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Guidelines for Assessments of the Global Information and Communication Technology Sector's Direct Energy Use and Climate Impact: Key Aspects and Future Scenarios

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Abstract

Digital technologies are profoundly influencing all economic sectors and have potential to contribute towards a sustainable society. At the same time, the production, use and waste management of these technologies, which lie at the core of the economic sector of information and communication technology (ICT), are causing environmental impacts. Previous studies have applied life cycle assessment (LCA) methodology and life cycle thinking to assess current and future direct energy use and climate impact of the global ICT sector. These studies frequently arrive at contradictory results regarding future impacts. Calculation approaches applied differ significantly, the consideration of key aspects varies, fast-growing digital technologies are seldom included in future scenarios and uncertainty analyses are typically limited. The aim of this study is to develop guidelines for assessments of the current and future direct energy use and climate impact of the global ICT sector based on LCA methodology and life cycle thinking. The guidelines have been developed based on literature reviews, the authors' aggregated and broad expertise in this topic and in workshops. Key aspects in influencing the current and future direct energy use and climate impact of the global ICT sector, covering its three subdomains of end-user devices, networks and data centres as well as all life cycle stages, are identified. These include, for example, the number of end-user devices, number of subscriptions and the annual electricity use of networks and data centres. The guidelines address challenges for practitioners and can contribute towards more transparent and coherent future studies.

Highlights

- Challenges for global ICT sector energy use and climate impact studies are reviewed
- Key aspects and methodological guidelines for assessments are provided
- Practical suggestions for development of future scenarios are provided

Keywords: ICT; LCA; Digitalization; GHG emissions; Carbon footprint; AI; IoT;

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[1] AI=Artificial intelligence; CO_2-eq=carbon dioxide equivalent; CPE=Customer premises equipment; CPU=Central processing unit; EEA=European energy agency; E&M=Entertainment and media; GHG=Greenhouse gas; GPU=graphic processing unit; ICT=information and communication technology; IDC=International data cooperation; IEA= International energy agency; IoT=Internet-of-things; ITU=International telecommunication union; LCA=life cycle assessment; Machine learning (ML); Machine-to-machine (M2M); PCF=product carbon footprint; PSTN=public switched telephone network; PUE=power-usage effectiveness.

1. Introduction

Digital technologies are profoundly influencing all economic sectors and can contribute to a more sustainable society. For example, digitally-enabled process optimizations can increase energy efficiency and digital applications can entirely replace physical counterparts [1-4]. Significant investments are being made in the rapidly changing information and communication technology (ICT) sector and in fast-growing digital technologies, such as artificial intelligence (AI). At the same time, digital technologies are associated with both direct and indirect environmental impacts [1]. Direct climate impacts of ICT occur along their entire life cycle, including raw material acquisition, production, use and waste management [5]. In contrast to direct effects, which by definition lead to increased impacts, indirect effects describe the impacts of ICT applications in other sectors (e.g., transport, energy and buildings) and can lead to both reduced and increased impacts. Indirect impacts might be at least as important as direct ones; however, we cannot discuss them with credibility if not being able to discuss direct impacts, which is the focus of this paper.

The urgency of the climate crisis requires the minimization of current and future direct greenhouse gas (GHG) emissions and the related climate impact of the ICT sector. This sector can be divided into three major subdomains, or equipment types: end-user devices (e.g. laptops and smartphones), networks (e.g. core network, fixed-access and mobile-access networks) and data centres (e.g. servers). Environmental impacts of the ICT sector, its subdomains or specific ICT applications are commonly assessed using life cycle assessment (LCA) methodology [6]. In line with this methodology, each ICT subdomain can be divided into four life cycle stages [7]: raw material acquisition, production, use and waste management. LCA is applied to assess the potential environmental impacts of a product or service over its life cycle [8] and typically used to identify life-cycle impact "hotspots" and to avoid problem-shifting. Prospective LCA is applied to assess potential future life cycle impacts of technologies [9].

Previous studies that have applied LCA methodology and/or life cycle thinking to assess the current and future direct climate impact, or so-called carbon footprint, of the global ICT sector frequently arrive at contradictory results for future impacts [10, 11]. Some study scenarios projected that the climate impact might increase significantly in the future [12, 13] while others suggested that it will remain roughly stable or even decrease [13, 14]. A critical review of previous studies on the global ICT sector's current and future direct climate impact identified large differences in the calculation approaches applied, parameters applied for scaling, type of data used etc. [15, 16]. Uncertainties are typically stated to be considerable, but uncertainty analyses, e.g. via construction of different scenarios or sensitivity analysis, are rarely conducted. Notably, fast-growing digital technologies, such as AI, Internet-of-Things (IoT) and cryptocurrencies, as well as emerging technologies, such as quantum computing, are seldom included in future scenarios; even though these might become significant climate impact contributors. Furthermore, the inclusion of, and focus on, different key aspects, such as the number of end-user devices and the carbon intensity of electricity, vary considerably [17]. General recommendations have been provided for assessments of the global ICT sector's direct energy use and climate impact [18]. However, concrete guidelines for practitioners related to challenges for assessments, and especially for future scenario construction, are needed. In summary, several questions related to the ICT sector's current and future direct climate impact remain to be answered, including:

- How can key aspects be modelled in assessments of the current, and especially future, direct energy use and climate impact of the ICT sector, also including fast-growing and emerging technologies?
- How can future scenarios be constructed considering these key aspects including fast-growing and emerging technologies?

The aim of this study is to develop guidelines for assessments of the current and future direct energy use and climate impact of the ICT sector based on LCA methodology and life cycle thinking. This includes identifying key aspects that influence the sector's direct energy use and climate impact, describing related challenges and providing guidelines for scenario construction. The direct energy use of the ICT sector here refers exclusively to the use stage energy of end-user devices, networks and data centres. In contrast, climate impacts refer to all life cycles stages and subdomains of the ICT sector. Assessments of specific services is not in scope. The guidelines are developed to support researchers and LCA practitioners by suggesting modelling approaches, suitable input data and ways to address methodological challenges to increase the robustness of study results. Recommendations on future research directions to address important knowledge gaps are also provided. Several key aspects, i.e. a set of critical assessment model parameters, are suggested. Other important aspects and challenges for assessments, such as scope and future scenario construction, are also raised. The guidelines provided in this paper have been developed based on a review of identified knowledge gaps and related challenges in practice, the authors' aggregated and broad expertise in this topic and on extensive workshop discussions, see further **Section A1** in **Appendix A**.

2. Current state-of-the-art in practice and related challenges

2.1. Scope of the ICT sector

In LCAs, the goal and scope of the study must be precisely defined and all ICT subdomains and life cycle stages should ideally be considered. The study goal can, for example, be to identify strategies for decarbonizing the ICT sector and provide useful information to companies, consumers and policymakers. A clear definition of the scope is essential to compare changes in the sector over time, and to consistently compare or combine results of different studies. OECD [19] defines the ICT sector as "industries whose products primarily fulfil or enable the function of information processing and communication by electronic means". In this definition, the sector boundaries are defined by the intersection of a *functional criterion* (information processing and communication) and a *technological criterion* (electronic means). This excludes non-electronic information and communication services, such as paper media and postal services, as well as electronic products whose primary function is not information processing and communication, such as a connected vehicle. ITU-T [18] defines the ICT sector as all goods "that handle (e.g. access, create, collect, store, transmit, receive, disseminate) information and communication". In this case, the sector boundaries are solely based on the functional criterion, regardless of technology.

