Chapter III

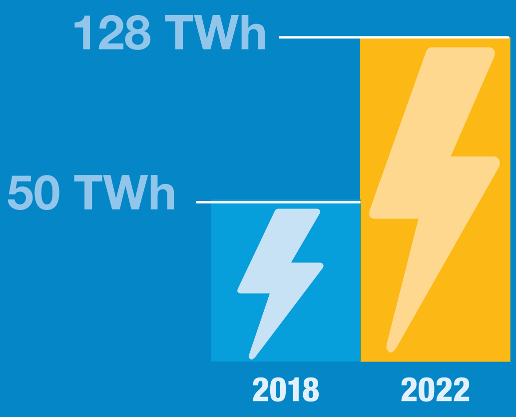
Environmental impacts in the use phase of digitalization

The growing use of rapidly evolving digital technologies and services around the world accounts for an important part of the environmental footprint of digitalization.

This chapter explores the primary environmental impacts stemming from the utilization of end-user devices, data transmission networks and data centres in light of current trends and developments.

The studies reviewed point to growing energy and water consumption as well as GHG emissions arising from this phase of the life cycle as a significant environmental concern. However, limited availability of data and transparency regarding the full picture of these environmental impacts hamper assessments.

With the adoption of ever more sophisticated, compute-intensive digital services, there is a need to give greater attention to the environmental footprint of digitalization and develop targeted policies to mitigate local and global impacts.



The electricity consumption of the 13 largest data centres operators more than doubled between 2018 and 2022

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A. Introduction

The operation of end-user devices, data transmission networks and data centres contributes to the environmental impacts of the ICT sector. Demand for digital technologies and services is rapidly increasing, generating a greater need for data to be transmitted, stored and processed. This triggers the use of a series of complex physical systems, including various digital devices, transmission infrastructure, data centres, servers, cables, satellites and routers.

Operating these digital technologies requires energy and can lead to adverse environmental impacts. Multiple criteria are important to assess the environmental footprint. This chapter focuses in particular on three, namely GHG emissions linked to energy use, water stress and noise pollution. Since digital technologies are widely deployed across all sectors, the environmental impacts of the use of digital devices and infrastructure should be closely understood, monitored and managed.

Energy consumption (especially electricity) and associated GHG emissions have drawn growing attention from the media and the research community. However, estimates of the electricity consumption and associated carbon footprint of the ICT sector diverge considerably due to the variety of different methodologies and data used (chapter I).

Other environmental considerations that should be taken into account – such as water consumption – are often overlooked when assessing the environmental footprint of the use phase. Improving the evidence base in this context is important to enhance public understanding, inform policymaking and influence business and consumer behaviour to achieve environmentally sustainable digitalization.

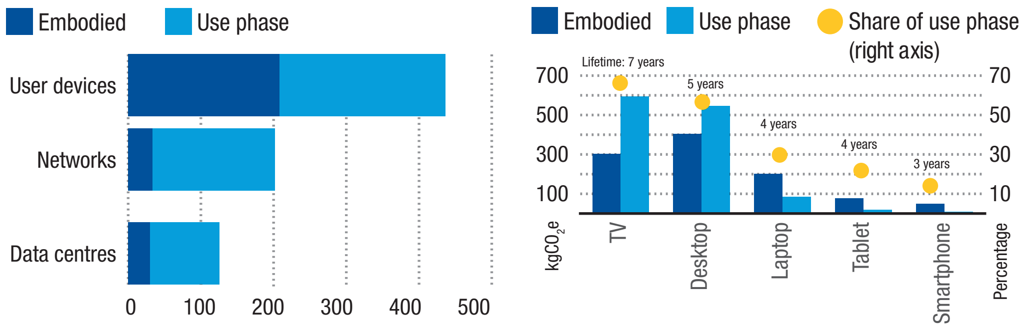
Against this background, this chapter summarises the state of research, identifies key data gaps and uncertainties and outlines potential future trends. It also explores opportunities for mitigating various environmental risks with a view to enhancing the sustainability of digitalization. Section B provides an overview of environmental impacts that may arise from the operation of data centres, data transmission networks and end-user devices. Section C takes a deep dive into data centres, focusing on their impacts at both global and local levels. The situation of data centres in developing countries is briefly explored in Section D. Section E investigates how potential environmental impacts depend on the services and underlying technologies used, including emerging technologies such as AI, blockchain, 5G and the Internet of things. Section F provides concluding observations.

> Operating digital technologies requires energy and can have adverse environmental impacts, such as GHG emissions, water stress and noise pollution

B. Main environmental impacts

In terms of energy use and GHG emissions, it is estimated that 56–80 per cent of the ICT sector's total life cycle impact can be attributed to the use phase (chapter I). However, the share varies depending on the different products used and on the energy mix associated with their use. For data centres and data transmission networks, due to their high energy intensity and utilization rates (i.e. operating 24/7) the use phase may account for over 80 per cent of GHG emissions over their life cycle

Figure III.1
Greenhouse gas emissions



a) by the three parts of the ICT sector, 2020

(megatons of CO_2 equivalent emissions)

b) by end-user device type, global averages

(kilograms of CO_2 equivalent emissions and percentage of total emissions)

Source: Malmodin et al. (2024, left) and Malmodin and Lundén (2018, right).

Notes: Carbon emissions for device types (right) are representative of global averages. Actual carbon emissions from devices depend on the carbon intensity of electricity supply and the device's assumed lifetime. Life cycle GHG emissions include use stage emissions and embodied emissions (embodied emissions are those occurring outside of the use stage, include those from raw material extraction, production and transport) in Malmodin et al. (2024).

(figure III.1.a).[1] In contrast, for connected devices, the use phase represents less than half of the life cycle energy and GHG impact; for battery-powered devices – such as smartphones and tablets, which are highly energy-efficient by design – the share is even lower, typically around 10–20 per cent. Around 80 per cent of the life cycle energy and GHG impact of a smartphone comes from the manufacturing stage (Clément et al., 2020; Ercan et al., 2016).

According to Malmodin et al. (2024), the ICT sector used about 4 per cent of global electricity in the use stage and accounted for about 1.4 per cent of global GHG emissions in 2020. Both electricity consumption and GHG emissions in the use phase have increased since 2015, reflecting the enhanced uptake of various digital technologies, devices and services.

Relatively little attention has been given to the water consumption associated with the use of digital technologies. This is starting to change. In recent years, several studies have stressed that the water footprint is an indispensable part of the overall environmental impact of digital technologies (Li, Yang, et al., 2023; Mytton, 2021). However, the evidence base is still limited. There is generally poor availability of relevant data, particularly from developing countries. This reflects various factors, including the reluctance of technology companies to share data and the lack of requirements and incentives for them to do so. Assessing the water footprint of digital technology therefore remains a challenge.

The following sections briefly look at use effects related to end-user devices, data transmission networks and data centres, respectively. For user devices and networks, energy consumption and the associated GHG emissions are the main environmental impacts under discussion; for data centres, water consumption is also explored.

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[1] For more information, see Andrae (2020); Malmodin and Lundén (2018); Malmodin et al. (2024); Masanet et al. (2013); Whitehead et al. (2015).

1. End-user devices

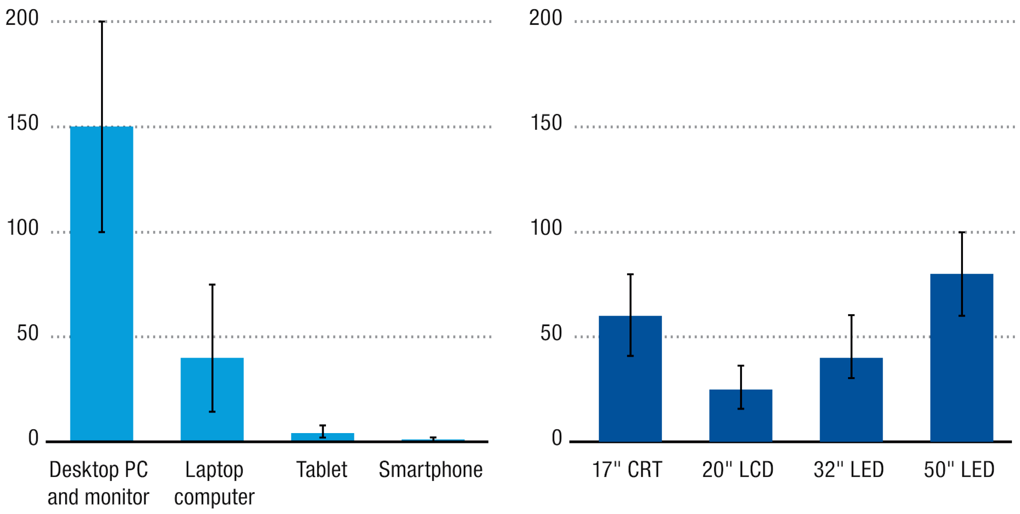
During the use phase of the ICT sector, end-user devices account for the largest share of GHG emissions (figure III.1.a). However, the share differs significantly between device types. For mains-powered devices, such as desktop personal computers, the relatively high level of power consumption means that more than half of life cycle energy use and emissions can be attributed to the use phase. While for more energy-efficient devices, such as smartphones, the production phase is the dominant source of emissions (figure III.1.b). The greater the number of devices used around the world, the greater the environmental impact in the production phase (chapter II), and on waste generation at the end of life (chapter IV).

Although the total number of end-user devices has increased rapidly over the past decade, overall energy consumption associated with their use has been found to be relatively flat (Malmodin and Lundén, 2018; Malmodin et al., 2024). This reflects in large part the shift towards smaller, more energy-efficient devices (e.g., from desktop computers to laptops, tablets and smartphones), as well as the shift to more energy-efficient screens (e.g., from cathode ray tube (CRT) to liquid crystal display (LCD) to more efficient light-emitting diode (LED) screens; figure III.2). The larger the screen of a computer device or monitor, the higher the level of power consumption. In some cases, smartphones have effectively replaced other consumer electronics (e.g., digital cameras, portable music players), reducing the need to manufacture and power a variety of single-function devices (Mims, 2012). At the same time, growing demand for larger screens for monitors and televisions is offsetting some of the efficiency gains from shifting to more efficient display (“panel”) technologies.

Variations in time frame, scope, assumptions and data sources result in different estimates of the energy use of connected

Figure III.2
Typical daily power consumption of computing devices and monitors
(Watts)

a) by device **b) by monitor type and size**



Source: UNCTAD, based on Urban et al. (2017) and Kamiya (2020a).

Note: Error bars are illustrative of the lower and upper ranges of power consumption for most products in each device type. For example, a low-end desktop PC with a small monitor may consume 100W or less, while a gaming PC with a large monitor may consume 200W or more.

devices. For example, one set of studies estimates that ICT end-user devices – comprising mobile devices, PCs and customer premises equipment (such as Wi-Fi routers) – consumed 345 terawatt-hours (TWh) in 2020, and IoT devices (such as smart meters and surveillance cameras) consumed 75 TWh (Malmodin, 2020; Malmodin and Lundén, 2018; Malmodin et al., 2024). Televisions and other non-ICT consumer electronics and peripherals (for example, gaming consoles, set-top boxes) accounted for an additional 500 TWh.[2] Together, these devices bring the estimate to 920 TWh in 2020. Other studies have estimated that end-user devices, including televisions and other non-ICT consumer electronics, consumed 600–1,000 TWh in 2020, equivalent to 2.5–4 per cent of global electricity use (Andrae, 2020; Andrae and Edler, 2015).

