT sector is difficult. Rapid technological and economic changes further complicate measurement, with numerous factors affecting environmental impacts, such as resource depletion, GHG emissions, water consumption, biodiversity and noise. Taking a broad, multicriteria perspective on the environmental footprint, available research suggests that the production phase has the greatest impact. This is due to mineral and metal depletion, the volume of GHG emissions generated and water-related impacts (Duporte et al., 2022). During the use phase, GHG emissions and water consumption are the main concerns (Agence de la transition écologique (Ademe) and Autorité de régulation des communications électroniques, des postes et de la distribution de la presse (Arcep), 2022; Bordage, 2019; Freitag et al., 2021).

1. Measurement challenges

Comprehensive assessments of the environmental footprint of digitalization are scarce, due to five factors. First, there is a lack of timely, comparable and accessible data regarding the energy and environmental impacts of the ICT sector, with no harmonized reporting standards. Additionally, there is often limited disclosure of impacts such as the effect on local watersheds (Koomey and Masanet, 2021; Pasek et al., 2023). Data scarcity leads to analytical studies having to rely on hugely varying and potentially outdated data sources, given the speed of change in the digital economy (Freitag et al., 2021). There is also no standardized approach for converting ICT energy use in kilowatts per hour (kW/h) into tons of GHGs emitted, as these depend on the technologies and source of energy used. Consequently, estimates vary significantly between countries and sectors (Chiarella et al., 2022). Nevertheless, as energy use and GHG emissions data are still the most frequently available, much research has focused on these areas.

Second, the scope of the ICT sector varies between studies. For instance, televisions and consumer electronics are included as part of the sector in some studies (Andrae and Edler, 2015; Malmodin and Lundén, 2018), but not in others (Belkhir and Elmeligi, 2018). More importantly, new applications, such as AI, blockchain and the IoT, are often not yet considered, likely underestimating the overall sectoral impact (Freitag et al., 2021). The increasing integration of digital technologies into other sectors further complicates the ability to set clear boundaries when assessing the sector's environmental footprint.

Third, studies also vary in the definition of the life-cycle stages of the ICT sector. ITU has introduced standards on conducting life-cycle analyses of the ICT sector (such as the ITU-T L.1410 and L.1450), but they have not been consistently followed by researchers, with some exceptions (ITU, 2020; Malmodin and Lundén, 2018; Malmodin et al., 2024).

> **Comprehensive assessments** of the environmental footprint of digitalization **are scarce**

Fourth, even those studies that look at similar life-cycle stages have reached different conclusions due to varying assumptions and models adopted to estimate the environmental impact. For example, variations include anticipated growth of the ICT sector, its correlation with energy consumption (reflecting assumptions on efficiency gains in computing power) and the extent to which ICT will contribute to emissions reductions in other sectors (Freitag et al., 2021).

Moreover, existing literature mainly looks at the global environmental impact, overlooking location-specific effects.[12] As such, studies neglect consequences that are highly region- or country-specific, such as mining for raw materials, which primarily affects developing countries, and water use, both of which have profound environmental implications that extend beyond the generalized impact of global GHG emissions.

The need to improve availability of quality data and common measurement methodologies must not be an excuse for policy inaction

Such methodological challenges have led to considerable variation in estimates of the ICT sector's environmental impact (Koomey and Masanet, 2021) and of its subsectors. For example, to calculate network energy intensity (i.e. the energy needed per amount of data sent across the Internet), existing estimates differed by a factor of 20,000 a decade ago (Coroamă and Hilty, 2014). Disagreement also persists on whether overall impact is overestimated – due to outdated data, excessive growth assumptions and projections that extrapolate too far into the future (Koomey and Masanet, 2021) – or underestimated, because these estimates exclude relevant technologies and trends (Freitag et al., 2021). As it is vital to estimate and analyse impacts to inform policy actions, the need to improve the availability of quality data must not be an excuse for inaction. However, more work is needed to develop commonly accepted measurement methodologies that can help in policymaking.