There exist two main approaches for defining the ICT sector scope in practice. The first scoping approach is based on the *technological criterion* and includes all products that implement digital technologies (e.g., for sensing, information processing, connectivity), regardless of their primary function. With this approach, the system boundaries include all products embedding digital technology, including all three ICT subdomains and, at least, all connected objects. A variant of this approach is to restrict the system boundaries to the electronic sub-parts of products that implement digital technology. The second scoping approach is based on the *functional criterion* and includes all products and sub-parts of products whose purpose is to provide ICT function(s), whatever the underlying technology, be it non-digital. The ICT function(s) then need to be defined, e.g., information processing and human-to-human communication. With this approach, the system boundaries include all products whose functions are primarily ICT-related (e.g., smartphones, analogue TV/radio broadcast, postal services), plus the sub-parts of products whose primary function is not ICT-related, but which include an ICT function (e.g., the infotainment modules of a connected car).

In practice, it is common to define, explicitly or implicitly, the ICT scope as an intersection of these two scoping approaches, but with different views on what are the specific technologies and functions of ICT. For instance, previous studies often differ in their definition of boundaries between ICT subdomains (e.g. including customer premise equipment (CPE) in the end-user device or network subdomain) [15]. Boundaries set to other sectors also differ (e.g. including TVs, printers etc. in the ICT or entertainment and media (E&M) sector). There is a trend to categorize some of the end-user devices in the E&M sector as ICT devices because of the proximity of these devices to the functional criterion of ICT and the fact that they use electronic means. Some studies considered both the ICT and the E&M sectors albeit with a distinction between them [14].

Because of the massive digitalization and introduction of fast-growing technologies, such as AI, IoT and cryptocurrencies, there is a need to continuously revisit the boundary definition of the ICT sector and its subdomains. To that end, AI and IoT are addressed in **Section 2.8**. The mining equipment for cryptocurrencies are, similar to AI, also hosted in datacentre-like infrastructure, but by different actors, and their main function is not well aligned with the functional criterion. Therefore, cryptocurrencies are usually excluded from ICT sector studies.

2.2. Calculation approaches

2.2.1. Bottom-up and top-down approaches

Different calculation approaches exist in practice for the ICT sector's direct energy use and climate impacts. In general, these approaches fall into two main types – bottom-up and top-down (or a combination thereof) – each with their own advantages and disadvantages [20, 21]. These concepts are often interpreted and applied in different ways. In this paper, we apply these terms as follows: A bottom-up study estimates quantities of specific devices (e.g. smartphones, mobile network antennas, servers) and multiplies those with the energy use and climate impact per device. A top-down study estimates the energy use and climate impact for aggregate clusters that contain a larger set of different device types, such as the energy use and climate impact reported by a mobile or data centre operator.

Bottom-up studies, such as [22], use detailed data on the installed base and shipments of ICT equipment and their energy use. These studies are useful for exploring the effects of policies and technological change but are time- and resource-intensive, and some data inputs might be expensive and proprietary. Top-down studies use existing estimates on e.g., network electricity use from companies, which are typically based on measured data and thus useful to observe year-to-year changes. However, such data are not available for all countries or organizations and the methodologies applied, scopes as well as reported level of details vary. Therefore, only a portion of the overall scope can be reliably estimated with a top-down approach, leading to the requirement of other complementary approaches to ensure completeness, such as extrapolating company data based on number of subscriptions or global revenue share [14]. Studies that largely or partly rely on top-down approaches include e.g. [20, 23].

2.2.2. Approaches to assign embodied emissions to specific years

The term "embodied emissions" is here used to denote emissions related to raw material acquisition, production and waste management. ICT sector studies are typically assessing annual impacts (i.e. "per year"). In order to identify how the embodied impact of ICT subsectors evolves over time, it is important to consider how to model embodied impacts per year. Two different approaches exist in practice to assign embodied emissions to specific years [15]. In the first approach, embodied emissions are assigned to the year of ICT equipment production, see e.g., the modelling of end-user devices in [23]. This implies that the annual embodied emissions of the global ICT sector in a specific year are calculated based on the embodied emissions of shipments (flows) of equipment, assumed to represent equipment production, in that year. For this approach, data on lifetimes of ICT equipment are not needed as the embodied emissions are assigned to the equipment's production year. In the second approach, embodied emissions are distributed over the equipment's lifetime by dividing the total embodied emissions of the installed base (stock) of ICT devices by their lifetime [see e.g., 12]. In this case, the global ICT sector's embodied emissions in a specific year depends on shipments (flows) in that year, on shipments in previous years and the equipment's lifetime. Data on the lifetime of ICT equipment are thus needed to assign embodied emissions to a specific year.

2.3. Future scenarios

Developing reasonable energy use and climate impact scenarios for ICT can be immensely challenging due to extensive uncertainties associated with rapid (and difficult to predict) changes in technologies, demand and efficiency. The energy efficiency of underlying technologies has been increasing rapidly [24]. Yet, these efficiency improvements have been consumed by growing numbers of users and usage. The result of these two major trends has been a slight increase in the overall electricity use of the ICT sector between 2007 and 2020

[23]. Whether these two major trends will continue in the same way in the future is however not certain.

One possibility to account for such uncertainty is the construction of different types of future scenarios. Scenarios can be divided into predictive, explorative and normative ones [25]. These categories are defined according to what kind of question they respond to. Predictive scenarios respond to "what will happen?", explorative scenarios to "what can happen?" and normative scenarios to "how can a specific target be reached?". The point of this categorization is to highlight that the future can be approached from widely different perspectives and the selected scenario type will influence the outcome.

Predictive scenarios model a development some time into the future, they start out from explicit and/or implicit assumptions and then try to depict what will happen. Creating a set of explorative scenarios, and then analysing what demands this sets on the ICT system is another way to explore future ICT impacts and investigating uncertainties. Then the scenario analysis outcome will be a mixture of assumptions regarding how technology develops and explorations of how society unfolds. Explorative scenarios explore a limited number, often about four, different futures and can be developed based on a "leading idea" of what could happen with ICT in the future. Such scenarios can be inspired by qualitative scenarios, such as a "life-online-scenario", where people lead full lives online while the physical environment is mostly neglected, and "valued environment scenario" in which the development and implementation of ICT are dedicated to solving environmental problems [26].

In practice, scenarios for the global ICT sector have typically been limited to the construction of predictive, or in some cases explorative, scenarios [15]. The International Telecommunications Union (ITU) has provided some recommendations for normative scenarios for assessments to be in line with specified climate budgets [18, 27].