Higher speeds of newer mobile networks induce **more use and traffic**, leading to rebound effects

2. Data transmission networks

Data transmission networks transmit data between two or more connected devices. They comprise all core networks, mobile access networks (2G to 5G), copper- and fibre-based fixed broadband access networks, traditional public switched telephone networks and enterprise networks.[3] Data transmission networks consumed an estimated 260–360 TWh in 2022, equivalent to 1.1–1.5 per cent of global electricity use. Mobile networks – mostly through radio access networks (GSMA, 2023c) – accounted for around two-thirds of the total (Malmodin et al., 2024). The main impact on GHG emissions from data transmission networks arises in the use phase (figure III.1). Total use stage GHG emissions for networks are estimated to be 168 megatons of CO_2 equivalent ($MtCO_2e$) in 2020 (figure III.1.a).

The energy efficiency of data transmission – measured in terms of energy use per unit of data transferred – has greatly improved in the past decade. The energy needed to transmit one gigabyte (GB) of data through fixed-line networks has been observed to halve every two years (Aslan et al., 2018), corresponding to annual efficiency gains of 30 per cent; while mobile-access network energy efficiency has improved by 10–30 per cent annually (Fehske et al., 2011; Pihkola et al., 2018). Each successive generation of mobile network uses less energy to transmit data than the previous generation.[4] For example, in 2015, 4G networks typically used around one fiftieth of the energy[5] of 2G networks to transfer the same amount of data (IEA, 2017).

However, higher speeds of newer mobile networks also induce more usage and traffic, thereby giving rise to rebound effects. Between 2015 and 2020, the number of mobile broadband connections more than doubled to nearly 7 billion, and mobile data traffic grew 17 times to 90 EB per month. As a result, despite improvements in energy efficiency, total mobile network energy use increased by around 25 per cent (Malmodin et al., 2024). Meanwhile, the energy used by fixed networks fell over the same period, helping to moderate overall network energy use (Malmodin et al., 2024). Some of the savings from fixed networks may be attributable to the replacement of traditional copper networks with more energy-efficient fibre optic networks (Obermann, 2020).

While energy per unit data (for example, kWh/GB) is a widely used and reported

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[2] See Malmodin and Lundén (2018); Malmodin (2020); Malmodin et al. (2024).

[3] Customer premises equipment, such as routers and modems, are not included in "data transmission networks" but are accounted for in "connected devices". For more details, see Malmodin and Lundén (2018) and Malmodin et al. (2024).

[4] See Pihkola et al. (2018); STL Partners (2019); 4E EDNA (2019); *Orange Hello Future* (2022).

[5] The average energy intensity of mobile networks can vary greatly depending on their capacity utilization. As traffic within a given access mode (for instance, 2G, 3G or 4G) increases, its overall average energy intensity (kWh/GB) can decrease, which makes comparisons highly case-specific. In general, energy use is not directly proportional to data traffic in networks, since data networks have a significant baseload energy demand, regardless of the amount of network traffic.

indicator of energy efficiency of data networks (Body of European Regulators for Electronic Communications, 2023; ITU, 2015), it does not appropriately characterize the energy performance of networks, in particular the last-mile access network (Coroamă et al., 2015). Moreover, it does not adequately measure the energy use of a specific digital service such as data-intensive, high-traffic applications.[6] To understand and monitor energy efficiency progress of transmission networks, it is important to track both total energy use and energy efficiency indicators, based on the number of connections, peak traffic, and/or coverage as well as quality of service (Next Generation Mobile Networks Alliance, 2023).

3. Data centres

Data centres require huge computing capacity and accordingly consume large amounts of both energy and water. Based on a literature review, the IEA (2023d) estimates that in 2022, global data centre electricity consumption (excluding cryptocurrency mining, section E.3) was 240–340 TWh, representing around 1–1.5 per cent of global electricity use.[7] This can be compared with the annual electricity consumption, for example, of the United Kingdom (250 TWh), Spain (256 TWh), Indonesia (270 TWh) and Mexico (294 TWh).[8] GHG emissions of data centres during use phase in 2020 have been estimated at 95 $MtCO_2e$, which is three times greater than the GHG emissions of the production stage, according to Malmodin et al. (2024) (figure III.1a).

In the use stage, water consumption is mainly associated with the operation, and especially the cooling, of data centres. For data centres, particularly hyperscale ones, which have massive computing power and generate a substantial amount of heat, effective cooling is needed to ensure uninterrupted operation. Water and electricity consumption are interlinked and need to be considered holistically.

Although some cooling technologies can be operated without water, they may then instead consume large amounts of electricity (Hidalgo, 2022). In the next section, a more detailed analysis is provided of the environmental implications of the operation of data centres.

> Data centres require huge computing capacity and thus consume large amounts of both energy and water

C. Deep dive into data centres

Data centres are at the heart of the digital economy, storing and processing vast volumes of data for consumers, businesses and the public sector. Data centres with various capacities are deployed to support the provision of digital services ranging from emailing to video streaming and technologies from blockchain to AI.[9] Demand for these services is rising rapidly, raising questions about their impact on energy use, GHG emissions, water consumption and other environmental concerns. Available research has mainly looked at data centres in developed countries, notably in the United States as well as in Europe (Mytton and Ashtine, 2022).

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[6] See DIMPACT (2022); Kamiya (2020a); Malmodin (2020); The Carbon Trust (2021).

[7] See also Andrae (2020); Hintemann and Hinterholzer (2022); Malmodin (2020); Masanet et al. (2020).

[8] For comparison with other end uses, the global electric vehicle fleet consumed 110 TWh in 2022, while space cooling globally consumed around 2,000 TWh (IEA, 2022a, 2022b). See also IEA (2023e, 2023f); Red Eléctrica de España (2022); United Kingdom, Department for Business, Energy and Industrial Strategy (2022).

[9] Data centre capacity can be measured in terms of power, space, cooling, and power/network port connections that are needed to meet the requirements of current and future IT demand.

1. Energy consumption

National statistical agencies and intergovernmental organizations, such as the European Commission and IEA, collect and publish official statistics on the energy use of many sectors and services, such as industrial subsectors (including steel, cement) and transport modes (for example, road transport, rail). However, to date, there has been a lack of data regarding the energy use of data centres, with only a few countries having measured or estimated this.[10]

Global data centre energy consumption data are all derived from modelled estimates, employing a variety of methodological approaches. These can be broadly categorized into three types – bottom-up, top-down and extrapolation, or a combination of them (Mytton and Ashtine, 2022) – each with their own advantages and disadvantages (box III.1).

Since 2015, several research groups have produced global estimates, with wide-ranging results (table III.1). A comprehensive review of 46 publications and 179 global data centre energy estimates between 2007 and 2021 identified a number of methodological issues and underlined the need for greater data transparency (*Data Centre Dynamics*, 2022a; Mytton and Ashtine, 2022).[11]

Estimates for global data centre energy use vary significantly, making it hard to compare and draw sound conclusions

Available estimates and projections for global data centre energy use in 2020 range from around 200 TWh to over 1,000 TWh (figure III.3). Differences in methodology, system boundaries and underlying data sources make it hard to compare the various estimates. Drawing sound statistical relationships and measures has proven practically infeasible (Mytton and Ashtine, 2022). This points to the need for more standardized and objective methodologies for measurement. That would enable Governments to better plan electricity management in zones where data centres operate or may be commissioned. Nevertheless, recent research suggests that energy use by data centres can be expected to grow significantly, fuelled by increased use of compute-intensive activities linked to, for example, cryptocurrencies and AI (section E).

2. Energy efficiency and cooling trends

Global data centre energy use (excluding cryptocurrency mining) appears to have grown less than may have been expected over the past decade, considering the strong expansion in demand for data centre services. This has mainly been attributed to efficiency improvements in IT hardware and cooling systems, and a shift from inefficient enterprise data centres towards more efficient cloud and hyperscale data centres (IEA, 2017, 2023g; Masanet et al., 2020; Shehabi et al., 2016). Running applications in the cloud requires 60–90 per cent less energy than using on-premise data centres.[12] Smaller data centres serving companies that are less reliant on cloud services tend to be much less energy-efficient and are not always included in studies estimating the global impact of data centres.

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[10] Data centre energy use has been estimated based on metered electricity consumption data in Ireland and the Kingdom of the Netherlands (Ireland, Central Statistics Office, 2022, 2023; Kingdom of the Netherlands, Statistics Netherlands, 2021). Government agencies have modelled national data centre energy use in Denmark (Denmark, Danish Energy Agency, 2023), Finland (Hiekkanen et al., 2021), France (Ademe and Arcep, 2022), Singapore (Singapore, Ministry of Communications and Information, 2021), Sweden (Sweden, Swedish Energy Agency, 2023) and the United States (Shehabi et al., 2016).

[11] Common problems include sources listed without explaining where or how they are used, citations of unreliable sources, assumptions without explanation and model parameters without values. For example, the underlying link between network traffic and energy consumption used to be a key assumption in some publications, which has been refuted in later research.

[12] See 451 Research (2019); Microsoft (2020); S&P Global Market Intelligence (2021a, 2021b); Zheng and Bohacek (2022).

Box III.1
Approaches to estimating data centre energy use

Bottom-up studies use detailed data on technology, such as equipment specifications (including server power use), data centre infrastructure characteristics (such as power usage effectiveness (PUE) and installed base and equipment shipment values.[a] Their main advantage is that they can explain underlying drivers and trends, and are useful for assessing efficiency potential. However, the substantial data requirements make them resource- and time-intensive. Some data inputs, such as proprietary market data, can be expensive or difficult to obtain, which limits transparency. Examples of bottom-up studies include Hintemann and Hinterholzer (2020; 2022), Masanet et al. (2020) and Montevecchi et al. (2020).

Top-down studies compile measured or estimated energy consumption data from Governments and companies. Their main advantage is that they are based on fairly reliable data that is easy to collate and update. At the same time, the limited availability of data from Governments and companies means that only a portion of the overall scope can be estimated, requiring extrapolation or other complementary approaches to ensure comprehensive coverage. Some government data (for instance, metered energy consumption) may focus only on large data centres and exclude smaller ones, while company-reported data may include non-data centre energy use (such as offices, stores). Examples of measured or estimated consumption data from Governments include Ireland, Central Statistics Office (2022, 2023) and the Kingdom of the Netherlands, Statistics Netherlands (2021). Malmodin et al. (2024) use a combination of top-down estimates from company data and other studies.

Extrapolation approaches combine high-level activity indicators, such Internet protocol (IP) traffic, with energy-intensity assumptions to project total energy use under different activity and efficiency-improvement scenarios. Extrapolation approaches require a baseline energy consumption estimate from a bottom-up or top-down model, and decisions around growth rate (including energy-efficiency improvement, data volume growth). These studies are typically more transparent and relatively easy to generate and update. The main disadvantages are their low explanatory power and a higher risk of misuse (for example, developing exaggerated estimates from long-term projections). Examples of extrapolation approaches include Andrae (2019a, 2020), The Shift Project (2019a, 2021) and Belkhir and Elmeligi (2018).

Source: UNCTAD, based on Mytton and Ashtine (2022).

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[a] PUE is a measure of how efficiently a data centre uses energy; the most efficient hyperscale data centres can have values of around 1.1, meaning that for every 1.1 kWh of electricity used, 0.1 kWh is used for cooling/power provision and 1 kWh is used for IT equipment.