2. Estimates of the carbon footprint of the ICT sector

As noted, energy use and GHG emissions are the most researched aspects of the ICT sector's environmental footprint. The energy use of devices, data centres and networks has been estimated to account for approximately 6 to 12 per cent of global electricity use (about 1 to 2 per cent of global energy use), depending on use patterns, number of devices and associated energy consumption (IPCC, 2022a). Still, since 2015, studies assessing total GHG emissions of the ICT sector have arrived at vastly different results (table I.3). Estimates of life cycle emissions for 2015 range from 0.73 to 1.1 metric gigatons of CO_2 equivalent ($GtCO_2e$) emissions (1.4–2.2 per cent of global GHG emissions), and for 2020 from 0.69 to 1.6 $GtCO_2e$ emissions (1.5–3.2 per cent of global GHG emissions). Differences are even greater if the most optimistic and most pessimistic estimates are also considered.

These differences become more pronounced in longer-term projections. For example, Andrae and Edler (2015) estimate in their "best case" scenario that the ICT sector (excluding televisions and associated devices) could emit 1.3 $GtCO_2e$ in 2030 but as much as 19 $GtCO_2e$ in the "worst case" scenario – representing a 15-fold difference.

Many of the studies in table I.3 are widely cited, but this does not mean they are necessarily robust to changes in model assumptions and underlying data. For example, Andrae and Edler (2015) and Belkhir and Elmeligi (2018) largely rely on relatively simplistic extrapolations.[13] More

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[12] A recent study by ITU and the World Bank provides estimates in country case studies, highlighting the variation in data collection approaches for climate data in the ICT sector (Ayers et al., 2023).

[13] The latter study extrapolates GHG emissions from data centres using a study from 2009–2010 (Vereecken et al., 2010), applying an assumed compound annual growth rate from an industry report, implicitly disregarding underlying drivers of data centre demand growth and efficiency improvements.

recently, Andrae (2019a, 2020) significantly revised downwards earlier estimates from Andrae and Edler (2015) – in some cases by more than half for 2020 – indicating the limited usefulness of extrapolations beyond a few years.[14] The rapidly evolving nature of digital technologies makes long-term projections highly uncertain and further complicates defining the scope of the ICT sector's footprint as more objects become connected to the Internet.[15]

The methodological approach of Malmodin and Lundén (2018) involves a more comprehensive combination of bottom-up data (e.g. shipment data of devices, servers, other hardware), detailed life-cycle analyses, reported operator data and benchmarking with other high-quality studies that have focused on specific ICT subsectors (e.g. data centres). However, their methodology has also been criticized in Freitag et al. (2021) for lacking transparency and replicability. ITU (2020), largely based on Malmodin and Lundén (2018), and Malmodin et al. (2024) provide greater transparency regarding the methodologies and assumptions applied.

In the case of energy use and associated GHG emissions, different studies have estimated that 56–80 per cent of the ICT sector's total life cycle emissions come from the use phase (Andrae, 2020; Bordage, 2019; Malmodin and Lundén, 2018; Malmodin et al., 2024; Masanet et al., 2013; Whitehead et al., 2015). However, the relative shares of each phase differ greatly between data centres, data transmission networks and connected devices. The production phase is the most important for devices, especially for highly energy-efficient battery-powered devices (such as smartphones and tablets). Around 80 per cent of the GHG impacts of a smartphone's life cycle can be attributed to the production phase (Ercan et al., 2016; Lhotellier et al., 2018; Clément et al., 2020; Ademe and Arcep, 2022). Meanwhile, the use phase dominates the GHG impact of life cycles of data centres and networks due to their high energy intensity and constant operation (Andrae, 2020; Bordage, 2019; Malmodin and Lundén, 2018; Malmodin et al., 2024; Masanet et al., 2013; Whitehead et al., 2015).

3. Environmental footprint beyond emissions and energy

Direct environmental impacts of digital technologies also concern, among other impacts, raw material depletion, water consumption and quality, local air quality, soil, biodiversity and waste. The importance of these impacts differs across ICT products and the different life cycle stages. For example, material use, water and air quality and biodiversity impacts are particularly important in the production phase, while waste generation is most important, but not exclusively, in the end-of-life phase. In studies applying comprehensive, multicriteria analyses, the production phase emerges as the life-cycle stage that has the most adverse effects on the environment (Ademe and Arcep, 2022; Bordage, 2019).

