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ICT sector electricity consumption and greenhouse gas emissions – 2020 outcome

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ABSTRACT

The Information and Communication Technology (ICT) sector has gained much attention in the discussions on climate change, as it could impact global emissions both positively and negatively. The objective of the present study is to provide estimates for the 2020 use stage electricity consumption and ICT sector's total lifecycle greenhouse gas (GHG) emissions divided in three main parts: user devices including internet-of-things, networks and data centers. The study builds on a high number of data sources including measured and reported data from 150 companies that is estimated to cover about 80% of network subscriptions, about 55% of data center electricity, and about 35% of upstream GHG emissions. To understand the development, the results are put into the perspective of earlier studies. In conclusion, the ICT sector used about 4% of the global electricity in the use stage and represented about 1.4% of the global GHG emissions in 2020. The use stage electricity consumption and the total GHG emissions have increased since 2015, but the impact per subscription has decreased. The user devices accounted for over half of all GHG emissions, with equal parts relating to use stage and other lifecycle stages. For networks and data centers, the use stage GHG emissions are dominating. The electricity consumption and GHG emissions are also estimated for the closely related areas Entertainment and Media (including e.g., TVs), paper media, and cryptocurrencies.

1. Introduction

The recently published Synthesis Report by the Intergovernmental Panel on Climate Change (IPCC, 2023) sees climate change as a threat to human well-being and planetary health, and emphasizes that every increment of global warming will intensify multiple and concurrent hazards, while escalating related losses and damages. However, even at 1.1 °C above pre-industrial levels, IPCC still sees a window of opportunity (*albeit* rapidly closing). Limiting human-caused global warming requires net zero CO_2 emissions. Here, IPCC

Abbreviations: AEC, Annual Electricity Consumption; BB, broadband; CO_2e, carbon dioxide equivalent; DC, data center; GHG, greenhouse gas; ICT, Information and Communication Technology; PC, personal computer.

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states that all global modelled pathways that limit the warming to 1.5 °C or 2 °C, involve rapid, deep and immediate greenhouse gas (GHG) emissions reductions in all sectors this decade.

One sector that has gained much attention is the Information and Communication Technology (ICT) sector which, including both direct and indirect effects, has been named a 'wildcard' which could impact global emissions substantially in both positive and negative directions (Falk & Gaffney, 2020; D4S, 2023, CODES, 2022). As the dependency on digital services grow, so does the concerns that the ICT sector's GHG emissions may follow. Addressing this concern, the International Telecommunication Union (ITU), jointly with GSM Association (GSMA), Global Enablement Sustainability Initiative (GESI) and Science-based Targets Initiative (SBTi) has published a normative 1.5 °C trajectory for the decarbonization of the ICT sector requesting an emission reduction of 45% 2020–2030, assuming an initial reduction of 7% 2015–2020 (IEA, 2020a, 2020b, 2020c, pp. 1–2020). Though not legally binding, the trajectory lay out the path for the sector towards Net Zero (ITU, 2021, ISO, 2022).

In this context, various stakeholders have studied different aspects of the sector's GHG emissions and electricity consumption. This includes studies by researchers (e.g. Bieser et al., 2020), by organizations (ITU/WBA, 2022; Carbon Trust/Dimpact, 2021) and studies commissioned by policy makers (VHK and Viegand Maagoe, 2020; BEREC, 2022). Studies also focus on different contributions to the ICT sector footprint (Clément et al., 2020; Hintemann & Hinterholzer, 2019) and may focus on either recent (Malmodin & Lundén, 2018) or future (Belkhir & Elmeligi, 2018) impacts. Despite the existence of an international standard (ITU, 2018) guiding the assessment of the GHG emissions of the ICT sector, studies of its carbon footprint apply different boundaries, data sets and methodological approaches resulting in a diverse set of estimates. Moreover, studies combine measured data and theoretical models differently, consider technical and economical constraints to a varying extent and use data of different age. A recent comprehensive meta study by Bieser et al. (2023) could identify only six studies of the ICT sector carbon footprint, including both forecasts and estimations of the current situation. In particular, Bieser et al. (2023) note that all studies except (Malmodin & Lundén, 2018) that focused on data for 2010–2015, are prospective studies.