Despite improvements in energy efficiency, the strong increase of workloads handled has resulted in energy use by co-location and hyperscale data centre operators expanding by 10–30 per cent per year since 2020.[13] In particular, for 13 of the largest data centre operators, for which data is available, the estimated company-wide electricity consumption more than doubled between 2018 and 2022 (figure III.4).[14]

Data centres need energy to power IT and infrastructure equipment. Globally, the vast majority of IT-related energy in data centres is consumed by servers (80 per cent),

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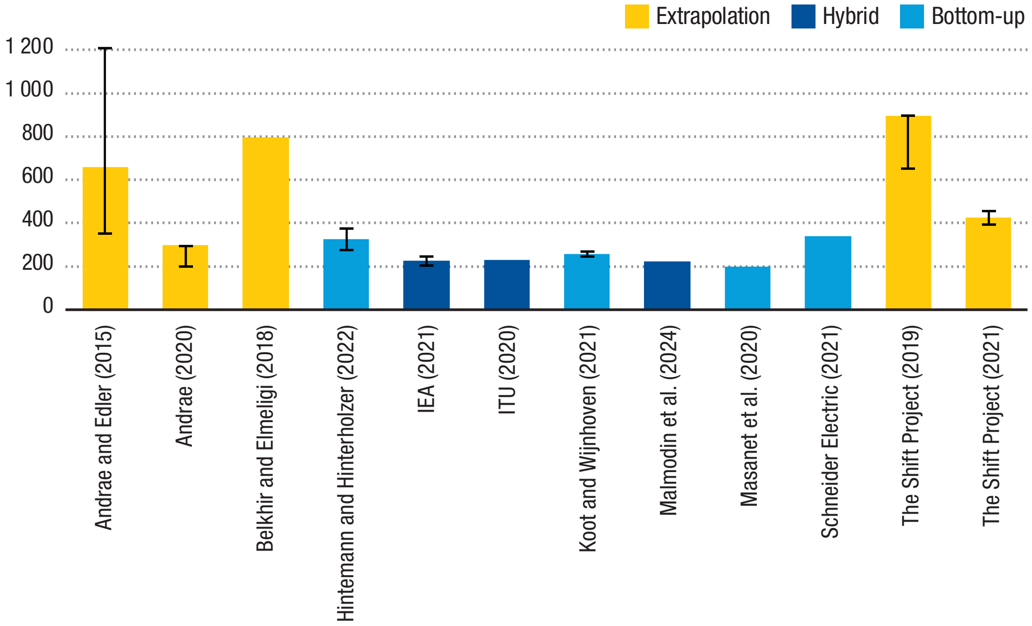
[13] See Alibaba (2022); Apple (2022, 2023); Baidu (2023); Digital Realty (2022, 2023); Equinix (2022, 2023); Google (2023, 2022); Meta (2022, 2023); Microsoft (2022, 2023a); Tencent (2021, 2022, 2023); VNET Group (2023).

[14] Some of these companies also have significant non-data centre business divisions, such as retail stores and warehouses that use electricity, but most of the electricity used by these companies is likely to be related to their data centres, making these trends an appropriate proxy for their data centre energy use trends.

Figure III.3

Global data centre energy use, selected estimates and estimation methodologies, 2020

(Terawatt hours)



Source: UNCTAD.

Notes: Error bars, where shown, indicate the range of estimates in each study. Values exclude cryptocurrency mining.

followed by storage devices (18 per cent) and network equipment (3 per cent), while most infrastructure-related energy use is related to cooling (Masanet et al., 2020). Currently, the global average PUE in data centres is around 1.6, meaning that for every 1.6 kWh of electricity used, 1 kWh is used for IT and 0.6 kWh for cooling and other non-IT equipment (Davis et al., 2022). The theoretical minimum value of PUE would be 1, where 100 per cent of the energy used is for IT. The average PUE of Google and Meta data centres – some of the most energy-efficient in the world – is already around 1.1 (Google, 2022; Meta, 2022).

Given the significant share of cooling in overall energy use by data centres, reducing such energy use has become a major focus for data centre operators. Traditional, inefficient cooling designs have been largely replaced by more efficient cooling systems, including hot and cold aisle contained cooling systems (Heslin, 2015). Allowing data centres to operate at slightly higher temperatures has also enabled energy savings, as has locating data centres in cooler climates. As the power density of racks (structures that hold computer equipment) increases, liquid cooling – such as immersion cooling, where dielectric fluids absorb heat from a computing device or processing chip – is becoming an important cooling method.

Other innovative approaches are currently being tested. For example, in 2020, Microsoft completed a two-year trial in which a data centre holding over 800 servers was placed on the sea floor off the coast of Scotland. The data centre was powered entirely by renewable energy from onshore wind and solar and offshore tidal and wave sources (Microsoft, 2023b). The underwater data centre did not use any water (BloombergNEF, 2023b) and required less energy for cooling (PUE of 1.07 compared with 1.125 for the company's new land-based data centres). It also reported almost 90 per cent lower failure rates

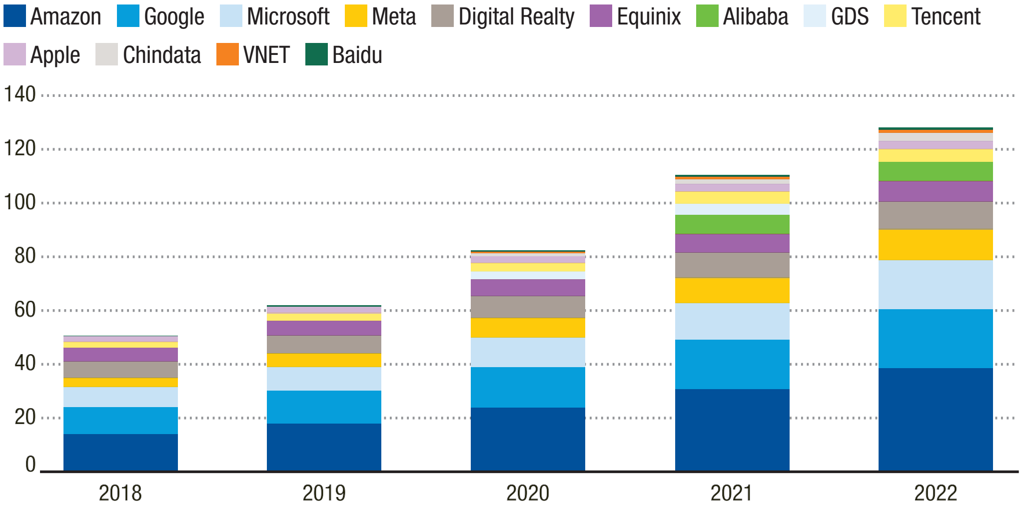
Table III.1
Global energy use of data centres: Overview of studies, 2015–2024

Institution and publications	Estimates	Approach
Beijing Normal University; Global Energy Interconnection Development and Cooperation Organization		
Liu et al.(2020)	450–550 TWh in 2017 600–800 TWh in 2020 (projection)	Based primarily on assumptions and approach in Andrae and Edler (2015), with revised projections for PUE under different decentralization scenarios.
Borderstep Institute		
Hintemann (2020)	310–330 TWh in 2018 (400 TWh including cryptocurrency)	Bottom-up estimate based on data centre market developments (primarily in Europe), technical characteristics of servers, storage, and networking (energy use, age) and data centre infrastructure (air conditioning, power supply, uninterruptable power supply). Some of the estimates include cryptocurrency mining.
Hintemann and Hinterholzer (2022)	270–380 TWh in 2020 (350–500 TWh including cryptocurrency)	
Ericsson; Telia		
Malmodin and Lundén (2018)	220 TWh in 2015 (245 TWh including enterprise networks)	Hybrid estimate based on bottom-up estimates based on hardware shipments, complemented by benchmarking to other studies and reported company data.
Malmodin et al. (2024)	223 TWh in 2020	
GreenIT.fr		
Bordage (2019)	312 TWh in 2019	Based on the number of servers in operation and life cycle assessments of three different data centres.
Huawei		
Andrae and Edler (2015)	397 TWh in 2015 (“Expected” case) 345–1200 TWh in 2020 (projection)	Extrapolation with data centre IP traffic extrapolations and energy intensity per unit of IP traffic under updated efficiency improvement scenarios.
Andrae (2019a)	211 TWh in 2018	Updated IP traffic and energy efficiency assumptions from 2015 study.
Andrae (2020)	196–299 TWh in 2020	
International Energy Agency		
IEA (2017)	194 TWh in 2014 200 TWh in 2020 (projection)	Global model based on expanded model from Shehabi et al. (2016).
IEA (2021d, 2022d, 2023c)	200–250 TWh in 2020 220–320 TWh in 2021 240–340 TWh in 2022	Hybrid estimate based on the bottom-up modelling in IEA (2017) and Masanet et al. (2020) and global estimates by Hintemann and Hinterholzer (2022) complemented by reported energy consumption data from large data centre operators.
International Telecommunication Union		
ITU (2020)	220 TWh in 2015 230 TWh in 2020 (projection)	Based primarily on IEA (2017), supplemented by Malmodin and Lundén (2018a), Shehabi et al. (2016) and Fuchs et al. (2017).
Lawrence Berkeley National Laboratory; Northwestern University; University of California Santa Barbara		
Masanet et al. (2020)	205 TWh in 2018	Bottom-up estimate based on shipment data for servers, drives, networking, energy use characteristics and lifetimes, combined with assumptions for each type of data centre class and region-specific PUE.
McMaster University		
Belkhir and Elmeligi (2018)	599 TWh in 2017 797 TWh in 2020 (projection)	Extrapolation using estimate on the data centre energy use in 2008 from Vereecken et al. (2010) and an annual growth of 10 per cent based on a market research company’s projection.
Schneider Electric Sustainability Research Institute		
Petit et al. (2021)	341 TWh in 2020	Bottom-up estimate based on workloads, data storage requirements and global average PUE.
The Shift Project		
The Shift Project (2019a)	559–593 TWh in 2017	Based on the model developed by Andrae and Edler (2015) with updated assumptions and scenarios.
The Shift Project (2021)	393 TWh in 2019 (438 TWh including cryptocurrency)	
University of Twente		
Koot and Wijnhoven (2021)	286 TWh in 2016 240–275 TWh in 2020	Hybrid approach combining top-down indicators and bottom-up data (e.g. workloads per application).

Source: UNCTAD, based on studies cited.

Figure III.4
Company-wide electricity consumption by data centres, selected companies, 2018–2022

(Terawatt hours)



Source: UNCTAD, based on company sustainability reports and external verification statements of environmental, social and governance data.

Notes: As Amazon did not publicly report electricity consumption in 2018 and 2019, these values are estimated by UNCTAD based on other publicly reported data from Amazon (scope 2 emissions, renewable energy share) as well as comparable data and indicators from other companies. For operators and years for which relevant data are not publicly available, estimates could not be derived, as follows: Alibaba (2018–2020), Baidu (2018), Chindata Group (2018–2019), GDS (2018–2019, 2022) and VNET (2018–2019).

compared with on-land data centres (Microsoft, 2023b).[15] Submarine data centres are also being explored in China (BloombergNEF, 2023b). However, the potential impact of underwater data centers on marine life and the environment will need to be further assessed.

The low PUEs at Google and Meta seem to have plateaued in recent years, suggesting declining opportunities for further improvements in the energy efficiency of cooling systems. In the future, energy efficiency improvements in the largest data centres are likely to come from improving the energy efficiency of computing activities. Such improvements cannot be captured by the PUE indicator since this does not measure the energy efficiency of the IT equipment (i.e. energy used per unit of useful output or service provided, such as computation and data storage). This again points to a need to track a wider range of energy indicators and environmental indicators related to GHG emissions, water usage and waste (Lin and Bunger, 2021).

Highly compute-intensive tasks, such as training large language models, are currently driving the use of specialized hardware such as application-specific integrated circuits (ASICs) and graphics processing units. For instance, Google's custom ASIC was found to be 30–80 times more energy efficient than general-purpose central processing units (Jouppi et al., 2017). However, the use of powerful graphics processing units and ASICs for machine learning applications could drastically increase the power density of data centre racks and the amount of heat generated, which may in turn require more energy and water for cooling (see also section C.4).

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[15] Land-based data centres are affected by corrosion from oxygen and humidity, temperature fluctuations, and movement from technicians who replace broken components.

Computing hardware has become ever more powerful and efficient over the past 50 years.[16] However, as efficiency improvements from hardware begin to slow – and eventually reach theoretical limits (see section E) – software-related opportunities to improve energy efficiency become more important (Leiserson et al., 2020). Substantial energy efficiency gains can be achieved by using more energy-efficient code, removing "software bloat",[17] and tailoring software to hardware features.