2.4. End-user devices

2.4.1. Current situation for end-user devices

The number of end-user devices in use, such as smartphones, laptops etc., influence the direct energy use and climate impact of the global ICT sector. Different approaches are applied in practice to estimate the number of units for shipments and installed base of devices. Shipments of different end-user devices and installed base estimates are often published by market analysts and might be benchmarked towards subscription numbers, e.g. for smartphones. However, such analyses often group devices differently, leading to varying results between sources.

To estimate the electricity use of devices, data on actual device usage patterns (e.g., operational service time per year) are required. In practice, studies on the ICT sector's direct climate impact usually do not collect device usage data but rely on secondary data from various sources. These include, for example, measurements in households [28] and device LCA studies that already include assumptions about device usage patterns [12]. The embodied emissions of end-user devices, on the other hand, depend on the types of raw materials used, manufacturing process characteristics and assumptions of future waste management strategies for devices. Different approaches exist to derive average embodied emission values [29] and for modelling specific life cycle stages, like waste management [30, 31] (see further **Section A.2.1** in the **Appendix**).

The lifetime of end-user devices describes the time between their manufacture and disposal, whereas the (active) service lifetime can be shorter as devices are often kept in storage after use and before being disposed of, also called hibernation [32]. Lifetimes of devices may be required to assign embodied emissions to a specific year depending on the calculation approach applied (see **Section 2.2.2**). They also directly influence the demand for new ICT devices and, thus, the number of devices manufactured (the shorter the lifetime, the more devices need to be produced in response to a specific demand). Furthermore, if the lifetimes of existing devices are significantly shortened (e.g. due to a significant technological leap), the number of disposed devices can significantly increase. Average device lifetimes vary by region and device type and also change over time, which makes quantification of device lifetimes challenging.

2.4.2. Future scenarios for end-user devices

Different approaches are used for extrapolating the number of end-user devices and their annual electricity use and embodied emissions into the future [15]. The number of end-user devices are commonly extrapolated based on projected trends. Values for the annual electricity use and embodied emissions of end-user devices sometimes are kept unchanged over time or adjusted based on projected energy efficiency improvements. Future changes in device lifetimes are usually not accounted for in practice but in some cases, best-/worst-case scenarios are applied for dealing with uncertainty [see e.g., 12, 13]. Future changes in device lifetimes are highly uncertain as they depend on a variety of factors, such as marketing campaigns, legal restrictions and technological leaps which could make devices obsolete (e.g., from 4G to 5G and 6G), changes in business models (e.g., from selling to renting devices) or awareness for sustainability issues in the population [32]. It is even more challenging to predict the lifetime of new device classes still in development. Another challenge is related to when to consider a repair or refurbishment process, e.g. when smartphone parts are replaced with new ones, as an extension of the service life of an existing device or the start of the service life of a new device [33].

2.5. Networks

2.5.1. Current situation for networks

Many different approaches are applied in practice to assess the current direct energy use and climate impact of networks. In the study by Andrae and Edler [13], the direct energy use was assessed based on data traffic volumes and the related electricity intensity per data traffic for some specific network technologies. Sometimes, networks direct energy use is estimated as a total value for the ICT subdomain based on other studies' electricity use estimates and an assumed annual growth rate [12]. For enterprise networks, specifically, GeSI and BCG [34] estimated the electricity use based on the number of computers used in the network and related operations overhead. Embodied emissions are sometimes estimated in relation to quantified use stage emissions with consideration of energy efficiency improvements [13]. In other cases, embodied emissions are excluded motivated by that the use stage impact of networks, which operate 24/7, is more significant [12].

Another approach includes collecting network operators' annual energy use and reported GHG emissions [14, 23, 35]. Data on number of subscriptions are then used to extrapolate the collected data to cover all subscriptions globally applying a top-down approach. Note that it is typically only so-called human subscriptions and not subscriptions for IoT/Machine-to-machine (M2M) that are used in these extrapolations. Challenges related to using subscriptions for extrapolation of network energy use to the global scale include e.g., the risk of double-counting human subscriptions when customers change operator. Another challenge is that fixed telephony subscriptions statistics can include both voice over internet protocol and public switched telephone network (PSTN).

Sometimes, bottom-up models are used by multiplying the number of installed network equipment by their associated electricity use and embodied emissions per unit [36-38]. In this case, the challenge is to understand and model the actual network architectures, determine the number of base stations, etc., and to assess their individual impacts. In some countries, open public data can be used to find out how much equipment are installed in a given territory. Otherwise, the information must be obtained from network operators. Sometimes, power consumption models are applied to estimate networks' electricity use and there exist LCAs of power consumption of different network equipment, such as cellular base stations [39]. However, this bottom-up approach is generally more complex than the top-down approach and hence less commonly applied in practice.

Similar to end-user devices (**Section 2.4.1**), lifetimes of network equipment may be required to assign embodied emissions to a specific year (see **Section 2.2.2**). The lifetime of network equipment is typically longer than for end-user devices. For example, the lifetime of mobile antenna towers, fixed cables in the ground and ducts, is typically over 20 years [40] while active equipment, such as switches, routers, servers, and exchange solutions, generally has a lifetime at about 10 years.

2.5.2. Future scenarios for networks

For networks, data traffic growth and potential improvements in energy efficiency are commonly applied in practice and highlighted as important for future projections [see e.g., 13, 41]. For example, some studies suggested that while 5G networks are expected to use less energy to transmit one bit of data than their 4G counterparts, the overall energy and climate impacts of 5G are likely to grow due to increasing traffic volumes, higher network density, and higher energy use per site [37, 42-44]. However, the modelling of these aspects and how they might influence network energy use is very challenging. For example, the methodologies behind data traffic estimates and measurements are not transparent and system boundaries can be defined differently [45]. Confounding this, there is potential variability between data providers owing to lack of standardisation. Instead of using data traffic, an alternative approach based on human subscription forecasts was applied in [14] and [27]. In line with ITU-T [27], the approach also included projections of network electricity consumption, e.g., by considering build-out of more coverage and capacity.

2.6. Data centres

2.6.1. Current situation for data centres

Published estimates of the direct energy use and climate impact of global data centres are wide-ranging and inconsistent. For example, estimates for 2020 range from around 200 TWh/year [22] to nearly 1000 TWh [12, 46] while near-term projections and scenarios diverge by up to 25-times [47]. These differences are mainly due to diverging data sources and modelling approaches [21, 48]. The literature identifies three main approaches for the assessment of data centre energy use: bottom-up, top-down, and extrapolation [20, 21]. Following the more detailed terminology proposed in Kamiya and Coroamă [48], several approaches – or combinations thereof – have been employed in practice to estimate global energy use of data centres. Bottom-up approaches are based on estimates of the installed server base combined with equipment specifications, such as the average server power consumption, and further energy-influencing attributes, such as the power usage effectiveness (PUE). Aggregated totals approaches, often described in the literature as "top-down" [20, 21], rely on national/regional or organisational energy use data, which have been directly – but roughly – measured or estimated. By contrast to bottom-up models, these measurements or estimates do not take place at equipment level, but typically for an entire data centre site, and are then aggregated across all data centres of an organisation or nation/region. Bottom-up and aggregated totals approaches can also be combined. In such a hybrid approach, a global estimate could be obtained by combining bottom-up and aggregated total estimates for individual countries [see e.g., 23]. In a geographic extrapolation approach, results can be geographically scaled-up, e.g. from a country to the global level [49]. Occasionally, other methods have also been deployed, such as system dynamics modelling to model data centre energy consumption due to AI [50].