The production phase emerges as the stage with **the most adverse environmental effects**

Biodiversity and livelihoods can be severely affected by the water use of digital technologies and infrastructure,[16]

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[14] The Shift Project's 2019 report, largely based on modelling by Andrae and Edler (2015), has been widely cited despite similar methodological issues. A review of data centre energy estimates by Mytton and Ashtine (2022) also noted its methodological problems.

[15] Some studies, such as Andrae and Edler (2015), used exponential growth rates to arrive at alarming figures that have been widely quoted in the media (Koomey and Masanet, 2021). They projected that the ICT sector could end up using half of the world's electricity consumption by 2030, while accounting for nearly one quarter of global GHG emissions. This, however, is an improbable scenario given the time required to build ICT and energy infrastructure and the high costs of energy.

[16] Low-income countries have recently experienced a loss in their biodiversity likely linked to important land degradation from activities such as mining of critical raw materials in resource-rich countries, while other countries have gained in per capita terms through accelerated conservation efforts (IPBES, 2019; Balvanera et al., 2019).

Table I.3
Overview of selected recent assessments of global greenhouse gas emissions

Institution and studies	Approach	Strengths	Limitations	Greenhouse gas emissions estimates (Per year)
Ericsson; Telia (Malmodin et al., 2024; Malmodin and Lundén, 2018)	Hybrid approach combining bottom-up data (e.g. shipments of devices, servers, other hardware), previous life cycle analyses, top-down reported data from data centre operators, network operators, and major equipment manufacturers, and benchmarking to other studies such IEA (2017).	Strives to follow the ITU-T L.1450 standard. The analysis is based on rich and recent sources of bottom-up data, use of reported operator data, and benchmarking to established studies implies high degree of analytical quality.	Main limitation is the lack of transparency regarding some datasets (e.g., operator energy consumption). However, some of this data can be accessed through companies' sustainability reports or other disclosures. The 2023 study frequently refers to supplementary material that is not easily accessible.	0.73 $GtCO_2e$ in 2015 0.76 $GtCO_2e$ in 2020 1.4% of global emissions
GreenIT.fr (Bordage, 2019)	For data centres, based on estimated number of servers in operation and LCA of three data centres from previous studies. For networks, based on data traffic and access types. For devices, bottom-up estimates, based on sales figures and average lifespans.	Reports environmental impacts across multiple impact areas, including energy consumption, GHG emissions, water consumption and abiotic resource depletion.	While the scope appears to be comprehensive, the lack of detail regarding assumptions and data sources makes it difficult to evaluate its quality. The scope of the study includes televisions and peripherals and is limited to manufacturing and use.	1.4 $GtCO_2e$ in 2019 3.8% of global emissions (56% from use, 44% from manufacturing)
Huawei (Andrae, 2019a, 2019b, 2020, 2017; Andrae and Edler, 2015)	Data centres and networks estimated based on Internet Protocol traffic estimates from Cisco with varying assumptions for energy intensity per unit of Internet Protocol traffic (for data centres, fixed access networks, and mobile access networks). Devices estimated based on bottom-up data combining number of devices per year, expected electricity use, and expected lifespans. Projects three scenarios (best, expected, worst) to 2030 with differing assumptions for electricity use, pace of energy efficiency improvements, device lifespans, and share of embodied emissions.	High degree of transparency, with a supplementary model disclosing assumptions and detailed results.	Assumptions are transparent but lack sources or explanations, making some appear arbitrary, such as energy intensity assumptions, efficiency improvement factors and assumed lifespan of devices. The 2015 study's long-term projections, especially the "worst case" scenario, have been widely cited, suggesting that the ICT sector would consume half of the world's electricity and generate a quarter of global GHG emissions. These implausible long-term projections have created confusion regarding the actual climate impacts of digital technologies and have since been amended.	Andrae (2020) "Expected" scenario: 0.66 $GtCO_2e$ in 2015 0.69 $GtCO_2e$ in 2020 0.71 $GtCO_2e$ in 2025 1.3 $GtCO_2e$ in 2030 Andrae and Edler (2015) "Expected" scenario: 0.94 $GtCO_2e$ in 2015 1.3 $GtCO_2e$ in 2020 2.1 $GtCO_2e$ in 2025 4.4 $GtCO_2e$ in 2030
International Telecommunication Union (ITU, 2020)	Similar approach and data sources as Malmodin and Lundén (2018) aligned with ITU-T L.1450 and linked to the 1.5°C objective of the Paris Agreement.	Similar to Malmodin and Lundén (2018), strives to follow the ITU-T L.1450 standard. Provides significant methodological detail in an annex.	Projections aim to align ICT sector emissions with the 1.5°C objective which adds additional uncertainty to the estimations, as outlined in the section "Risks".	0.74 $GtCO_2e$ in 2015 0.69 $GtCO_2e$ in 2020 0.53 $GtCO_2e$ in 2025 0.39 $GtCO_2e$ in 2030
ITU; World Bank (Ayers et al., 2023)	Bottom-up extrapolation based on environmental, social and governance reports from the largest telecommunications operators, data centre operators, equipment manufacturing and use.	Clear on which life cycle stages are included and which are not (no transport, end-of-life). Takes into account variations in electricity mix into its global aggregates.	Due to data limitations, estimates of data centres are limited to relatively efficient co-location data centres, cloud computing and social media storage, leading to a lower bound estimation of the impact from this section of the ICT sector. Not all life-cycle phases included.	0.57 $GtCO_2e$ in 2022 1.7% of global emissions (Telecom operators: 0.133 $GtCO_2e$ Co-location data centres: 0.042 $GtCO_2e$ Cloud and content data centres: 0.032 $GtCO_2e$ PC manufacturing: 0.065 $GtCO_2e$; PC use: 0.187 $GtCO_2e$ Smartphone manufacturing: 0.057 $GtCO_2e$; their use: 0.018 $GtCO_2e$; Network manufacturing: 0.033 $GtCO_2e$)