Storage devices account for about one-fifth of IT-related energy consumption by data centres (Masanet et al., 2020); reducing their energy use could therefore be an important source of efficiency gains. The share of solid-state drives, which are generally more energy efficient than hard disk drives (Tomes and Altiparmak, 2017), in installed storage capacity increased from less than 3 per cent in 2010 to around 30 per cent in 2018 (Masanet et al., 2020).

Addressing "dark data" and using cold storage could represent other means of storage (and energy) savings.[18] Some analysts estimate that such data account for over half of worldwide storage and are responsible for the emissions of millions of tons of CO_2 annually (Al Kez et al., 2022; Veritas, 2020). Companies and organizations should look into analysing existing dark data to derive insights and educate employees on how to overcome instincts to hoard unnecessary data (Gartner, 2017).

Overall, data centre energy use is likely to continue to grow significantly over the next few years. Longer-term trends are highly uncertain and depend on:

- The pace of overall demand growth for data centre services, particularly from emerging technologies and services such as AI and machine learning, blockchain and the metaverse (section E);
- The evolution of cryptocurrency prices and whether major cryptocurrencies move to less energy-intensive consensus mechanisms (section E);
- Further energy efficiency improvements in IT hardware and cooling technologies and approaches, including breakthrough technologies or efficiency limitations (section F);
- The extent to which existing workloads in enterprise data centres will be migrated to the cloud;
- Broader trends in digital technologies and services that influence data centre developments, such as a greater need for low latency services that would increase demand for edge data centres, and the development of global data governance (UNCTAD, 2021a).[19]

Data centre energy use is likely to continue to **grow significantly** over the next few years

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[16] Moore's Law describes the long-term trend that the number of transistors incorporated in a computer chip doubles every two years, making chips more powerful (Moore, 1965). While Koomey's Law refers to the doubling of peak-output efficiency every 1.57 years for computing hardware (Koomey et al., 2011). Peak-output efficiency is the number of computations that can be performed per kWh of electricity consumed. More recent analysis shows a slowing of this trend to every 2.7 years since 2000 (*IEEE Spectrum*, 2015; Koomey and Naffziger, 2016).

[17] Software that has increasingly unnecessary features use more memory, disk space or processing power.

[18] Dark data refers to unstructured and abandoned data that has been gathered or stored with little value potential (Al Kez et al., 2022). This includes, for example, old emails and attachments, and partially developed and then abandoned applications. Cold storage refers to the storage of inactive data that is rarely accessed, used, or shared in low-cost equipment (Seagate, 2023). Data is stored in a safe, low-cost location – in-house or in the cloud – that can be accessed when needed. Cold data storage is generally much more economical (and uses much less energy) than "hot storage" of active data (Dell, 2023)

[19] An "edge" data centre is a small data centre that is located close to the edge of a network. Its main benefit is the quick delivery of services with minimal latency. See https://www.techtarget.com/searchdatacenter/definition/edge-data-center.

3. Greenhouse gas emissions and sources of energy

Data centres are highly electrified. This means that comparatively, it is easier to decarbonize than in sectors such as transport and manufacturing that rely more heavily on fossil fuel consumption (IEA, 2022b). The impact of data centres on GHG emissions depends primarily on the source of the electricity supply.

The largest data centre operators have sought to reduce GHG emissions by purchasing renewable energy, mainly in the form of power purchase agreements (PPAs). These agreements are long-term commitments between the buyer and renewable electricity generators. They seek to reduce risks for new projects and allow access to project finance, while locking in a low and stable price for the buyer.

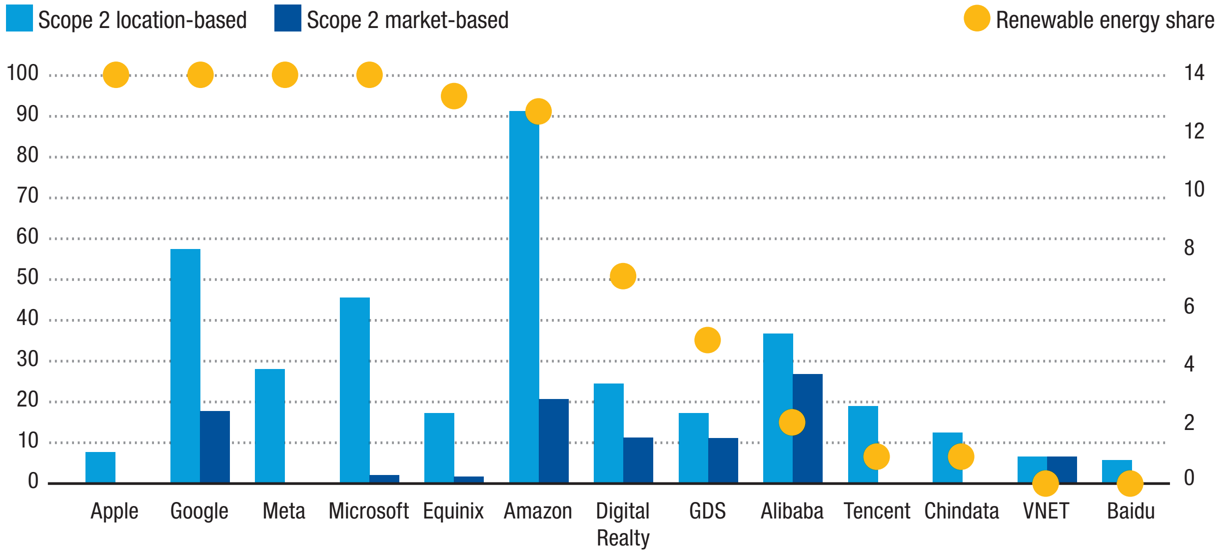
Some companies have relied on energy attribute certificates, which are transferrable proofs of renewable energy generation.

These purchases can help reduce operators' market-based scope 2 emissions as reported under Greenhouse Gas Protocol standards relative to location-based ones (figure III.5). Apple (3.2 TWh), Google (21.8 TWh), Meta (11.5 TWh) and Microsoft (18.2 TWh) each purchased or generated enough renewable energy in 2022 to match 100 per cent of their total electricity consumption (Apple, 2023; Google, 2023; Meta, 2023; Microsoft, 2023a). Amazon, the largest data centre operator in the world, reached 90 per cent renewable energy matching across its operations in 2022 (Amazon, 2023a) and Equinix, one of the largest co-location data centre operators, reached a 96 per cent rate in the same year (Equinix, 2023). Data centre operators in China are relatively

Figure III.5

Renewable energy share and scope 2 emissions, selected data centre operators, 2022

(Percentage renewables in total energy use and megatons of CO_2 equivalents)



Source: UNCTAD, based on Alibaba (2023); Amazon (2023a, 2023b); Apple (2023); Baidu (2023); Chindata Group (2023); Digital Realty (2023); Equinix (2023); GDS (2022); Google (2023); Meta (2023); Microsoft (2023a); Tencent (2023); VNET Group (2023).

Note: Scope 2 accounting can use different methods that allocate emissions from the generator to end users. Location-based methods use the average emissions intensity of grids where energy is used, mostly based on average emission factors from those grids. Market-based methods reflect emissions from electricity that companies have intentionally bought through PPAs (World Resources Institute, 2015).

lagging behind in this area: renewables accounts for a smaller share of electricity use at Alibaba (15 per cent), Tencent (8 per cent) and Baidu (1 per cent), and at large data centre operators GDS (34 per cent) and Chindata (7 per cent).[20]

Large data centre operators based in the United States continued to dominate renewable energy purchasing in 2022, with Amazon, Google, Meta and Microsoft as the top four purchasers (BloombergNEF, 2023b). Amazon alone accounted for nearly one third of all renewable PPAs globally in 2022. As of the end of that year, Amazon had a renewable energy portfolio of over 20 GW, making it the seventh largest such portfolio globally, including utilities (Amazon, 2023b).

However, matching 100 per cent of annual demand with renewable energy purchases or certificates does not mean that data centres are powered exclusively by renewable sources. Wind and solar power may not always meet a data centre's energy demand, and renewable energy may have been purchased from projects in a different location to the demand (IEA, 2023d).

Energy attribute certificates, also known as renewable energy certificates and guarantees of origin, have been shown to have low or unclear environmental benefits (Bjørn et al., 2022). In contrast, on-site generation, PPAs and sourcing and matching zero-carbon electricity on a 24/7 basis within each grid where demand is located can increase additionality (IEA, 2022b).[21] These approaches have environmental benefits and can provide price predictability. However, on-site generation is limited by size and scale, while PPAs tend to have complicated contract structures and may not be available in all markets.

4. Water consumption

Water consumption during the use phase is mainly linked to the cooling of data centres. The water footprint of data centres is inherently context-specific. The cooling technology used is highly dependent on the climate and resource availability at the location of the data centre (Karimi et al., 2022). For example, in cooler regions (such as Northern Europe), relying on free air cooling is possible for most of the year, thus reducing the need for water consumption. In warmer regions (such as Africa and Southeast Asia), reducing water consumption for cooling is much more challenging. Given the anticipated expansion of data centres in these regions to support the growth of the digital economy and for reasons of data sovereignty, associated water demand may further complicate the effective management of often scarce water resources (section C.5) (Mytton, 2021).

In recent years, improvements in cooling technologies,[22] along with increased temperature tolerance of some IT equipment, have led to a reduction in the reliance on water-based cooling technologies[23] and offered more options for cooling data centres, especially large ones (Dietrich and Lawrence, 2022). In tandem with these developments, alternative sources of water such as reclaimed wastewater and even seawater are being explored to meet the high water demands of data centres.[24]

Water and electricity use by data centres needs to be considered holistically. Although some cooling technologies can be operated without water, they may instead consume large amounts of electricity (Hidalgo, 2022). Moreover, the water footprint of generating

Matching 100 per cent of annual demand with renewable energy purchases does not mean that data centres are powered only by renewable sources

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[20] Data on renewable energy consumption has not been publicly disclosed by the two largest telecommunications data centre operators, China Telecom and China Unicom (China Telecom, 2023; China Unicom, 2023).

[21] In the case of renewable energy purchases, a purchase may be considered "additional" if the associated renewable energy generation capacity would not have occurred without that particular purchase (ElectricityMaps, 2023).

[22] For example, Microsoft's immersion liquid technology, see Microsoft (2023c).

[23] For example, Chindata Group's X-cooling waterless technology; see Chindata Group (2022).

[24] For example, the cloud service providers Alibaba Cloud and Tencent Cloud in China use reclaimed water in their data centres; see Alibaba (2023) and Tencent (2023), while on seawater use, see. for example, Google's project in Finland (Google, 2023).

this additional electricity may more than outweigh the gains of not having a direct water footprint (Ristic et al., 2015). Data centre operators need to consider trade-offs between energy and water consumption when seeking the optimal cooling system for each site's technical and climate conditions (Karimi et al., 2022). As advancements continue to be made, the most sustainable option will be the one that focuses holistically on energy efficiency and responsible water consumption (O'Donnell, 2022).

A lack of transparency on the part of data centre operators makes it difficult to access up-to-date information and to assess the water consumption of the sector at a national or regional level. Only a few studies have considered water consumption by data centres in the United States (Shehabi et al., 2016; Siddik et al., 2021) and Europe (Farfan and Lohrmann, 2023b). For instance, their total annual operational water footprint in the United States was estimated at 513 million m^3 in 2018, placing data centres among the top 10 water-intensive industries in the country (Siddik et al., 2021). More research is needed to obtain a reliable evidence base for policymaking aimed at promoting sustainable water management in data centres.

> A lack of transparency on the part of data centre operators makes it difficult to assess the water consumption of the sector

5. Local impacts of data centres

a. Impacts on electricity grids

Due to their large size and the high intensity of energy use, data centres can have significant local energy-related and environmental impacts. In the United States, data centres are 10 to 50 times more energy-intensive (per unit floor area) than a typical commercial office building (United States, Department of Energy, 2023).