Based on this situation, the starting point for the present study is the lack of estimations of the recent development of the ICT sector's life cycle GHG emissions and use stage electricity consumption, i.e. the electricity consumed when running networks and data centers and charging equipment, but excluding the electricity used for raw materials acquisition, production and end-of-life treatment. Moreover, the outcome of year 2020 is of interest as this year has previously been studied from a forecast perspective. Substantial delay in data availability render the assessment of more recent years difficult. The carbon footprint is defined as the full life cycle GHG emissions measured in carbon dioxide equivalents (CO_2e). Emissions taking place outside of the use stage will be referred to as embodied emissions. The study uses ITU (ITU, 2018) as a methodological basis and prioritizes data from primary sources whenever possible. Data covering the full life cycle of user devices, networks and data centers, and sales statistics for 2020 are collected from public sources.

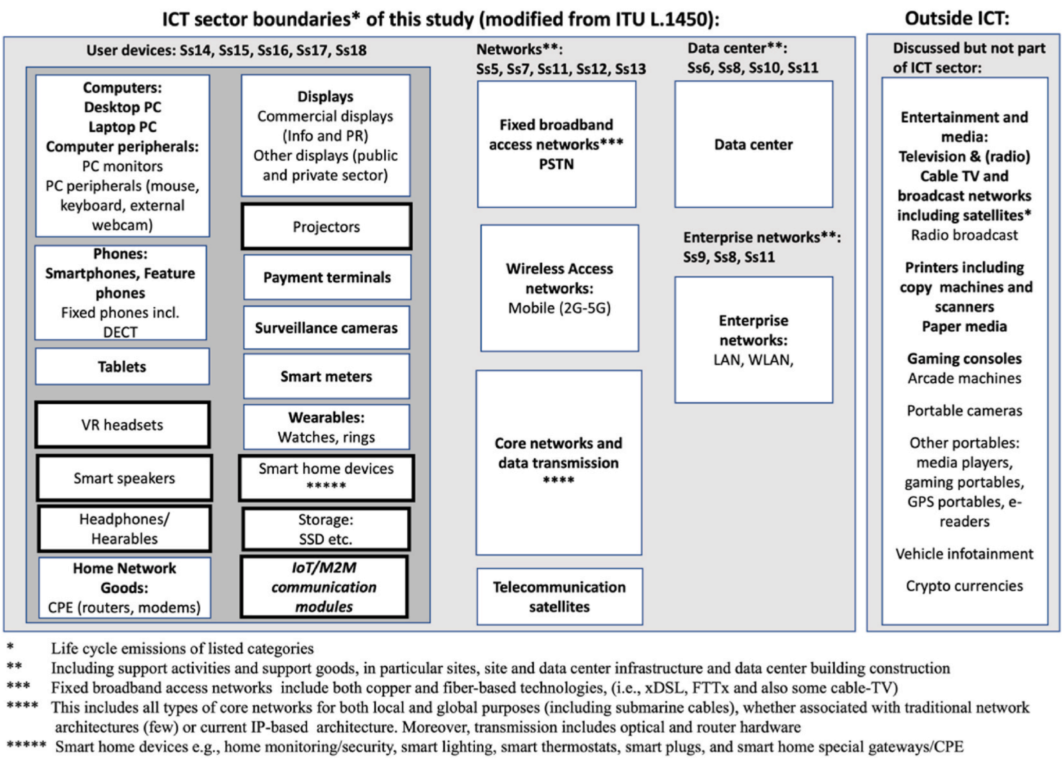

Fig. 1. ICT sector boundaries and the categories of equipment covered by the present study. Bold text represents categories defined by (ITU, 2018), other text refers to specifications or categories added. "Ss#" refers to the corresponding sheets in the Supplement file.