Institution and studies	Approach	Strengths	Limitations	Greenhouse gas emissions estimates (Per year)
Lancaster University (Freitag et al., 2021)	Detailed review of recent studies estimating the global GHG footprint of the ICT sector, focusing on Malmodin and Lundén (2018), Andrae and Edler (2015) and Belkhir and Elmeligi (2018).	Provides a useful comparative review of the three major global ICT GHG studies published since 2015, comparing scopes, methods, and assumptions.	Includes televisions and related peripherals in top-level results, contrary to the ITU recommendation to categorize them under the entertainment and media sector. Lacks critical assessment of the reviewed studies, implying equal validity of all three studies despite varying levels of quality.	1.2–2.2 $GtCO_2e$ in 2020 (including televisions) 2.1–3.9% of global emissions 0.8–1.7 $GtCO_2e$ in 2020 (excluding televisions)
McMaster University (Belkhir and Elmeligi, 2018)	Data centres and networks are extrapolations of trends from previous studies and industry reports on demand growth (e.g. Vereecken et al. (2010) for data centres and Van Heddeghem et al. (2014), Lambert et al. (2012) and Pickavet et al. (2008) for networks). Devices are estimated using a bottom-up approach based on published academic and industry estimates for units and life cycle impacts. Projections are based on linear extrapolation of carbon emissions for data centres and networks based on trends from around 2008 to 2012.	The main strength of this analysis is the bottom-up analysis of devices.	Emissions from data centres and networks ignore their embodied carbon (emissions from materials and manufacturing). The linear extrapolation of GHG emission trends for data centres and networks to 2040 does not take account of potential efficiency improvements and underlying drivers of demand growth, and likely overestimates future emissions if the historical trend is taken from a period of rapid growth. Three years after publication, the author notes in Freitag et al. (2021) that: "regarding data centres, Belkhir himself noted that his projection of 495 $MtCO_2e$ for data centres in 2020 is overestimated".	0.87 $GtCO_2e$ in 2015 1.1–1.3 $GtCO_2e$ in 2020 1.4–1.8 $GtCO_2e$ in 2025 7 $GtCO_2e$ in 2040
Schneider Electric Sustainability Research Institute (Petit et al., 2021)	Bottom-up estimation of number of devices and infrastructure. Given varying estimates of the existing stock of devices, the study focuses on growth rates rather than quantities.	As a post-COVID-19 study, this takes into account recent changes in the development of the ICT sector.	Study is not peer-reviewed. No information on distribution of emissions from manufacturing and embodied emissions, limited information on definition of embodied emissions. Does not consider end-of-life and transportation. Projections for 2030 are based on the sector's aim to reduce emissions by 50 per cent by that point.	0.96 $GtCO_2e$ in 2020 2.8% of global emissions; (27% from manufacturing) 0.89–1.2 $GtCO_2e$ in 2030 Or 2.6–3.4% of global emissions (with manufacturing accounting for 32% of 0.89 and 24% of 1.2 $GtCO_2e$)
The Shift Project (The Shift Project, 2019a, 2021)	Uses model from Andrae and Edler (2015) (same scope of technologies and life-cycle stages) with the institution's assumptions on data traffic and number of devices and introduces new scenarios. Projects four scenarios: expected updated; sobriety; higher growth higher energy efficiency; superior growth peaked energy efficiency.	Given that this analysis is based on the model developed by Andrae and Edler (2015), the same strengths outlined in Huawei also apply here.	Given that this analysis is based on the model developed by Andrae and Edler (2015), the same weaknesses outlined in Huawei also apply here.	1.8 $GtCO_2e$ in 2015 2019 study, "Expected updated": 1.6 $GtCO_2e$ in 2020 2.7 $GtCO_2e$ in 2025 2021 study "Expected updated": 1.4 $GtCO_2e$ in 2020 1.8 $GtCO_2e$ in 2025