New large data centre developments can significantly affect local power grids, with a hyperscale data centre requiring 100–150 MW of grid capacity and consuming hundreds of GWh of electricity annually (Kamiya and Kvarnström, 2019). New data centre developments in developing countries are likely to be smaller (up to tens of MW) as the electricity grids in these countries are generally less resilient, but the relative impact on each grid can still be significant.

Careful site selection and planning are essential to ensure that data centres have access to reliable electricity supplies to minimize the use of diesel backup generators and ensure high operational reliability. This is important to avoid any adverse impacts on local electricity grids, not least in countries with limited access to electricity.

Data centre buildings are usually constructed with excess capacity to allow for future growth, in anticipation of future customer demand, but they begin their operations well under maximum capacity. Grid capacity reserved for maximum usage may remain unused, blocking other users (Mytton et al., 2023). Managing capacity is an area where policy can be improved.

Although data centres (excluding cryptocurrency mining) only account for 1–1.5 per cent of global electricity consumption, in smaller countries with expanding data centre markets, their share can quickly become more significant. For example:

- In Denmark, data centres used about 1.1 TWh of electricity in 2021 (3 per cent of national use). By 2030, this is projected to increase to 8 TWh, which would be equivalent to around 13 per cent of national electricity consumption (Denmark, Danish Energy Agency, 2023);
- In Ireland, data centre electricity use more than quadrupled between 2015 and 2022, reaching 18 per cent of the country's electricity consumption in 2022 (Ireland, Central Statistics Office, 2023). The country's transmission system operator projects that this share could rise to as much as 28 per cent by 2031 (Ireland, EirGrid, 2022);
- In Singapore, data centres were responsible for around 7 per cent

of electricity demand in 2020 (Singapore, Ministry of Communications and Information, 2021).

In some communities and regions with a high or growing concentration of data centres there have been increasing concerns related to new data centre developments. Some Governments have also introduced restrictions or moratoriums on new investments, as follows:

- In Ireland, the County Council of South Dublin attempted to ban data centres in the region but, in accordance with a ministerial order, would allow their development. However, the country's transmission network operator, EirGrid, has stated that no new data centres are likely to be granted a grid connection until 2028 (*Data Centre Dynamics*, 2022b);
- In 2022, the Government of the Kingdom of the Netherlands announced stricter rules for hyperscale data centres and implemented a temporary moratorium on new developments in most of the country (*Data Centre Dynamics*, 2022c);
- The Government of Singapore implemented a moratorium on new data centres in 2019, which was lifted in 2022, though subject to strict conditions around resource efficiency.[25]

b. Impacts on water supply

In regions where water resources are under significant stress, data centre operators often compete with local communities for access to potable water. Cooling systems of data centres rely on clean freshwater sources to prevent issues such as corrosion and bacteria growth (Li, Yang, et al., 2023). In the United States, one-fifth of the direct water footprint of data centre servers reportedly comes from moderately to highly water-stressed watersheds, and nearly half of the servers are fully or partially powered by power plants located within water-stressed regions (Siddik et al., 2021). Given the energy needs discussed above, data centre operators are sometimes drawn to water-starved regions, especially if carbon-free solar and wind energy are available (*NBC News*, 2021).

Water consumption by data centres has recently stoked tension within local communities in both developed and developing countries:

- In the Kingdom of the Netherlands, the Parliament voted to subject a planned Meta data centre to an environmental review due to objections from the local farming community of Zeewolde;[26]
- Plans by Meta to build a data centre in Mesa, Arizona, United States, a desert city that is already home to large data centres owned by Apple, Google and other technology giants were opposed by local residents;[27]
- Google planned to build a data centre in Uruguay, which led to public debate. In 2023, the country experienced the worst drought in 74 years and more than half of its 3.5 million citizens were without access to potable tap water.[28]

In recent years, technology companies have shown more interest in exploring sustainable water management practices, illustrated by their commitment to reporting detailed water metrics and improving their sustainability credentials (Mytton, 2021). In its 2023 environmental report, Google (2023) disclosed that total water consumption at its data centres and offices globally in 2022 amounted to 5.6 billion gallons (about 21.2 million m^3). For the same year, Microsoft (2023c) reported that its water consumption was 6.4 million m^3. Amazon, Google and Microsoft have all

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[25] See https://www.straitstimes.com/tech/singapore-pilots-new-scheme-to-grow-data-centre-capacity-with-green-targets.

[26] See https://www.washingtonpost.com/climate-environment/2022/05/28/meta-data-center-zeewolde-netherlands/.

[27] See https://www.washingtonpost.com/climate-environment/2023/04/25/data-centers-drought-water-use/.

[28] See https://www.theguardian.com/world/2023/jul/11/uruguay-drought-water-google-data-center.

committed to replenishing more water than they consume.[29] The companies that reported total direct water consumption – Apple, Baidu, Digital Realty, Google, Meta, Microsoft and Tencent – together used an estimated 50 million m^3 of water in 2022. This figure does not include indirect water consumption, such as for electricity generation, which accounts for a significant share of their total water consumption. The impact of data centres' water consumption is primarily local, rather than global.

Transparency concerning water consumption has also seen an uptick among cloud service providers and data centre operators, including in developing countries. In China, leading carrier-neutral data centre operators GDS and Chindata revealed water consumption metrics for their data centres in 2021. Respectively, they reported 5.1 million tons[30] (about 4.5 million m^3) and 1.5 million tons[31] (about 1.3 million m^3) of water consumption (Chindata Group, 2022; GDS, 2022). Baidu Cloud (2023) began disclosing information on its water usage effectiveness in 2022.

These positive steps are primarily orchestrated by major hyperscale cloud providers. Most small and medium-sized data centres across the globe have yet to incorporate water data into their reporting. For example, in 2022, only 39 per cent of respondents to a data centre survey reported on their water consumption (Davis et al., 2022). Most operators stated that tracking water consumption lacked business justification. However, as a growing number of municipalities will only allow data centre developments if they are designed for minimal or near-zero direct water consumption, this metric is expected to become a more important factor in business decisions.

c. Impact on noise levels

Data centres generate noise from ventilation, air conditioning fans and diesel generators. Noise impacts can be a critical issue for residents and community officials, especially when data centres are built close to their customers to reduce latency (*Reuters*, 2022). Adverse health impacts observed in nearby residents include hearing loss, elevated stress hormone levels, hypertension and insomnia (Monserrate, 2022). For example, in 2019, residents in Chicago complained of constant fan noise from a nearby data centre, where levels of noise were reportedly higher than legally permitted.[32]

Noise control of data centres has gained the attention of some local governments in the United States, requiring more studies around noise and increased mitigation efforts, public outreach and regulation. One comprehensive study in this regard focused on Prince William County in the state of Virginia, finding that noise generated by data centres significantly exceeded the applicable ordinance levels (Lyver, 2022). However, as the local ordinance exempted the noise from ventilation and air conditioning systems, the study recommended that noise mitigation should be mandated at data centre sites in operation and form an integral part of data centre design during the planning process. It also argued that the local government should demand strong, contractual commitments for noise control (Shaw and Lyver, 2023). In 2023, the city of Chandler, Arizona, joined a list of cities across the United States to adopt a zoning

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[29] See https://blog.google/outreach-initiatives/sustainability/replenishing-water/; https://blogs.microsoft.com/blog/2020/09/21/microsoft-will-replenish-more-water-than-it-consumes-by-2030/; and https://sustainability.aboutamazon.com/natural-resources/water.

[30] This includes only the water consumption of operations at data centres that are leased and owned by GDS and its build-operate-transfer data centres. Water consumption at third-party data centres and individual offices is excluded.

[31] This includes only data centres located in Beijing, as Chindata states that data centres outside the city are outside of its full operational control. Water consumed includes both groundwater and municipal water supply.

[32] See https://www.datacenterdynamics.com/en/news/chicago-residents-complain-of-noise-from-digital-realty-data-center/.

code amendment to define the operation of data centres, including noise control.[33]

Some data centre operators have voluntarily attested to the responsible design and operation of their data centres. This includes leveraging new technology and solutions to ensure that the data centres operate as quietly as possible. For example, Microsoft has taken a series of measures in this regard, including infrequent use of backup generators, added attenuation to the generator design and minimizing the use of mechanic chillers when free air cooling can be used.[34]

There can be trade-offs between noise generation, energy use and water consumption in data centres. When data centres in Chandler, Arizona switched from water to electricity to cool their operations, noise complaints from nearby residents increased (*Reuters*, 2022). Data centre operators should assess potential local noise impacts during site selection and implement measures to mitigate impacts during operation. In some cases, this will require careful balancing between latency, energy use, water consumption and noise generation. Some new paradigms might avoid these trade-offs. For example, liquid-based cooling, a technique that is growing in popularity, is expected to eliminate the fans required to cool servers. It also tends to be more energy-efficient, making it doubly advantageous for businesses interested in reducing noise and increasing sustainability (IEA, 2023d; Kamiya and Kvarnström, 2019).

d. Mitigating local impacts

As low latency applications, data sovereignty and repatriation requirements drive more local data centre developments, operators will need to manage their impacts carefully, particularly in regions where energy and water are in limited supply. Data centres can mitigate some of their local energy-related impacts by developing, or investing in, local renewable energy projects, providing waste heat and participating in demand response programmes (IEA, 2023d; Kamiya and Kvarnström, 2019). These programmes aim to balance the demand on power grids by encouraging customers to shift electricity demand to times when electricity is more plentiful or other demand is lower, typically through prices or monetary incentives (IEA, 2023g).

In developing countries, Governments and utilities may consider opportunities to co-develop local electricity and water infrastructure with new data centre and network projects to expand electricity and water access in communities, with digital infrastructures serving as important anchor customers of electricity and water (Givens, 2016; International Solar Alliance, 2022; Ramchandran et al., 2016; Ranade, 2013).

Policymakers and regulators can play an important role in incentivising demand-side flexibility. For example, allowing for some leeway in ancillary service requirements (like longer notice periods or longer response times) may make it easier for data centre operators to participate in demand response programmes (IEA, 2023d; Malmodin, 2020; Malmodin and Lundén, 2018; Malmodin et al., 2024).

> Data centre operators need to carefully balance latency, energy use, water consumption and noise generation

In some countries, data centres support local energy systems by providing waste heat to help warm nearby buildings or supply industrial heat users, including swimming pools and greenhouses (*Data Centre Dynamics*, 2022d; Lalonde et al., 2022; Ljungqvist et al., 2021). To overcome potential barriers to using waste heat, such as achieving sufficiently high temperatures and contractual and legal challenges, policymakers, data centre operators and district heating suppliers should work together to develop adequate incentives and guarantees (IEA, 2023d). Governments of European Union countries have until September 2025 to introduce new requirements for new data centres on their waste heat management, following the publication of the Directive 2023/1791

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[33] See https://www.chandleraz.gov/news-center/chandlers-data-center-ordinance-now-effect.

[34] See https://local.microsoft.com/wp-content/uploads/2022/10/Noise-fact-sheet.pdf.

of the European Parliament and of the Council on energy efficiency.[35] Data centres above a certain size should use their waste heat or find options for others to use the heat they generate, except where a cost-benefit analysis renders this economically or technically infeasible.

D. Data centres in developing countries

Growth in data centre investments in developing countries is anticipated, and this comes with implications for local energy and water consumption

Most data centres are located in digitally advanced economies. This applies in particular to hyperscale data centres. At the same time, digital transformation in developing countries is driving increased demand for data centres in these countries. This is happening despite challenging climate conditions, limited availability of renewable energy, water scarcity, connectivity constraints and power outages. For latency reasons, the growth of IoT and 5G mobile networks also favours the establishment of data centres closer to users. Furthermore, various public policy objectives, such as protecting privacy and other human rights, national security and advancing economic development, mean that countries prefer to build data centres within their borders. Such preferences are likely to persist until there is a global approach to data governance, including for cross-border data flows, which would allow for value of data to be harnessed equitably for development independent of where data are stored (UNCTAD, 2021a). Further growth in data centre investments in developing countries is anticipated, and this comes with implications for local energy and water consumption. This makes it imperative to integrate sustainability concerns into the early stages of planning new data centres.