Each of these approaches have their advantages and challenges [48]. Bottom-up models offer strong explanatory power for assessing policy and technological effects. However, they are resource-intensive and often rely on proprietary and untransparent data sources. With the advent of AI and general diversification of server types, averages are less reliable than they used to be. Aggregated totals, often relying on directly measured energy use of entire data centres, largely avoid these drawbacks. They do not allow, however, to distinguish individual energy use sources within data centres or to link these with specific technological developments. Hybrid approaches could be used for corroborating results and to take advantage of the specific strengths of bottom-up and aggregated totals. However, there is a risk that new issues, such as double-counting, need to be handled. Geographic extrapolation is usually desired for broader results, but it also introduces new uncertainties and sources of error.

2.6.2. Future scenarios for data centres

Similar to networks, the future direct energy use and climate impact of data centres in global ICT studies are in practice often derived based on future data traffic growth and potential energy efficiency improvements [12, 13]. The expected future development of proxies, such as the amount of data stored in or transmitted from a data centre, is used to estimate the future global data centre energy use. Some literature calls this method simply "extrapolation" to distinguish it from the geographic extrapolation [48]. The modelling of data traffic, energy efficiency improvements and their influence on data centre energy use face similar types of challenges as for networks (see **Section 2.5.2**). Instead of using data traffic, another approach was applied in [27] based on server industry roadmaps. In a similar manner, the study by Masanet et al., [22] projected global data center electricity use applying a bottom-up approach.

2.7. Carbon intensity of electricity

2.7.1. Current situation for carbon intensity of electricity

The carbon intensity (or emission factor) of electricity, e.g., the amount of GHG emissions associated with the use of one kilowatt-hour (kWh) of electricity, provides a measure to estimate the emissions related to the use of electricity and is relevant for all ICT subdomains. In LCA studies, this intensity should cover the entire life cycle impacts of electricity generation and provisioning, including construction, maintenance and deconstruction of power plants and grids, electricity generation, own electricity use, transmission, and distribution losses. In practice, the values applied, and life cycle coverage, vary across studies' current scenarios. Some studies applied global carbon intensity factors [12, 34]. Others applied company-specific carbon intensities, so-called market-based accounting [14, 23] when this was possible in terms of data availability. Such company-specific carbon intensities consider direct purchase agreements or renewable energy certificates. Another alternative is location-based accounting, applying a carbon intensity representing the regional or national average electricity mix. Market-based accounting reflects incentives of certain ICT companies, such as data centre operators, to use electricity with lower emission intensities than the national average. However, obtaining comprehensive market-based data for all relevant global ICT sector companies is challenging. Moreover, market-based energy procurement methods face criticism, as their role in promoting renewable energy expansion is frequently questioned [11].

2.7.2. Future scenarios for carbon intensity of electricity

Sometimes studies do not apply carbon intensity of electricity as a scaling factor for future scenarios, which is problematic as this suggests that the current and future electricity system are the same [15, 16]. Others considered changes in carbon intensity of electricity in their future projections based on a varying share of renewables in the electricity mix [13]. Prospective grid carbon intensities can be utilized from integrated assessment models [51, 52], or other published national or global analyses [53]. Another approach involves employing energy models to estimate future grid carbon intensities under various scenarios (e.g. "business-as-usual" and "net-zero to 2050"), and linking these models and estimates to the ICT sector. Such models can, for example, estimate future carbon intensities as a function of the share of renewables in the electricity mix. This approach offers greater flexibility and deeper insight into the interplay between energy sources and ICT demands but may be limited by the availability of data and analysis capabilities. Challenges related to use of time- and location-differentiated emissions factors and the purchase of renewable electricity or emission credits by single actors also apply for future carbon intensities.

2.8. Fast-growing and emerging digital technologies

Fast-growing ICT technologies include, for example, AI and IoT and their use affect the end-user devices, networks and data centres required for these technologies. This category of ICT may not be included in current scenarios and are typically not included in future scenarios for the global ICT sector's direct climate impact [15, 16]. This despite concerns that these technologies might outpace more traditional ICT in the future [12]. In this section, in response to their limited inclusion in previous studies and the ongoing public debate on their impacts [see e.g., 54], we turn our focus on the fast-growing technologies of AI (**Section 2.8.1**) and IoT (**Section 2.8.2**), specifically. This while acknowledging that other digital technologies, such as blockchain, cryptocurrencies and novel and emerging technologies may also be important to consider in future studies.

2.8.1. Artificial intelligence (AI)

AI refers to computer-based systems that can mimic aspects of human intelligence by analysing data and inputs to learn, think and take actions. Many believe that AI could have transformational impacts across wide-ranging use cases across all sectors and services [55]. At the same time, the direct energy use and climate impacts of AI are potentially large [56, 57]. Kaack et al., [56] proposed a framework to consider machine learning (ML)-specific factors in LCAs, advocating for the use of existing standards and approaches that are employed to conduct LCAs of other digital technologies and services. Ligozat et al., [58] explored how LCA methodologies can evaluate the environmental impacts of AI services. The literature on LCAs of specific AI services, such as a generative AI service [59], is emerging. Additional information on AI studies is provided in **Section A2.2** in the **Appendix**.

In addition to the impacts AI has on the energy use and embodied emissions of data centres, operating and accessing AI models (called inference) could also increase energy use from end-user devices due to a growing number of devices equipped with AI acceleration hardware (e.g., neural processing units) to handle AI tasks locally. End-user devices with specialised hardware are also likely to have higher embodied emissions than conventional ones. In addition, if devices with AI-enabling hardware accelerates the early retirement and replacement of existing devices, this could result in a near-term increase in emissions from manufacturing devices. The net impacts on data transmission networks are likely to be smaller than in data centres and end-user devices but are uncertain.

2.8.2. Internet-of-things (IoT)

The IoT vision calls for connecting physical objects of the daily life to the Internet. While IoT has been around for some time and several devices already are connected, many market studies and white papers predict an exponential growth in the number of deployed IoT devices [60]. For example, all cars put on the EU market must according to legislation have at least one embedded subscription, sometimes two, to be automatically activated if emergency occurs [61]. Similar solutions will probably follow in other sectors. A significant difference between IoT and more traditional ICT end-user devices lies in the number of distinct IoT services spread across multiple economic sectors, e.g., from building to transportation to agriculture. This makes it difficult not only to collect data on the current IoT shipments and installed base but also to make projections on them. The multitude of IoT devices makes the scoping difficult and their inclusion requires a revision of the boundary for the end-user device ICT subdomain. This is challenging as IoT overlaps with other economic sectors, such as e.g., transportation and building management (see further **Section A2.3** in the **Appendix**). However, given its importance and increased use, IoT devices are increasingly included in studies [see e.g., 14, 23]. Device heterogeneity of IoT also causes challenges for assessments. The reasons for this are that the electricity use and embodied emissions of IoT devices can vary significantly depending on the type of device considered. In response to this, Pirson and Bol [60] proposed a parametric framework for the evaluation of the cradle-to-gate GHG emissions of IoT devices, see further **Section A2.3** in the **Appendix**.