Source: UNCTAD, based on Andrae (2017, 2019a, 2019b, 2020); Andrae and Edler (2015); Belkhir and Elmeligi (2018); Bordage (2019); Freitag et al. (2021); ITU (2020); Malmodin et al. (2024); Malmodin and Lundén (2018); Petit et al. (2021); The Shift Project (2019a, 2021).

Notes: Refer to Freitag et al. (2021) for a detailed review and critique of most of the studies presented in this table. All GHG estimates are for the ICT sector only and exclude televisions unless specified. Emissions excluding televisions in Freitag et al. (2021) were estimated by UNCTAD based on the primary data from the three studies reviewed by Freitag et al. GHG estimates for Andrae and The Shift Project have been recalculated using their publicly available spreadsheet models to exclude televisions and associated peripherals (set-top boxes, DVD players, etc.). The Shift Project did not publish their 2021 model, so those figures are estimated based on the relative share of televisions from their 2018 model (2019 study). ITU (2020) projections for 2020–2030 are based on decarbonization efforts of the electricity supply in line with the 1.5°C trajectory.

potentially threatening the balance of ecosystems (Mewes, 2023). Estimates of how much water is required to produce digital devices vary widely. For instance, for smartphones, estimates range from 100 to 13,000 litres of water per device depending on the underlying assumptions and modelling approaches (Friends of the Earth, 2015; Leahy, 2014; Merchant, 2017).

Beyond production, which includes mining, using ICTs requires large amounts of water for data centre cooling, with very limited water being reused (Monserrate, 2022). This effect is aggravated by the fact that many production hubs and data centres are located in areas under water stress (Jones, 2018; Farfan and Lohrmann, 2023; *The Guardian*, 2023).[17] Similarly, the end-of-life phase is linked to significant impacts on the water supply in some locations. Groundwater contamination from leaching, dumping and digitalization-related processing activities can adversely affect biodiversity and human health.

Adverse effects of device production and digitalization-related waste often **impact regions far from where the devices are mainly used**

Mining for digital technologies comes with a significant environmental footprint. The specific impact depends on the local ecosystem as well as on the mining technology used. As the overwhelming majority of earth and rock removed in mining is eventually discarded, this can lead to high levels of toxicity from mining by-products and soil damage (Dwivedi et al., 2022; The Shift Project, 2019a). Moreover, mining can be very water-intensive, often leading to competition for water between mining operations, agriculture and direct consumption (UNCTAD, 2020).