1. Africa

It is estimated that Africa accounts for less than 1 per cent of available data centre capacity in the world (Kadium Limited, 2022). According to Begazo et al. (2023), sub-Saharan Africa has only 0.1 data centre per 1 million people, compared with 0.5 per million in the world and 3.1 per million in North America. South Africa has emerged as a regional hub for data centres, accounting for more than two-thirds of data centre capacity in Africa, followed by Ghana, Kenya and Nigeria (Africa Data Centres Association, 2021). With growing numbers of Internet users, and in view of concerns related to data governance and data sovereignty, this region is expected to see a rise in data centre development.

Increasing demand for cloud-based services and modular data centre solutions from enterprises, particularly micro-, small- and medium-sized enterprises (MSMEs) and from government agencies, is expected to further boost the need for data centre capacity. The Africa Data Centres Association (2021) has estimated that the African data centre market will grow at a compound annual growth rate of 12 per cent between 2019 and 2025, reaching a value of $3 billion in 2025.

Electricity needs of data centres are estimated to increase from 1 TWh in 2020 to around 5 TWh in 2030, which would represent almost 5 per cent of total electricity demand growth in the services sector in Africa (IEA, 2022d). However, most sub-Saharan African countries find it difficult to meet even the basic (tier 1) reliability standards of electricity supply. For example, Eskom, the State-owned grid operator in South Africa, recorded at least 3,212 hours of load-shedding across the country's grid in 2022. On-site power generators, usually diesel-powered, are the most common

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[35] See https://energy.ec.europa.eu/news/new-energy-efficiency-directive-published-2023-09-20_en.

option for backup electricity supply, and are associated with relatively high GHG emissions (Smolaks, 2023). Growth of renewable energy and use of energy-efficient technologies (for instance, innovative cooling techniques) will be needed to meet demand from the anticipated increase in data centres (Begazo et al., 2023).

Some companies have already started to increase the share of renewable energy in the electricity supply. For example, Distributed Power Africa, a unit of the Zimbabwe telecommunications firm Econet, is overseeing the integration of alternative energy solutions into its data centres in Burundi, Kenya and South Africa (Africa Data Centres Association, 2021). Water consumption is also gaining more attention from data centre operators in Africa. There is an opportunity for data centre operators in Africa to spearhead a global drive to include water source and use metrics in their reporting and promote the wider use of water recycling in data facilities (Kadium Limited, 2022).

2. Asia

With rapid digitalization and surging demand for cloud-based services, the overall data centre market size in Asia and the Pacific is estimated to reach around $28 billion by 2024 (EcoBusiness Research, 2020). Much of the demand comes from global cloud providers, social media and e-commerce platforms, video streaming and banking, which all require robust IT infrastructure and data networks. According to the Digital Centre (2021), China leads the market in terms of data centre development, with India and Singapore among the frontrunners. Indonesia, Malaysia and Thailand are also making a sizeable contribution toward the region's growth.

Sustainability is becoming a key business imperative in Asia as customers, shareholders and the public are demanding accountability from corporations. Some of the challenges faced by data centres include rising carbon emissions, a tropical climate, which tends to be too hot and too humid for data centres, overcoming land constraints and the need for more efficient cooling technologies (Digital Centre, 2021). Accordingly, some Governments are adopting new policies to promote the sustainability of data centres (box III.2).

3. Latin America and the Caribbean

In Latin America and the Caribbean, the data centre market is still evolving. Echeberría (2020) estimates that there are currently about 30 data centres in the region with power supply capacities in excess of 15–20 MW. Brazil leads the market, with Chile, Colombia and Mexico emerging as important data centre locations. Investments in data centres in this region are expected to amount to $9 billion between 2021 and 2027.

Sustainability has become an increasingly important issue for the data centre industry in Latin America. Pressure is increasing on hyperscale data centres to demonstrate more efficient and cleaner operations, regardless of energy consumption. There have also been growing concerns in parts of Latin America over the large amounts of water required by data centres (McGovern and Branford, 2023).

Policies to promote more environmentally sustainable data centres in the region are still at a nascent stage. In June 2023, the Ministry of Development, Industry, Commerce and Services of Brazil and the Brazilian Agency for Industrial Development launched a study on the development of data centres in Brazil that will, among other things, look at how to secure better access to renewable energy.[36]

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[36] See https://www.bnamericas.com/en/news/with-unprecedented-diagnosis-government-begins-to-debate-policy-for-datacenters.

Box III.2
Data centre sustainability policies: Singapore and China

In Southeast Asia, Singapore is the main data centre hub. With 100 data centres, 1,195 cloud service providers and 22 network fabrics, the country has emerged as a global cloud connectivity leader. Singapore has taken various steps towards making data centres more environmentally sustainable, as follows:

- *Green Data Centre Standard:* Published in 2011 and revised in 2013, the Singapore Standard 564 (SS564) was developed by the Green Data Centre Standards Working Group under the industry-led Information Technology Standards Committee. The standard is modelled after the ISO 50001 standard on energy management but is tailored to meet the needs of data centres in Singapore. It defines a set of performance metrics for measuring their energy efficiency and includes a comprehensive set of recommended industry best practices for data centre design and operations;
- *Green Mark for Data Centres:* The Green Mark, first launched in 2012, is a rating system that encourages the adoption of energy-efficient design, operation and management of data centres. Since 2022, new data centres must meet updated requirements, including obtaining “platinum” certification under the Green Mark for Data Centre criteria, achieving a design PUE of 1.3 or below, and providing evidence of a clear pathway to achieving 100 per cent renewable energy;
- *Green Data Centre Technology Roadmap:* To address energy and climate change, the National Climate Change Secretariat and the National Research Foundation jointly commissioned the Green Data Centre Technology Roadmap, which was published in 2014. The roadmap highlights the pathways from research and development to deployment for technologies that can help increase energy efficiency and lower carbon emissions of data centres in Singapore;
- *Tropical Data Centre Standard:* In 2023, Singapore launched one of the world’s first standards (SS697:2023) for optimizing energy efficiency for data centres in tropical climates. The new standard aims to help data centres develop a roadmap to support the gradual increase in the data centre operating temperatures to 26°C and above (instead of the current industry practice of 18–22°C). This could lead to 2–5 per cent cooling energy savings, with every 1°C increase in the data centre operating temperature. The tropical standard forms part of the Digital Connectivity Blueprint, in which sustainability is a paramount factor.

The Government of China has also developed various policies to make data centres more environmentally sustainable. For example:

- In terms of data centre standard evaluation systems, the Ministry of Housing and Urban-Rural Development released the Technical Rules for Green Data Centre Building Evaluation in 2015; the Chinese Institute of Electronics released the Green Data Centre Evaluation Guidelines (T/CIE 049–2018) in May 2018; and the China Academy of Building Research released the Green Data Centre Evaluation Standard (T/ASC 05–2019) to evaluate and grade data centres on their environmental sustainability in 2019;
- In terms of data centre policies, the promotion of green data centres was proposed in 2012, and a series of policies and measures was introduced in the following years, standardizing and guiding the environmentally sustainable development of data centres;
- In order to promote more sustainable technology products for data centres and encourage environmentally sustainable and low-carbon development, the Ministry of Industry and Information Technology has been updating the Green Data Centre Advanced Applicable Technology Product Catalogue since 2016. The latest one was released in 2020 and involved 62 technical products in four fields, including efficiency improvements when using energy and resources, the use of renewable energy, distributed energy supply and microgrid construction technology products, waste equipment recycling and treatment, restricted substance use control technology, environmentally sustainable operation and maintenance management technology.

Source: UNCTAD, based on Chow et al. (2023), Singapore, Infocomm Media Development Authority (2023), Interesse (2023) and Li, Sun, et al. (2023)

E. Implications of different digital services and technologies

Environmental impacts in the use phase are not only affected by the types of devices used, but also by the activities and technologies involved. Digital services can encompass a wide variety of online activity, from web browsing, email and instant messaging, to social media, content-sharing platforms and video conferencing as well as services that rely on advanced technologies, for example, AI-powered large language models. The array of digital services used on a daily basis differ in how they employ technologies and infrastructure.

This section discusses the environmental impact of some widely used digital services, including video streaming and email, web searches and online advertisements. It then turns to more sophisticated digital services and their emerging underlying technologies, such as blockchain, AI, virtual reality, 5G and the IoT. These are poised to increase the demand for data services and affect the environmental footprint of the ICT sector, with some technologies (such as blockchain) primarily impacting data centres, and others, such as 5G and IoT, largely affecting networks and devices. Mitigating and managing the environmental impacts of these emerging technologies will require concerted efforts from all stakeholders.

1. Video streaming

The delivery of videos from content providers to viewers requires energy consumption across the ICT system, including in data centres, through data transmission networks and viewing devices. The energy and carbon footprint of video streaming has attracted significant media attention recently. For example, one study concluding that half an hour of streaming emitted as much CO_2 as driving 6.5 km (equivalent to consuming 6.1 kW of electricity per viewing hour) was widely quoted in the media (Kamiya, 2020b). Another estimate was that 7 billion YouTube views of the song “Despacito” had consumed 1.66 kW per viewing hour (900 GWh) (Kamiya, 2020a). Marks et al. (2020) first estimated that streaming 35 hours of high-definition video consumed 11 kW per hour (382 kWh in total). These estimates have since been revised downwards by over 90 per cent to 0.78–0.98 kW per hour (Makonin et al., 2022). As a comparison, a typical 50-inch LED television consumes about 0.08 kW per hour.

More recent analyses, using updated assumptions and methodologies, have concluded that the initial studies significantly overestimated the energy and carbon footprints (Moulierac et al., 2023), by up to 140 times in some cases (IEA, 2021d; The Carbon Trust, 2021). The European Commission (2023a) found that the full life cycle emissions of a typical hour of video streaming in Europe were responsible for 55g CO_2e, including emissions from device and digital infrastructure manufacturing, distribution, use and end-of-life phases.

Although earlier analyses by Obringer et al. (2021) and the Shift Project (2019b) and media articles had recommended that viewers reduce the resolution of videos to minimize their environmental impact, other research suggests that reducing bitrates has almost no impact on network energy use (Adelin et al., 2010; Chen et al., 2022; Koomey and Masanet, 2021; Malmodin, 2020; Schien et al., 2023). This is because data and network energy use are not proportional. Most network equipment consumes a similar amount of energy regardless of the volume of data traffic (Chan et al., 2016; DIMPACT, 2023). For example, a home Wi-Fi router might consume 10 W when a connected user is browsing the web. When the same user starts streaming a 4K resolution video – increasing data

Environmental impacts in the use phase are not only affected by the types of devices used, but also by the activities and technologies involved

The most effective way to reduce the energy footprint of video streaming is to use a smaller device…

…typical viewing patterns in low-income economies may therefore be less energy intensive than in high-income economies

traffic by around 3,000 per cent – the router might only use 10 per cent more energy, not 3,000 per cent more (Malmodin, 2020).

Actual environmental impacts for each user depend primarily on the viewing device and the electricity generation mix. For example, a 50-inch LED television consumes roughly 100 times more electricity per hour than a smartphone, and five times more than a laptop (figure III.2). Thus, the most effective way to reduce the energy footprint of video streaming is to use a smaller device. In developing countries, fewer individuals and households have a television compared with those who have mobile phones and use data. Typical viewing patterns in low-income economies may therefore be less energy intensive than in high-income economies.