Another important aspect is that IoT devices also influence the usage of networks and data centres as it significantly impacts the types of edge devices used. For example, some IoT solutions require specific communication protocols. This requires the addition of a specific gateway device to interface this specific network to the generic network infrastructure, similarly to the CPE in fixed networks. The impacts of these gateways should thus be considered, e.g., by conducting a bottom-up LCA of gateways [62]. Other IoT solutions rely on specific versions of the cellular mobile-Internet network. These communication protocols allow a low power use for the IoT devices and a high coverage at the expense of a low data rate. Consequently, the usage of the time-frequency resources in the base stations is not as low as the traffic would suggest.

3. Guidelines for sector analysis of ICT with a focus on key aspects and future scenarios

3.1. Scope of the ICT sector

The growing digitalization of the economy across activity sectors, combined with fast-growing and emerging technologies, makes it important to clarify the scoping approaches for the ICT sector. While different scoping approaches are possible (**Section 2.1**), we recommend to explicitly mention the scoping approach applied and how it is used to draw the ICT sector system boundaries. As previous studies differ in their ICT sector definition, in boundaries set between ICT subdomains and in boundaries set to other sectors, we point out the need for caution when aggregating and/or comparing estimates from different studies.

To facilitate the combination and/or comparison of different future works, we suggest defining the scope of ICT at the intersection of functional and technological criteria as: digital electronic products that handle (e.g., access, create, collect, store, transmit, receive, disseminate) information and communication and as illustrated in **Table 1**. This aligns with ITU-T [18], except that enterprise networks are assigned to the network and not the data centre subdomain. This because enterprise networks are a type of access network and therefore better grouped with networks. **Table 1** also provides more details on e.g., what is comprised in consumer electronics for communication purposes and IoT devices than what is provided in ITU-T [18]. Additionally, we recommend that only the ICT part of connected objects like IoT (typically a processing unit, a memory chip, a communication module and perhaps some sensors) is considered for attribution to the ICT sector. The heuristic decision tree from ARCEP and ADEME [63] can be used as a basis for drawing the ICT sector boundaries in the IoT context, but further research is needed for consolidation. Results for the E&M sector and cryptocurrencies can also be considered depending on the goal of the study, but should then be estimated and presented separately. The decision whether or not to include e.g., cryptocurrencies in future ICT sector studies requires a specific discussion that goes beyond the scope of this paper. In all cases, we recommend full transparency on what (parts of) products that are included and not.

Table 1. Suggested scope of the ICT sector. Note that this list is not exclusive but will need to be updated as new digital technologies are developed and become available. CPE=customer premises equipment. IoT=internet-of-things. M2M=machine-to-machine.

ICT subdomain	Products within the scope of the ICT sector
End-user devices	Smartphones, feature phones, tablets, laptop computers, desktop computers, computer monitors, CPE (primary home routers), extended CPE (secondary access points), computer peripherals (mouse, keyboard, external web camera), fixed phones, displays in public and private areas, projectors, commercial displays (information boards), fixed wireless access equipment, wearables, headphones/hearables, smart speakers, virtual reality headsets. *IoT and M2M devices*: Smart meters, smart home devices, fixed payment terminals, mobile payment terminals, all other IoT communication modules (used in e.g. government security, military, utilities, buildings, industry, public information, health care, etc.), professional surveillance cameras, smart home cameras.
Networks	Mobile access networks, fixed access networks, enterprise networks, satellite telecommunication and telecommunication-related data centres.
Data centres	Data centres from "in closets" to hyperscale, excluding telecommunication-related data centres.

3.2. Calculation approaches

Our recommended key aspects (**Table 2**) reflect current pragmatic calculation approaches for the three ICT subdomains; bottom-up approaches for end-user devices as well as data centres and a top-down approach for networks. If additional data are available, such as measured data on energy use from data centre companies, other calculation approaches are possible and/or might be preferable given the study goal. The key aspects need to be considered for specific ICT subdomains, and for all life cycle stages, as shown in **Figure 1**.

When possible, we recommend practitioners to combine bottom-up and top-down approaches (see **Section 2.2.1** and Section **A3.1** in the **Appendix**). Combining bottom-up and top-down approaches can be helpful in avoiding over- or underestimations, which bottom-up estimates might lead to. At the same time, such a combined approach would reap the benefits from a bottom-up approach in terms of the possibility to identify hotspots at a lower level of aggregation, enable a more detailed investigation of uncertainties and having high transparency of the results. While measurements or aggregated data on energy use via top-down approaches might be directly available from companies for the current situation. Bottom-up approaches can potentially better accommodate the evaluation of future scenarios regarding individual energy use sources for specific ICT subdomains, technological developments and changes to system elements (such as the sector-wide benefit of more stringent regulation of stand-by power draw).

Practitioners should clearly describe their selected calculation approach(es) and data used. Preferably, publicly available data should be used as this enhances transparency. We also recommend practitioners to consider both procedures for assigning embodied emissions to a specific year (see **Section 2.2.2**). If possible, depending on data availability and the level of aggregation in data, the direct energy use and climate impact should be presented separately and per ICT subdomain and life cycle stage.

Examples of data sources for the recommended key aspects are also provided in **Table 2**. For example, average embodied emissions per end-user device type can be developed through product LCAs or product carbon footprint (PCF) data published by manufacturers, scientific articles or other studies. Data on service lifetimes can be obtained from surveys and from companies (see further examples for end-user devices in **Section A3.2** in the **Appendix**). **Table 2** also illustrates that the total number of network subscriptions are collected, aggregated and reported by national regulatory authorities, for operators, countries, regions, and up to the global level through the ITU and GSMA. For data centres, data on energy use and embodied emissions can be obtained e.g., through LCAs or PCFs. Furthermore, initiatives like the European Commission's Energy Efficiency Directive [64], will contribute to future collection and reporting of data centres' energy performance. Data collection is marked by many challenges, such as data confidentiality and incompleteness (**Section 2**). Importantly, sufficient efforts are needed to ensure consistent calculation methodologies and system boundaries when data are obtained from various sources, e.g., LCAs/PCFs. Recommendations to practitioners include e.g., to acknowledge these challenges via uncertainty analysis (see further **Section 4**).