The objective of the present study is thus to provide estimates for the 2020 use stage electricity consumption and carbon footprint of the entire ICT sector including the three main parts: user devices, networks and data centers, and putting those into the perspective of earlier developments (Malmodin et al., 2010, 2013; Malmodin & Lundén, 2018). The present study builds on results from previous recent studies on embodied GHG emissions of user devices (Lövehagen, Malmodin, Bergmark, & Matinfar, 2023a, 2023b) and the use stage electricity and related GHG emissions of networks based on data from operators with headquarters in Europe (Lundén et al., 2022). The Supplementary file contains all details that cannot fit within the limitations of the paper and readers are encouraged to refer to all of those for a detailed description of modelling and data sets.

2. Scope and methodology

2.1. Scope

The main study objective of this paper is the ICT sector. The applicable ICT sector boundaries when calculating the sector's carbon footprint are specified by the international standard ITU Recommendation L.1450 (ITU, 2018) which establishes three main categories: ICT end-user goods, ICT networks and Data center, here referred to as user devices, networks and data centers. The present study refers to enterprise networks as a separate category (instead of included in the Data center category as in (ITU, 2018)). The composition of each main category is detailed in Fig. 1. The composition builds on (ITU, 2018) with a few exemptions which are detailed and discussed in section 8.5. A detailed mapping between L.1450 and the present study is available in the Supplement (sheet 24). The boundaries between the ICT sector and other sectors are not static, therefore the impacts of ICT related equipment and activities outside of the sector boundaries outlined in Fig. 1 are estimated and discussed in section 8.4.

The user devices category includes traditional categories of personal equipment such as laptop and desktop personal computers (PCs), computer peripherals such as PC monitors, as well as phones, tablets and wearables and associated hearables. Moreover, emerging devices such as VR headsets and smart speakers are included. Beyond personal devices this category includes customer premises equipment (CPE), i.e. routers and modems, displays, projectors, storage device, payment terminals, surveillance cameras, smart meters, smart home devices and IoT/M2M communication modules. A full list of user devices included is available in the Supplement (sheet 14 and 18). The networks category covers all mobile access networks (2G-5G), all fixed broadband (BB) access networks (both copper and fiber based: Digital Subscriber Lines (xDSL), Cable-TV BB part, Fiber-to-the-X (FTTx, a generic term for any broadband network architecture using optical fiber), and the traditional Public Switched Telephone Network (PSTN), as well as core networks and data transmission connecting all the access networks. The data center category includes the ICT equipment of the data center including both storage and internal networks, as well as any office equipment. The term data center in the present study covers all server installations ranging from local installations to large hyperscale data centers. Finally, the enterprise networks category includes Local Area Networks (LAN) and Wireless Local Area Networks (WLAN).

The ICT service category, covering ICT consultants and software development additional to software development undertaken by