Most studies position themselves as global analyses. However, the environmental impacts can have varying effects at local, regional and global levels. For example, air pollutants have adverse impacts on local air quality and human health, whereas the impacts of climate change from GHG emissions are global.

Moreover, digital technologies can also affect other dimensions of sustainability, notably gender equity and human rights. It is important to ensure that the human rights impacts and the unique challenges confronting women and girls, youth, indigenous peoples and other groups at risk of being left behind, are not overlooked. For instance, nearly 12.9 million women and many children work in the informal sector managing waste from digitalization, which makes them significantly more likely to be exposed to potential negative consequences for their health (Parvez et al., 2021; World Health Organization (WHO), 2021a).

From an equity perspective and in view of today's highly complex global supply chains, it is important to recognize that adverse impacts associated with device production and waste generation at end-of-life often affect regions located far away from where the devices are predominately used. While developed countries remain the primary users of many aspects of the ICT sector, considerable harm may accrue in regions that currently use and benefit less from digitalization. However, to date, research specific to the environmental impact of the digital economy on developing countries remains scarce.[18] This results in policy discussions being skewed towards the concerns of high-income countries that are better positioned to harness the benefits of digital technologies.

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[17] Overall, the share of global population affected by water stress is rising. In 2018, about 10 per cent of the global population – more than 733 million people – lived in countries with high water stress (Food and Agriculture Organization (FAO) and United Nations Water, 2021), with projections predicting a 40 per cent shortfall of freshwater by 2030 (Global Commission on the Economics of Water, 2023), triggered by human activity (Yao et al., 2023) and leading to increasing tensions within and between countries and the displacement of affected populations.

[18] This mirrors the scarcity in environmental research, especially on climate impacts, for low-income countries. In these countries, 23 per cent of the population live in areas that remain uncovered by research on local climate impacts, compared to only 3 per cent in high-income countries (Callaghan et al., 2021). This is also the case in dimensions such as water access.

4. Environmental sustainability in the context of digital and development divides

In the digitalization and environmental sustainability nexus, the distribution of environmental impact is linked to countries' geographical location and socioeconomic status. The disparities in income, wealth, digital access and use, and development have been further exacerbated by the COVID-19 pandemic and recent geopolitical tensions. This underscores the need for nuanced policy responses to address these divides.

Developed countries have generated the bulk of emissions while propelling their economic development, with Europe and North America responsible for approximately 40 per cent of anthropogenic CO_2 emissions since 1850 (Chancel et al., 2023; Diffenbaugh and Burke, 2019; IPCC, 2023). The Paris Agreement of 2015 (UNFCCC, 2016) acknowledged this historical fact and placed a greater responsibility on these countries for future GHG reduction efforts.

However, the inequality in emissions transcends national borders, reflecting a stark divide in consumption patterns across different income groups. The wealthiest 10 per cent of the population in every region emit significantly more than the global average (Chancel et al., 2023), associated with overconsumption by wealthy individuals.

While global Internet use surged from 35 to 67 per cent between 2013 and 2023, the digital divide remains a significant barrier to socioeconomic development in an increasingly digitalized world.[19] Despite advances in ICT infrastructure, disparities in access and use persist, particularly between high-income and low-income countries, including LDCs. These divides encompass not just the number of devices and Internet connections per capita, but also the affordability of digital services, the quality of infrastructure and the digital literacy of individuals and businesses. The disparities in Internet use intensity – the data divide – are driven by varying levels of development and highlight missed chances for leveraging digitalization for the Sustainable Development Goals (UNCTAD, 2021a). Particularly pronounced in LDCs and remote Small Island Developing States, the digital divide is exacerbated by factors such as socioeconomic status, location, age and gender.