Table 2. Key aspects for assessments of the global information and communication technology (ICT) sector's current and future direct energy use and climate impact based on life cycle assessment (LCA) methodology and life cycle thinking. Examples of data sources are also provided. Embodied emissions refer to emissions from the life cycle stages of raw material acquisition, production and waste management. Note that other calculation approaches than bottom-up for end-user devices, top-down for networks and bottom-up for data centres are possible and/or might be needed. CO_2-eq=carbon dioxide equivalent. EEA=European Energy Agency. IDC=International Data Cooperation. IEA=International Energy Agency. ITU=International Telecommunication Union. PCF=product carbon footprint. PUE=Power sage effectiveness.

ICT subdomain	Key aspect	Unit	Examples of data sources (mainly for the current situation)[d]
End-user devices	Number of devices (shipments and installed base)	million units	Industry data (Gartner, ITU, GSMA, etc.)
	Annual electricity use[a]	kWh/device·year	End-user device measurements, power models, LCAs/PCFs
	Embodied emissions[b]	kg CO_2-eq/device	LCAs/PCFs, supply-chain data from companies
	Lifetime[c]	years	Surveys, end-user device company data
Networks	Number of subscriptions	million subscriptions	Industry data (e.g. ITU, GSMA, national and international statistics)
	Annual electricity use[a]	kWh/subscription·year	Network operator company data
	Embodied emissions[b]	kg CO_2-eq/subscription	LCAs/PCFs, network operator company data
	Lifetime[c]	years	Surveys, network company data
Data centres	Number of servers (shipments and installed base)	million units	Industry analysts/ organisations (e.g. IDC, Gartner)
	Annual electricity use[a]	kWh/server·year	LCAs/PCFs, data center operator company data
	PUE	-	LCAs/PCFs, data center operator company data
	Embodied emissions[b]	kg CO_2-eq/server	LCAs/PCFs, supply-chain data from companies
	Lifetime[c]	years	Surveys, data centre company data
All	Carbon intensity of electricity	kg CO_2-eq/kWh	IEA, EEA

[a] Note that the term "annual electricity use" is applied since end-user devices, networks and data centres energy use is dominated by electricity. Potential other energy uses should also be considered in assessments and then the "carbon intensity of electricity" also need to reflect this.

[b] If data on embodied energy are available, that could also be used, see further **Section 4**.

[c] Note that whether the key aspects of lifetimes of end-user devices, networks and data centres need to be considered or not depend on the approach applied for assigning impacts to a specific year, see **Section 2.2.2**.
[d] Note that data for these key aspects might not be directly available but may need to be derived based on different types of data. For example, data on the total electricity use of a network and on the number of subscriptions for that network might be needed to derive the annual electricity use of that network in kWh/subscription·year. Another example is that the average utilization rate by different types of servers (storage/compute, central processing unit (CPU)/graphic processing unit (GPU), etc.), their idle energy and power etc. might be needed to derive the annual electricity use of data centres.

	End-user devices	Networks	Data centres
Embodied emissions (including raw material acquisition, production and waste management)	• Number of devices • Embodied emissions per device • Lifetime of devices	• Number of subscriptions • Embodied emissions per subscription • Lifetime of networks	• Number of servers • Embodied emissions per server and related infrastructure • Lifetime of servers
Energy use and related emissions (use phase)	• Number of devices • Annual electricity use per device	• Number of subscriptions • Annual electricity use per subscription	• Number of servers • Annual electricity use per server • Power usage effectiveness of data centres

Figure 1. Key aspects influencing the direct energy use and climate impact of the global ICT sector in a specific year and their relation to specific ICT subdomains and life cycle stages. Note that the term "annual electricity use" is applied since end-user devices, networks and data centres energy use is dominated by electricity. Potential other energy uses should also be considered in assessments and then the "carbon intensity of electricity" also need to reflect this. Embodied emissions relate to all the life cycle stages of raw material acquisition, production and waste management. If data on embodied energy are available, that could also be used, see further **Section 4**. Note that whether the key aspects of lifetimes of end-user devices, networks and data centres need to be considered or not depend on the approach applied for assigning impacts to a specific year (see **Section 2.2.2**).

3.3. Future scenarios

For future scenarios, measurements are not available and challenges existing for assessments of the current situation are even more extensive in future scenarios due to the inherent uncertainty of the future. This is why transparency on assessments and the related assumptions is of utmost importance. We suggest that predictive scenarios are important as starting points in futures studies of the ICT sector's direct energy use and climate impact. This since they give an idea of the direction in which development is heading right now, or at least the dominating idea of where it is heading. However, we recommend complementing these scenarios with other kinds of futures studies, such as explorative scenarios that can be used to investigate different ICT trajectories as well as their opportunities and barriers. We suggest that given the fast pace of technological change, ICT sector projections, or predictive scenarios, are only meaningful up to about five years into the future. This is due to significant uncertainties regarding new and potentially disruptive technologies (such as blockchain, generative AI and quantum computing) or services (such as cryptocurrencies and chatbots). After that, other types of scenarios, such as explorative ones, should be used given that longer-term predictions are inherently uncertain. Guidelines for predictive and explorative scenario construction for key aspects and the scaling of these into the future are provided in **Sections 3.4** to **3.7**.

3.4. End-user devices

It is recommended that the future number of end-user devices is obtained by considering it as a function of the device's penetration rate in the global population, while considering regional differences. When the number of units are known for the current situation (e.g., based on sales statistics over time providing data on both flows and stocks), this can be used as a starting point. Such data can also be re-calculated into a penetration rate of the global population based on knowledge of global population figures. Then, the number of units in future scenarios can be calculated based on assumed penetration rates in specific years by also considering changes in the global population over time. The values applied should be justified, e.g., based on relevant references for specific projections or trends. Explorative scenarios can be constructed to reflect the range from a low to a high penetration rate of the global population.

Predicting the number of IoT/M2M subscriptions is challenging. For connected objects with human interaction, estimation and projection could be based on the penetration rate, the device lifetime and the human population as for traditional ICT. However, this method is hardly applicable to IoT devices with M2M communication, such as IoT for building management. The recommended approach is to constitute a detailed inventory of the IoT solutions used in each economic sector as in Bengassem [65] and to project the evolution per solution type. An alternative/simplified approach is to consider one specific IoT device type or a mix of IoT devices across the economic sectors and to make volume projection from market studies [60]. The simplified approach is much easier to implement but only provides rough trends.

It is recommended that estimates of future service lifetimes are based on a combination of extrapolation from historical trend data and expert judgment. These judgments can also be informed by stocks and flow (simulation) models of ICT devices, which have been developed for some device types and regions [66, 67]. In addition to this, it is recommended that uncertainty-treatment techniques are applied (e.g. by the construction of best-/worst-case scenarios). Importantly, it must be ensured that the climate impact savings from repair, refurbishment, and reuse of resources and components are only counted once, by reducing embodied emissions or by extending the life of devices.