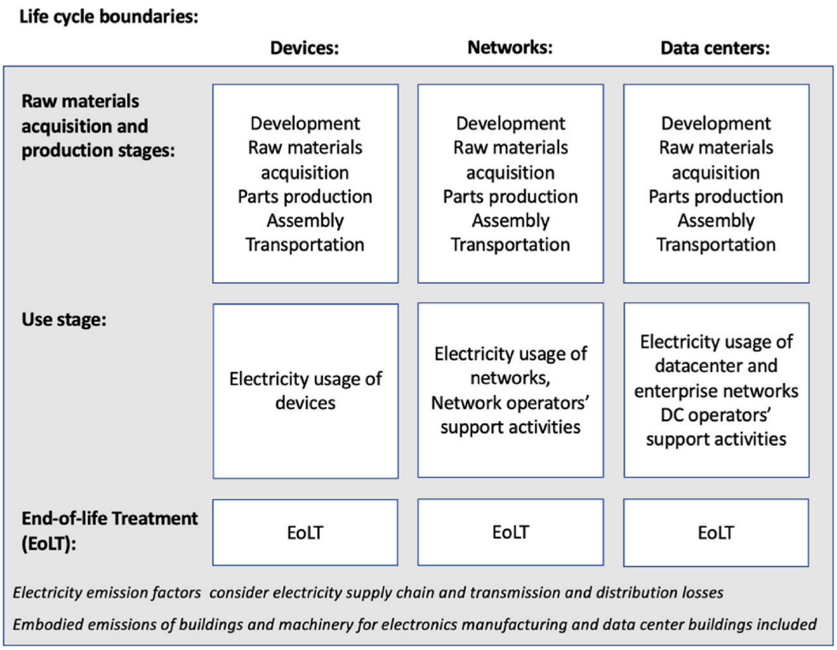

Fig. 2. Life cycle stages and activities covered by the present study. The term 'embodied emissions' is in the present study used to refer to raw materials acquisition, production and EoLT stages.

providers of networks, data centers and user devices, is not explicitly included in the present study. However, the use of user devices, networks and data center of the ICT service sector is already accounted for in other categories (in line with allocation rules (ITU, 2018)), but emissions related to use of buildings etc. by ICT consultants and software providers is not included. The main reason for not including this category is the high uncertainty and lack of reliable statistics. For 2015 an estimate for the ICT service category was made but it was considered too uncertain to be included in the total results (Malmodin & Lundén, 2018). ITU's decarbonization trajectory also excluded the ICT service category (IEA, 2020a, 2020b, 2020c, pp. 1–2020). In line with the ITU standard (ITU, 2018), the present study also takes a full life cycle perspective and cover both embodied emissions and use stage emissions. The embodied emissions include end-of life treatment (see section 7). Moreover, support activities are included such as use of offices, stores for operation and maintenance activities, and business travel and employee commuting. The different life cycle activities covered are further detailed in Fig. 2.

In line with the standard (ITU, 2018) the reference unit is defined as "the overall GHG emissions generated by the global ICT sector (as detailed in this section) over one year (2020)". More specifically this refers to one year of operation and embodied emissions associated with the sales volumes of that year.

2.2. Overall methodology

Data of electricity usage and GHG emissions have been collected from publicly available company reporting covering both electronic equipment companies, user device manufacturers, network manufacturers, operators and data center provides. These data are grouped into the three areas: networks, data centers and user devices. For these areas the use stage and embodied emissions are calculated separately. The embodied emissions for electronics are estimated using the total embodied GHG emissions for the entire electronics industry in 2020, as well as allocated values for key user devices, other ICT devices, networks and data centers, and for electronics in other sectors, as calculated by Lövehagen et al. (2023a, 2023b). This calculation was based on data from company reporting in various parts of the electronics sector and an additional estimate for materials and mechanics for the ICT sector based on Malmodin et al. (2018). For key user devices, the results of Lövehagen et al. (2023a, 2023b) were compared to published life cycle assessments and product carbon footprints scaled up by the sold number of devices for 2020. For user devices, the embodied emissions represents the annual sales and not the installed base (the alternative approach would be to depreciate embodied emissions over the lifetime of devices, but if the annual shipments are similar from year to year the result would be the same). The embodied emissions for electronics give an upper boundary for all estimates in the present study which helps to reduce the uncertainty of the overall embodied emissions. For the networks, enterprise networks and data centers estimates of embodied emissions are made in addition to Lövehagen et al. (2023a, 2023b) to cover infrastructure.