Overall, the divides in terms of development, environment and digitalization are interrelated, emphasizing the need to address them holistically. Developing regions are primary providers of many of the raw materials required for digitalization, with extractive processes that can lead to land degradation. Furthermore, developing countries contribute to the part of global value chains where value addition is relatively small and therefore have limited scope for accelerated economic growth. At the end of the life cycle of digital technologies, developing countries are the destination for an important share of waste from global digitalization, which opens up another dimension of the digital divide. As noted above, these countries are also more affected by climate change, which directly impacts their options for socioeconomic development. Moreover, low-income countries are less able to afford and harness digital tools to mitigate various environmental impacts. Thus, the opportunities for technologies to address these environmental concerns in the short term are possibly overstated.

Divides in development, environmental responsibility and impact, and digitalization are interrelated and need to be addressed holistically

By contrast, consumption patterns in developed countries and of wealthy individuals everywhere are increasingly marked by overconsumption. This is both in terms of digitalization, for instance measured by the number of devices per person, and the environment, measured in terms of the multiples of CO_2 emissions per capita. Additionally, this group causes

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[19] ITU (2023). Key ICT indicators, available at https://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx.

environmental externalities in developing countries due to the production of devices used in developed countries.

These factors point to the need for developed countries and digitally advanced economies to assume particular responsibility for ensuring a transition towards a more environmentally sustainable digital economy that can generate inclusive development. At the same time, efforts are needed to strengthen the ability of many developing countries to better harness opportunities from digitalization in an environmentally sustainable manner.

C. Conclusions and roadmap for the rest of the report

Amid environmental crises and digitalization, **developing countries face a double bind…**

…they are **most vulnerable** to digitalization's negative impacts **yet least equipped to use digital tools for mitigation**

This chapter has highlighted the need to give more attention to the interlinkages between the rapidly evolving digital economy and environmental sustainability, and how they relate to trade and development. The expanding scale and changing nature of digitalization have environmental implications at all three stages of the life cycle of digital devices and infrastructure. Depending on their positioning, countries will encounter different opportunities and challenges at each stage. There is a need to improve the understanding of how countries at different levels of development are affected and how this affects global trade dynamics.

The relationship between digitalization and sustainability is bidirectional. Against a backdrop of multiple environmental crises and the importance of leveraging digital solutions for economic development and to tackle these challenges, it is increasingly important to consider how to reduce the environmental footprint of digitalization. However, this comes with a double bind for developing countries, in particular LDCs. On the one hand, they are often the most vulnerable to potential negative environmental and social effects arising from digitalization, relating to raw material extraction, carbon emissions, water consumption and waste from digitalization. On the other hand, they are less equipped to harness digital technologies to mitigate risks from climate change and other environmental crises.

Trade and technological change are integral parts of the significant transformation process that the world is undergoing. This is underscored by the urgent need to reduce carbon emissions, address widening economic inequalities and enable economic diversification and structural transformation. In the context of the interrelated nature of the Sustainable Development Goals, this requires policy integration and coherence at the national, regional and international levels. Against this background, this report seeks to contribute to a better understanding of the environmental impact of the production, use and end-of-life phases of digital devices and ICT infrastructure with a view to informing policy debates on digitalization, trade and environmentally sustainable and inclusive development.

While digital tools and solutions can be used to reduce the global environmental impact of various sectors and bring the 2030 Agenda for Sustainable Development back on track, positive outcomes cannot be taken for granted. As shown in this chapter, the overall environmental footprint of the digital economy is hard to assess and remains largely unknown. Identifying opportunities and risks from digitalization is hampered by a lack of agreement on what constitutes the ICT sector and its associated services, what criteria to include in an environmental impact assessment, a lack of broadly agreed methodologies to measure impact, and a lack of data.

The remainder of this report explores the direct environmental impacts along the three main stages of the ICT sector life cycle. Chapter II focuses on the environmental impacts of the production phase, from raw materials extraction and processing, as well as manufacturing of ICT devices and infrastructure. Chapter III turns to the use phase, giving special attention to the environmental impacts related to data centres and emerging technological applications. Chapter IV focuses on the end-of-life phase and the potential for fostering more circularity related to digital devices and infrastructure. Chapter V explores a case of indirect and rebound effects from ICT use, notably in the context of e-commerce. Finally, chapter VI discusses actions and policies to facilitate a more environmentally sustainable digital economy which is conducive to inclusive development.