3.5. Networks

We consider the number of subscriptions to be a key aspect to capture the direct energy use and climate impact of networks (see **Section 2.5.1**), as access networks are dimensioned based on numbers of active subscriptions. Historical data collected directly from EU operators show that energy use per human subscription has been relatively stable over time, at least for the last decade [68]; although there exists significant variability between technologies and regions (e.g. urban vs rural). Thus, despite significant data traffic increases [69], networks overall energy use has remained flat, largely due to the deployment of newer efficient networks capable of carrying more data per unit of energy, along with windfall gains from retiring legacy networks. So far, IoT/M2M subscriptions have had little or no impact on how networks have been designed, built and operated. Therefore, it is recommended to use human subscriptions in top-down extrapolation calculations at the global scale for the current situation. Embodied emissions of networks are high upfront, but when assigned per lifetime year it is less significant than the use stage emissions for networks. Still, we recommend that embodied emissions of networks are included in assessments for completeness. Further details are provided in **Section A3.3** in the **Appendix**.

Envisioning future needs of network infrastructures, including continuous roll-out and decommissioning of network equipment to meet expected functionality, capacity and coverage needs, is challenging. As neither direct energy use nor climate impacts of the global ICT sector are proportional to data traffic volumes [70], we recommend practitioners to consider other modelling approaches for future studies (see **Section 2.5.2**). For example, a top-down approach applying the number of subscriptions (**Table 2**), while acknowledging that other approaches might also be applied, see **Section 3.2**. The best practice recommended is to be transparent of choices made for e.g., estimating the number of subscriptions, to separate between human subscriptions and IoT/M2M subscriptions, and describe how these are used in assessments.

At the macro level, it is extremely challenging to extrapolate energy use based on traffic growth due to the heterogeneity of traffic and efficiency trends between network types and regions and the lack of data from operators. On the level of specific digital services on the other hand, which is outside the scope of this paper, various approaches such as extrapolation using data traffic or usage time have been explored [70-72] but lack broad consensus. There is currently no agreed method to assess the emissions from specific digital services in a future-oriented manner and further research is needed.

Predictive scenarios for network developments can be based on subscription forecasts. It is recommended that forecasts of numbers of subscriptions are made for different network technologies and in terms of penetration rates relative to the global population. The trajectory of energy use per subscription depends upon several factors, including the expected decommissioning of older 2G/3G-based technology, the deployment of new 5G/6G networks and the rate of mobile network modernization. In contrast to mobile networks, the electricity use per fixed broadband subscription is decreasing as new fibre-based subscriptions replace less energy efficient copper-based and cable television-based solutions. PSTN subscriptions is expected to continue to decline, with the technology ultimately being decommissioned, except in a limited number of cases, leaving only a few lines in operation beyond 2030. For the near future, the networks are expected to cope with new demands supporting increased use of new end-user devices like extended reality headsets and self-driving cars, however complemented with an increased number of satellites to expand the global coverage. At some point, the IoT/M2M subscriptions also need to be taken into consideration as these will likely impact the capacity requirements and, consequently, the built-out and operation of networks. Therefore, it is important to continue monitoring M2M subscriptions and their potential influence on networks.

In explorative scenarios, it is possible to envision different network futures. For instance, a continued expansion rate of networks increasing the emissions per subscription could be compared to a scenario of maintenance and replacement of old equipment. Other scenarios could encompass changes in market behaviour and a general situation in which it becomes more profitable to decommission, refurbish and resell active network equipment, thereby prolonging their lifetimes. Other factors to consider for explorative scenarios are premature modernization, which result in equipment being replaced before reaching its technical lifetime, and that the energy use of future equipment might be load dependent and hence connected to the data transmitted. The future use of communication satellites, in the light of competitiveness and the global development, is also important to consider in explorative scenarios.

3.6. Data centres

In line with the recommendations provided for networks (**Section 3.5**), we advise practitioners to consider other modelling approaches than scaling with data traffic for future studies. Data traffic is a poor proxy for data centre energy use, which much more relates to computation in volumes of servers and stored data (the former of which does not relate at all to traffic, and the latter of which only vaguely relates to traffic). Scaling with data traffic often also do not do enough justice to future efficiency gains. For example, global internet traffic and data centre workloads rose by 400-700% between 2015 and 2022, while global data centre electricity use (excluding cryptocurrencies) only increased by about 40% [69]. This was made possible due in part to efficiency improvements in ICT hardware and cooling, but also to a shift away from small, inefficient enterprise data centres towards more efficient cloud and hyperscale data centres. These trends would not be possible to capture in future studies that rely primarily on data traffic and efficiency improvement scenarios based on historical trends.

Instead, we recommend practitioners to use other approaches, such as bottom-up estimates of servers for data centres as illustrated in **Table 2**. Other approaches (see **Section 2.6**) or a combination of approaches might also be possible (see **Section 3.2**). Practitioners need to be transparent on the data sources, assumptions, and methodology deployed. Predictive scenarios can be based on sophisticated methods such as systems dynamics [50]. Ideally, these should not start from aggregated totals in the present, but from bottom-up or combined assessments that allow to distinguish the influence of individual factors, such as different server types [73]. In a top-down approach, data might be extrapolated from a geographical region to generalise the findings; however, the assumptions need to be explicitly and transparently stated and the regional differences must be accounted for (e.g., the share of highly efficient hyperscale data centres is much higher in the United States than in most other parts of the world [22], so if extrapolating, assuming a similar average level of efficiency globally, that would lead to an underestimate). Furthermore, at some point in time, the IoT/M2M subscriptions also need to be taken into consideration, e.g., via explorative scenarios.

3.7. Carbon intensity of electricity

Electricity is used throughout the ICT life cycle, and the calculation methodology and system boundaries applied for the carbon intensity of electricity should be consistent to the extent possible (for a discussion on challenges for embodied emissions in this regard, see further **Section 4**). In contrast to raw material acquisition for ICT hardware, their production mainly takes place in a limited set of countries. Therefore, it is particularly advisable to use location-specific emission factors for production. However, it is also advisable to account for regional differences in the use stage if data are available. Some regions might operate more end-user devices and infrastructures than others while applying renewable energy sources. Utilizing global averages on carbon intensities of electricity supply would not allow to account for such differences but might be used as a first approximation.

It is recommended that data on carbon intensity of electricity for the current situation are obtained from recognized organizations, such as international and/or national energy agencies, when possible. IEA [74] provides annual country-specific GHG emission factors from electricity and heat generation, however, a paying subscription is needed for access. European country-specific data on carbon intensities of electricity mixes are for example provided by EEA [75]. The carbon intensity of electricity should be selected to cover the entire life cycle of electricity generation and provisioning, be in line with the study scope and be described in a transparent manner. Preferably, publicly available data should be used as this enhances transparency. If country- or company-specific data are applied to obtain a global average, simplifications are necessary and must be justified and reported transparently. In the case that the current carbon intensity is unavailable, it is recommended to be developed as a function of the share of renewables, i.e. solar, wind, hydropower and others, in electricity generation in another year or another country with relevant assumptions clearly motivated.