Finally, assessing the energy and carbon footprint of video streaming (or any other digital service) requires a comparison with the relevant counterfactuals as well as an assessment of possible rebound effects. In the case of video streaming, the counterfactual case may be another form of video consumption (such as going to the cinema or renting a DVD). Rebound effects would be determined by how much more viewing is taking place due to the flat cost of video streaming. Incorporating both the positive and negative impacts is critical to understanding whether a certain digital service provides a net benefit or net cost to the environment.

2. Email, web searches and online advertising

Digital activities that are not data intensive, such as email and web searches, are also drawing media attention regarding their carbon footprints, with calls to cut back on emails to reduce carbon footprints. A widely cited suggestion is that more than 16,000 tons of CO_2 emissions per year in the United Kingdom could be avoided if every adult sent one less unnecessary email per day (*Bloomberg*, 2020; *Financial Times*, 2020; *The Guardian*, 2019).[37] More recent estimations are much lower. In fact, sending fewer emails is now seen to have almost no impact on energy use or GHG emissions (*BBC News*, 2020; Viana et al., 2022). Nevertheless, there can still be other environmental benefits – and, more importantly, operational and productivity-related benefits – from sending fewer unnecessary emails and sharing files through the cloud instead of sending them as email attachments.

Advertising is now ubiquitous on the Internet, with the average Internet user being exposed to thousands of advertisements per day. Pärssinen et al. (2018) concluded that online advertising used 20–282 TWh in 2016. More recent analysis by Cabañas et al. (2022) estimates that online advertisements consume 2–91 TWh per year, and Pesari et al. (2023) found that online advertisements and trackers consumed only 0.61 TWh in 2019. The significant variation in these figures – with low and high estimates differing by a factor of nearly 500 – reflect the lack of methodological consistency. Much larger environmental impacts of online advertising are likely incurred in other sectors through its indirect effects, for example, by influencing purchase decisions (like encouraging consumers to buy more items; see chapter V) and other unsustainable behaviours (for instance, encouraging vacation travel to distant locations) (Hartmann et al., 2023).

3. Blockchain

Blockchain and other distributed ledger technologies are major energy users and generators of digitalization-related

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[37] These claims were based on analysis by OVO Energy, an energy utility company in the United Kingdom, which assumed that one unnecessary email emitted 1g of CO_2 (*Financial Times*, 2020; Ovo Energy, 2019). In 2021, Ademe, the French Agency for the Ecological Transition, similarly reused estimates from 2011 regarding the GHG emissions impact of an email or web search (Bio Intelligence Service and Ademe, 2011; *TF1 Info*, 2021).

waste.[38] Blockchain uses energy to validate transactions and mine cryptocurrencies using ASICs.

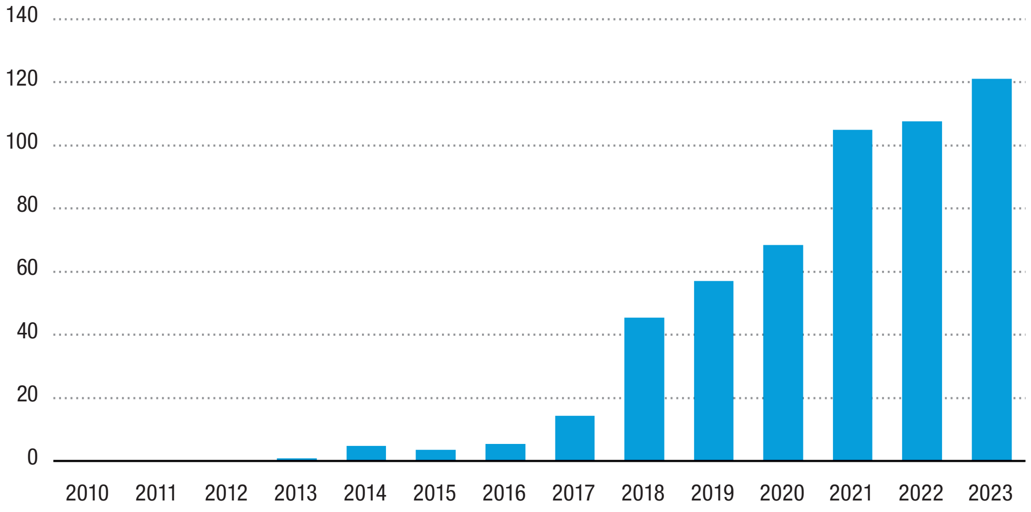
This hardware is often housed in facilities that are effectively data centres, some analysts have included cryptocurrency energy use when estimating global data centre energy consumption (Hintemann and Hinterholzer, 2022). But others have chosen to analyse the energy and climate impacts of these activities separately (IEA, 2023d; Malmodin et al., 2024; Masanet et al., 2020).

Including blockchain within data centre energy use metrics greatly increases overall energy use. Energy use specifically due to blockchain activities grew by 2,000–3,500 per cent between 2015 and 2022, while other data centre energy use grew by 20–70 per cent (IEA, 2023d). Highlighting the energy and climate impacts of cryptocurrencies can raise awareness to the issue and point to the need for developing the necessary technology and policy options to mitigate adverse impacts.

Bitcoin is the most prominent example of a "proof-of-work"[39] blockchain. It is the most valuable cryptocurrency by market capitalization. Bitcoin consumed an estimated 120 TWh in 2023, 33 times more than in 2015 (Cambridge Centre for Alternative Finance, 2024) (figure III.6). Ethereum, second behind bitcoin in terms of market capitalization and energy use, consumed around 17 TWh in 2021 (McDonald, 2022). In September 2022, Ethereum transitioned from a "proof-of-work" consensus mechanism to "proof-of-stake",[40] expected to reduce energy use by 99.95 per cent (de Vries, 2022). Some cryptocurrency advocates state that bitcoin mining is "green" because it absorbs

According to IEA, energy use due to blockchain activities grew by 2,000–3,500% between 2015 and 2022

Figure III.6
Annual bitcoin energy consumption, 2010–2023
(Terawatt hours)



Source: UNCTAD, based on Cambridge Centre for Alternative Finance (2024).

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[38] See Digiconomist (2023); de Vries and Stoll (2021); Cambridge Centre for Alternative Finance (2024); McDonald (2022); Gallersdörfer et al. (2020).

[39] "Proof-of-work" is a consensus mechanism that ensures trust across the network. Computers on the network – "miners" – compete with each other to solve a complex computational puzzle, requiring vast amounts of computing power and energy (Kamiya, 2019a).

[40] "Proof-of-stake" is an alternative consensus mechanism to proof-of-work. In this case, the scarce resource is no longer computing power as in proof-of-work, but capital (or stake) as proven by the ownership of cryptocurrency linked to the corresponding blockchain (Coroamă, 2021).

excess or stranded renewable energy generation, reducing curtailment and carbon emissions (Square, 2021; *Time*, 2022). This requires further analysis as cryptocurrency mining can be expected to be undertaken where electricity is cheap, not where it is supposedly plentiful (Coroamă, 2022).

The environmental footprint of cryptocurrencies is concentrated in a few countries that host most of the mining activities.[41] Following restrictions by China on cryptocurrency mining, introduced in May 2021, some mining capacity shifted to fossil-fuel heavy regions such as Kazakhstan (Cambridge Centre for Alternative Finance, 2024; de Vries et al., 2022). Kazakhstan hosts roughly one sixth of global cryptocurrency mining operations, with a very high water intensity for electricity generation (Siddik et al., 2023). The effect of the geographical redistribution of cryptocurrency mining operations has led to an increase in global water consumption associated with such activities of an estimated 73 per cent, but led to a 10 per cent decrease in GHG emissions (Siddik et al., 2023).

Other environmental aspects of cryptocurrency mining include digitalization-related waste generation from specialized mining hardware, which cannot be easily repurposed for other computing tasks. Given the enormous energy use of bitcoin mining, operators are incentivized to use the latest, most powerful and energy-efficient hardware. Although this can reduce energy use, it comes at the expense of creating more waste (chapter IV).

The increased demand in machine learning is likely to result in a significant net growth in total AI-related energy use

4. Artificial intelligence

Climate change implications of AI and machine learning are significant but highly uncertain (Cowls et al., 2021; Kaack et al., 2022; Rolnick et al., 2023). Just as ICT impacts climate change more generally, the environmental implications arising from AI and machine learning can be categorized into direct effects (GHG emissions resulting from computing) and indirect effects (the effect of GHG emissions from applications of AI or machine learning, as well as structural or “system-level” GHG effects induced by these applications) (Kaack et al., 2022).

Machine learning systems require computing resources and hardware, primarily in large data centres, that use energy, water and materials. The majority of machine learning-related GHG emissions today likely comes from computing loads in large data centres, with a smaller share from distributed computing (for example, PCs and smartphones). These emissions result both from operational energy use during computation and from other phases of the hardware life cycle (including embodied emissions).

Early studies of the environmental footprint of AI and machine learning focused on the energy use and carbon emissions associated with the training of large machine learning models.[42] However, training a single model represents only a share of the overall energy and GHG emissions of machine learning. Recent data from Google and Meta suggest that the training phase accounts for 20–40 per cent of overall machine learning-related energy use, with 60–70 per cent for inference (application/use) and up to 10 per cent for model development (experimentation) (Patterson et al., 2022; Wu et al., 2022).

Understanding inference-related energy use will become more important as mainstream AI applications become more widely adopted, especially if there are no financial costs to the user that could limit its deployment. OpenAI, the company behind ChatGPT, has estimated that the average cost “is probably single-digits cents per chat” (Kinsella, 2022). Semianalysis (2023) found that an average ChatGPT query

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[41] For example, Canada, China, Ireland, Kazakhstan, Malaysia, Singapore and the United States (Chamanara et al., 2023; Siddik et al., 2023).

[42] See Lacoste et al. (2019); Luccioni et al. (2020); Schwartz et al. (2019); Strubell et al. (2019).

costs around $0.0036 (3.6 cents). Based on this estimate, Ludvigsen (2023a, 2023b) concluded that ChatGPT used about 4 GWh in January 2023 (in a range of 1.1–23 GWh). This is about three times more electricity than was used to train GPT-3 (1.3 GWh) (Patterson et al., 2022), a large language model that provided the basis for ChatGPT. For comparison, 4 GWh is roughly equivalent to the monthly electricity consumption of 400 households in the United States.

Only a fraction of total ICT energy use is attributable to AI and machine learning, although its exact share is not known. There is limited data and no clarity on how to define the boundaries (i.e. what is included or excluded from AI and machine learning), and no established methodology for measuring energy use (Kaack et al., 2022). Based on estimates of global ICT energy use (IEA, 2022c) and shares of data centre workloads and data centre IP traffic attributed to AI (Cisco, 2018; Compton, 2018), machine learning and AI may have accounted for less than 0.2 per cent of global electricity use and less than 0.1 per cent of global GHG emissions in 2021 (Kaack et al., 2022).

While Google reports that machine learning accounts for less than 15 per cent of the company's total energy use, it is growing at a similar rate (20–30 per cent) as overall company-wide energy use (Google, 2022; Patterson et al., 2022). Computing demand for machine learning training and inference at Meta have increased annually by more than 100 per cent in recent years, compared with 40 per cent for its overall data centre energy consumption (Meta, 2022; Naumov et al., 2020; Park et al., 2018).

The combination of rapid growth in the size of the largest machine learning models (OpenAI, 2018) and the increasing energy needs for machine learning-related compute demand (Wu et al., 2022) are expected to outpace potential energy efficiency improvements in the coming years. This trend is likely to result in a significant net growth in total AI-related energy use. This will make measuring and reducing the energy, carbon and water footprint of AI even more critical. The use of low-carbon energy – both in powering data centres as well as in manufacturing machine learning-related hardware – will become essential to reduce GHG emissions from AI.

The need for more powerful hardware (such as graphics processing units) is also set to attract growing interest in AI-related water consumption in data centres (*Bloomberg*, 2023; Li, Yang, et al., 2023). Microsoft training of GPT-3 in its data centres in the United States directly consumed an estimated 700,000 litres of clean freshwater; that volume would have tripled if training had taken place in their data centres based in Asia (Li, Yang, et al., 2023). It is also necessary to reconcile the water-carbon conflicts for AI model training and inference to cut the water footprint. For example, to reduce the carbon footprint, it is preferable to "follow the sun" to where solar energy is more abundant, while to reduce the water footprint, it is preferable to "unfollow the sun" to avoid high-temperature hours in the day. Computing loads in general, and training AI in particular, cannot only be shifted in time, but also geographically, to take advantage of low-carbon electricity – a paradigm known as carbon-aware computing (Radovanović et al., 2023). Thus, a holistic approach is desirable to address water footprint along with carbon footprint to enable more sustainable AI (Adelin et al., 2010; Chen et al., 2022; Koomey and Masanet, 2021; Malmodin, 2020; Schien et al., 2023).

To reduce carbon footprint of data centres, it is preferable to **"follow the sun";** while to cut the water footprint, it is preferable to **"unfollow the sun"** to avoid high-temperature hours in the day

Policymakers and companies should also pay attention to the indirect effects of AI on climate change, given the potentially large impacts of such applications on GHG emissions. Artificial intelligence can induce various economic, environmental, and societal benefits in several other domains such as medicine or weather forecasting. Recently, for example, a machine learning model outperformed the best traditional numerical weather prediction algorithms (Lam et al., 2023). This not only induces economic, environmental and social indirect benefits, but even direct environmental benefits within the ICT sector, as traditional numerical weather prediction is computationally much more complex than the machine learning models that outperform them. Conversely, some uses of machine learning could escalate emissions in other sectors and services, for example, if they increase the competitiveness of emissions-intensive activities such as fossil-fuel extraction or induce additional consumption through recommender algorithms.

5. Virtual reality in the metaverse

The so-called “metaverse” provides a digital immersive environment for people to communicate, work, entertain and trade by using technologies such as virtual reality and augmented reality (Zallio and Clarkson, 2022).

Widespread adoption of augmented reality, virtual reality and the metaverse could present both positive and negative environmental impacts. On the one hand, immersive realities can have indirect positive effects and reduce GHG emissions by replacing physical travel, meetings and sightseeing with virtual events. On the other hand, the metaverse and the technologies that power it may have significant direct adverse environmental impacts. The metaverse generally requires advanced end-user devices, higher edge computing power and fast networks which consume substantial amounts of electricity and water and, accordingly, may generate more GHG emissions.

The metaverse consumes energy mainly through three layers, namely the infrastructure layer, which supports computation in the form of data centres and network infrastructures; the interaction layer, which supports human–computer and human-to-human interaction in the form of hardware, software, end-user devices and networking equipment; and the economy layer, which supports transactions between users in the metaverse in the form of cryptocurrencies (Liu et al., 2023). It has been estimated that GHG emissions associated with the metaverse could be as high as 115 MtCO$_2$e by 2030, which would account for an estimated 0.5 per cent of global carbon emissions (Liu et al., 2023).

Some believe that the metaverse may reduce more emissions than it causes by accelerating decarbonization and the energy transition, and by reducing gaseous pollutant emissions (Stoll et al., 2022; Zhao and You, 2023). For example, a study on GHG emissions of the metaverse in the United States suggested that a growing metaverse sector could reduce emissions by 10 GtCO$_2$e in the United States by 2050 (Zhao and You, 2023). However, the risk of increased emissions due to inefficient substitutions, induced demand and rebound effects remains (Stoll et al., 2022). Further empirical research and model-based studies on net effects of virtual activities are needed to guide stakeholders onto a pathway that benefits rather than harms the progress towards net-zero.

The metaverse is still in a nascent state (Kshetri and Dwivedi, 2023). Policymakers, investors and other stakeholders need to help design a metaverse that is not only environmentally sustainable but also inclusive. Entry barriers, such as high upfront costs (due to, for instance, hardware) and required infrastructure (including high-speed Internet), could lead to the exclusion of relatively disadvantaged groups participating in the metaverse.

6. 5G and the Internet of things

As noted in chapter II, the share of 5G in global mobile data traffic is expected to rise significantly in the coming years. 5G mobile networks are anticipated to be more energy-efficient than 4G mobile networks per unit of traffic and benefit from improved “sleep modes” (*IEEE Spectrum*, 2018; *Orange Hello Future*, 2022; STL Partners, 2019). At the same time, higher traffic volumes and a larger number of base stations[43] will likely mean increased overall energy use and emissions from widespread 5G deployment, as indicated by studies from countries in Europe (Bieser et al., 2020; Golard et al., 2023; France, Haut conseil pour le climat, 2020; Williams et al., 2022).

IoT adoption is also set to grow rapidly, facilitated by the roll out of 5G mobile networks. IoT devices are generally expected to be energy-efficient, but the growth in their number could have important implications for standby energy use and embodied energy and material (chapter II). In addition, more and more applications involving video transmission and tracking large amounts of data will impact energy demand (Pohl and Hinterholzer, 2023).

> Expansion of IoT significantly increases standby energy use and embodied energy and material

F. Concluding observations and recommendations

This chapter looked at the environmental footprint of the use phase of the digital economy. Special attention was put on the role of data centres, as their environmental impacts are particularly important during the use phase. It is expected that their role will continue to expand in view of the increased uptake of key emerging technologies and continuing digitalization. The chapter underlined the importance of not singling out individual environmental indicators (such as GHG emissions), as a guidepost for environmental sustainability. The most sustainable approach is one that focuses in particular on energy efficiency and responsible water consumption.

Given the rapid pace of technological progress, and difficulties associated with measuring energy use and its associated GHG emissions as well as water consumption, long-term forecasts of the environmental footprint of the use phase of the ICT sector beyond the next five years are extremely uncertain. One factor that contributes to this uncertainty is the scope for further energy efficiency improvements. If current energy efficiency trends in computing continue, processor efficiency limits could be reached by around 2040 based on the physical efficiency limits of transistors (Koomey et al., 2013).[44]

Data centre energy use is expected to continue to increase due to growing demand from compute-intensive AI applications and global expansion of digitalization. IEA (2024) estimated that in 2026, total electricity consumption by data centres (including cryptocurrencies) could more than double from 460 TWh in 2022 to more than 1,000 TWh. This increases the importance of powering data centres through renewable energy sources to curb GHG emissions (without crowding out the use of renewable energy by other sectors), while also reducing emissions from supply chains, and increasing circularity of data centre hardware (chapter IV). More attention will also need to be given to mitigating the impact of data centres on scarce water resources.

> **Forecasts** beyond the **next five years** of the environmental footprint are **extremely uncertain**

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[43] As 5G transmission uses higher frequency ranges than previous generations, the distance between the antenna and the end devices must be shorter, meaning more antennas will need to be manufactured and deployed (Pohl and Hinterholzer, 2023).

[44] In 1985, physicist Richard Feynman estimated that improvement by a factor of 10^{11} would be possible compared to computer technology at the time. While Feynman assumed a three-atom transistor to calculate his limit, smaller ones, could push these limits further (Fuechsle et al., 2012). Some experts (Demaine et al., 2016) estimate that maximum possible efficiency may be reached by around 2060 due to Landauer's principle – the minimal amount of energy needed to erase one bit of information (Bennett, 2003). They further assume that improvements in energy efficiency could slow down before reaching his limit.

To enable a global distribution of data centres that contributes to environmental sustainability, measures need to be taken to foster better data governance. Policymakers around the world need to assess the costs and benefits involved in deciding the physical location of data, taking into account the specificities of a country and their own development strategy needs. This points to the need for a robust international framework regulating cross-border data flows to ensure access and guarantee that any income gains from data are equitably shared. Such a framework would also need to be flexible, so that countries with different levels of readiness and capacities to benefit from data have the necessary policy space when designing and implementing their development strategies in a data-driven digital economy. These efforts should be complemented by improvements in the capacity to process data in developing countries (UNCTAD, 2021a).

Connected devices already consume more electricity than data centres. The sheer number of devices and the standby power consumption of connected devices are of particular concern. An increasing number of smart IoT devices use energy continuously to maintain connectivity. This trend adds to electricity demands linked not only to device usage, but to transmission networks and data centres.

Government policies to promote good practices together with efforts by the ICT industry to improve energy efficiency could play an important role in slowing down energy demand growth more generally. For instance, in data networks, policies to accelerate the early phase-out of energy-intensive legacy networks could be particularly important (Langham, 2022).

As energy already accounts for a significant share of the operating costs for data centres and network operators, there is a clear incentive to look for ways to make these even more energy-efficient. Even if further efficiency improvements are achieved, there is a need to ensure that future adoption of ever more sophisticated, compute-intensive digital services pays sufficient attention to their environmental footprint. Limiting the environmental impacts of these services will require careful planning and major investments in renewable energy and grid infrastructure.

On a smaller scale, users can influence the outcome by adapting their online behaviour. Even if some early assessments exaggerated the direct effects of sending emails or video streaming, important steps can still be taken. For example, an effective way to reduce the energy footprint of video streaming is to use devices with smaller screens and keep the devices for longer. Companies and organizations can also look into analysing dark data to derive insights while also educating employees on how to overcome instincts to hoard unnecessary data.

Some countries are beginning to act with a view to mitigating negative environmental effects from the use of ICT goods and services. However, these remain at a nascent stage in most parts of the world. Improved data and more research are needed, in particular studies and information that relate to the specific challenges faced in many developing countries. This would help to create a reliable basis for policymaking that promotes the use of sustainable energy and better water management for data centres. There is a lack of detailed data on the energy and water consumption characteristics of data centres and networks, as well as on particular segments (such as smaller data centres and supply chains). Better and more frequent tracking of a wider range of indicators related to GHG emissions, water consumption and noise generation are also required.

Given the anticipated growth of energy and water consumption by data centres and data transmission networks, it is critical to ensure that these operations are increasingly powered by low-carbon energy. This is the responsibility of both the public and the private sector. Corporations can minimize impacts by locating data centres in areas with sufficient renewable energy and water resources, while continuing to improve the efficiency of energy and water use. They should also transparently report data on relevant environmental indicators, including with regard to the energy and carbon footprints of AI.

Governments can play a leading role in accelerating research and development to advance more efficient, next-generation technologies and systems. Through regulation, they can promote the improved energy efficiency of data centres and renewable energy mandates to reduce the carbon footprints. Regulation needs to provide long-term planning security for private-sector investment, while recognizing the dynamic character of the ICT sector. This may require agile policymaking. Regulators should ensure that electricity market design provides clear and sufficient price signals for data centres and other large electricity users to participate in demand response programmes. For example, allowing for some flexibility in ancillary service requirements, such as longer notice periods and response times, may make it easier for data centre operators to participate in such programmes. Progress on demand response policies has recently been made in Australia, Brazil, the Republic of Korea, Singapore and California in the United States, as well as in the European Union (IEA, 2023g).

In developing countries, Governments and utilities could consider opportunities to co-develop local electricity and water infrastructure with new data centre and network projects to expand electricity and water access in communities, with digital infrastructure serving as important anchor customers of electricity and water.

To achieve sustainable digitalization, it is unlikely that further improvements in the energy and water consumption efficiencies of end-user devices, communications networks, data centres and service provision will be sufficient. Other steps are needed to reduce the environmental footprint. Sector regulations are important to foster circularity and sufficiency (Pohl and Hinterholzer, 2023). For example, considering the energy impact of AI from a sustainability perspective, it is crucial to weigh the risks and benefits of using AI. Given the limited availability of information on resource use related to AI, regulators could consider introducing specific environmental disclosure requirements to enhance transparency across the AI supply chain (de Vries, 2023).

> Corporations should transparently report data on environmental indicators, including the carbon footprint of AI