Regarding future carbon intensities of electricity, practitioners are recommended to adopt one of two primary approaches: Utilize existing grid carbon intensities from integrated prospective assessment models or employ energy models to estimate future grid carbon intensities under various scenarios. It is recommended that the choice between these approaches should be based on the specific assessment goals, resources, and analysis scope. For swift policy impact assessments, existing scenarios may suffice. For in-depth strategic planning, energy modelling may be preferable. The main trade-offs in the decision are the personnel and data requirements as well as the computational time for analysis. The second case is more demanding in all these aspects. Finally, in the study of the energy sector's carbon intensity, selecting scenarios is an important step, grounded in the extensive scenario literature [76]. At a minimum, it is recommended that the applied carbon intensity of electricity should represent a "business-as-usual" scenario; reflecting ongoing trends without additional mitigation efforts and a "Net-Zero" scenario, mirroring the Paris Agreement's ambition to curb global warming.

Adopting higher temporal and geographical resolution, e.g., via the use of time- and location-differentiated emissions factors or considering the purchase of renewable electricity or emissions credits by single actors, would increase modelling complexity. However, critiques to voluntary renewable electricity contracts and carbon markets need to be considered, for example by applying analytical actor-scale approaches, see [77].

4. Discussion

There are several topics related to the assessment of the global ICT sector's current and future direct energy use and climate impact that need to be further discussed due to their significance. One important topic is *uncertainty*. The main direct energy use and climate impact contributors, in terms of ICT subdomains and life cycle stages, need to be modelled using high-quality data. For some parts, such as the embodied impacts of networks and data centres, data might be difficult to collect and are marked by significant uncertainties. Although such parts might not contribute to the same extent to the total results, a rough estimate is recommended to use rather than excluding it completely. Parts marked by significant uncertainties should be treated with extra care. For example, a recent assessment of the global ICT sector's climate impacts for the current situation [23] highlighted the direct energy use of end-user devices and embodied emissions of networks/data centres as marked by greater uncertainty. One approach to address uncertainty could be to focus on one key aspect at a time via sensitivity analyses for detailed investigations of the influence of a specific key aspect on the total climate impact results. Minimum and maximum scenarios could be constructed by investigating the influence of changes in assumptions on all key aspects to identify a range for the total climate impact. Open data/models could help sharing best practices and promote transparency.

Furthermore, climate impacts are not the only important impacts to consider for the ICT sector. Other potentially important *environmental impacts* should also be considered in future work (see further **Section A4.1** in the **Appendix**). Also, *environmental impacts of software development* might be significant if considered during its entire life cycle [78]. Applying AI as an example, data from Meta and Google indicate that the training stage accounts for 20–40% of overall AI-related energy use [79, 80]. The design of software furthermore influences hardware requirements and performance. In this way, software development is a transverse aspect that will influence many of the key aspects in **Table 2**, such as the annual electricity use and embodied emissions for all ICT subdomains. Nevertheless, software development is often only partially considered in current assessments and impacts from all ICT consultants are generally overlooked. There is a need to further develop methodological approaches for LCA of software [81-83] (see further **Section A4.2** in the **Appendix**).

Indirect effects are not the focus of this paper; however, it is important to be aware of them because they are considered far greater than direct effects since ICT is a transformative technology and triggers many social and economic change processes [10]. Importantly, these effects can also influence direct effects because if ICT makes a product more attractive (in terms of costs or benefits), then the demand for the product, including its ICT components, increases. Several studies and standards have addressed the challenges in determining indirect effects and derived recommendations [84-86]. Industrial studies, in particular, focus heavily on GHG-reducing indirect effects, whereas academic studies also show that GHG-increasing effects can outweigh or at least offset the GHG-reducing effects [10]. Despite the significance of indirect effects, we are still far away from a consensus on the magnitude of these effects and methods for assessing them; therefore, further research is needed (see further **Section A4.3** in the **Appendix**).

Another topic is the application of *embodied emissions or embodied energy* in the modelling. While the use of embodied energy for ICT subdomains might enable less aggregated models and provide higher transparency, that type of data is seldom available. There is furthermore a risk that some non-energy related GHG emissions are left out if too much focus is put on life cycle energy use. For these reasons, this paper focuses on embodied emissions and not on embodied energy, see e.g., **Table 2**. However, applying embodied emissions also comes with challenges. For example, if embodied emissions are applied, it might be very tricky to ensure consistent calculation methodology and system boundaries for the carbon intensity of electricity. There might be limited transparency on how embodied emissions were obtained and what carbon intensity of electricity that was applied to convert energy data into emissions. Future studies are needed on embodied life cycle energy and if data becomes available, both approaches might be used. Finally, increased product complexity, e.g., in IoT devices, might lead to increased embodied emissions. This is also true for networks and data centres. At the same time, other factors, such as economic and societal ones, might slow down the development of ICT use to some extent.

5. Conclusions and recommendations for future research

The current state-of-the-art in assessments of the direct energy use and climate impact of the global ICT sector varies a lot and practitioners face many challenges (**Section 1** and **2**). In response to this, we propose key aspects and guidelines for such assessments (**Section 3**): For *end-user devices*, number of devices, annual electricity use per device, embodied emissions per device and device lifetimes are key aspects in influencing the energy use and climate impact of this ICT subdomain. For *networks*, number and types of network subscriptions to different network technologies, annual electricity use as well as embodied emissions of different network technologies and network lifetimes are critical. For *data centres*, number of servers, annual electricity use of servers, PUE of data centres, embodied emissions of servers and the lifetimes of data centres and installed technology are key aspects. The *carbon intensity of electricity* is influential for all ICT subdomains to convert electricity use into climate impact. We recommend scaling based on the number of subscriptions to estimate the future energy use and climate impact at the global ICT sector level. This is recommended instead of the commonly used approach, based on future data traffic growth and potential energy efficiency improvements, due to vast challenges to extrapolate energy use based on data traffic growth at a macro level. It is recommended that bottom-up and top-down calculation approaches are combined when possible. Recommendations are provided for AI and IoT, specifically, while other fast-growing and/or emerging digital technologies, such as cryptocurrencies, may also be important to consider in future studies.

Future estimations are always difficult, and the best practice recommended is to be transparent on choices made for key aspects, calculation approaches, apply a high level of disaggregation in data and results as well as to describe how data and related assumptions are used in future scenarios. We suggest that ICT sector projections are only meaningful up to about five years into the future and that other types of scenarios, such as explorative ones, should be used after that. Hopefully, the recommendations provided can lead to more transparent and robust assessments of the global ICT sector's direct energy use and climate impact. Such assessments can, in turn, inform various stakeholders in making decisions that can lead to energy and impact reductions.

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CRediT authorship contribution statement

Anna Furberg: Conceptualization, Investigation, Project administration, Writing - original draft, Writing - review & editing. **Shoaib Azizi/Jan Bieser/David Bol/Vlad Coroamă/Elina Eriksson/Francesco Fuso-Nerini/Louis Golard/Mattias Höjer/George Kamiya/Dag Lundén/Nina Lövehagen/Jens Malmodin/Daniel Schien/Göran Finnveden:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing.

Data availability statement

Data supporting the findings of this study are available in this article and its Appendix A.

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