Use stage electricity and related GHG emissions for user devices are estimated by combining a derived typical total electricity consumption per device category with the estimated installed base to calculate the annual electricity consumption. A similar approach is applied for IoT devices. For networks, data for electricity consumption and GHG emissions are collected per geographical region from operator companies representing a substantial share of overall emissions. GHG emission data collected cover scope 1 and 2 emissions and upstream scope 3 emissions. Scope 1 emissions are direct emissions from owned or controlled sources, scope 2 indirect emissions from the generation of purchased electricity and scope 3 emissions are all indirect emissions that occur in the value chain (GHG Greenhouse gas Protocol, 2022). The data are reviewed for consistency, and an additional estimate is made to cover the fuel supply chain and sometimes other parts of scope 3 reporting that are underreported. Scope 3 travel and commuting data are included as reported, while scope 3 transport data are handled carefully as there is a risk to double count the transport as the same transport can be reported by several companies. The results are extrapolated per geographical area by subscriptions to cover all subscriptions globally. For the networks part, the collected data from network operators covers approximately 80% of the global subscriptions. The result is compared to other studies. The networks operator data are further allocated to network types and company activities, e.g. office electricity, network electricity, (using the granular data collected for Europe (Lundén et al., 2022)). For data centers, the shipments and installed base of servers globally is used together with a data center electricity consumption study by Masanet et al. (2020) to estimate the data center electricity consumption. To capture the supporting activities, renewable electricity and GHG emissions, the environmental data reported by major data center companies are collected and used to complement the electricity consumption estimate derived based on Masanet et al. (2020). For network operators with large data centers, a share of emissions is allocated to those, as the reporting is seldom detailed regarding emission sources. The allocations introduce uncertainty; however, this does not affect the data quality of total electricity consumption or GHG emissions reporting. Further details of data, allocation and calculations are provided in the specific sections 3-7.

2.3. Electricity grid mix

Electricity is used in most parts of the ICT sector and the related GHG emissions are dependent on the energy sources used for the grid. The GHG emissions related to electricity depend on the origin of the electricity, which could be fossil fuels, renewable energy sources or low-carbon emitting sources. The electricity mix varies between countries and regions. Separate emission factors are used for China, USA, India, an average of Japan and Korea, western Europe (consisting of European Union, United Kingdom, Switzerland and Norway hereafter referred to as Europe-30) and rest of the world. The emission factors for 2020 are taken from Climate Transparency (2021) and transmission and distribution losses from Enerdata (2023a, 2023b). To cover for the full lifecycle of electricity production, an addition of 15% is added (IEA, 2020a, 2020b, 2020c, pp. 1–2020). When calculating the full emissions related to networks operations an emission factor of 0.03 kg CO_2e/kWh is applied to the reported renewable electricity to also cover for the full supply chain, based on an LCA from Vattenfall (n.d.).

The world average emission factor of 0.538 kg CO_2e/kWh includes the full life cycle emissions and effects relates to electricity production. All emission factors used are available in the Supplement (sheet 3). In the emission factor reported by a country there is an uncertainty how much any locally produced electricity is included. The company data used in the present study includes any reported use of low-carbon electricity (purchased or self-generated). However, in extrapolations for networks and data centers, the global average grid emission factor has been used in order not to presume a corresponding use of renewable electricity in the extrapolated part. Another source of emission factors are provided by the International Energy Agency (IEA, 2022a) however as that is behind paywalls the IEA emission factors cannot be explicitly stated, but the impact of using the IEA emission factors is investigated in the sensitivity analysis.

2.4. Subscriptions and data traffic

The total global number of subscriptions used presented in Table 1, are taken from an ITU data base (ITU, n. d.). Subscription numbers are counted per mid-year, not end-year (calculated as average of 2019/2020 values). An additional table showing the subscriptions covered in the studied regions is available in the supplement (sheet 4).

3. Networks

Based on network operators' sustainability reports, networks' global electricity consumption and GHG emissions can be estimated. Reported data from 57 operators (listed in supplement sheet 2) have been collected, estimated to cover about 80% of mobile and fixed subscriptions globally. Besides their size, operators were chosen to *cover different subscription types and different countries/regions as equally as possible*. Extrapolations have been made by total number of subscriptions in each country/region and specific electricity emission factors per country/region have been used. Many operators report only scope 1 and 2 emissions (sometimes including scope 3 partly) and therefore scope 3 emissions have been added and adjusted when needed in the study e.g. to include the whole fuel/energy/electricity supply chain. When there are data gaps in scope 1 and 3 reporting, reporting operators' data have been used to estimate these. The collected data are provided in the supplement (sheet 5).

Some operators are also large data center service providers, for these, an estimated share of emissions are allocated to these data centers (23 TWh). These are subtracted from the network emissions and added to the data center category. However, the telecommunication data centers (server-like or server-based equipment in network core nodes) remain allocated to the networks category. Many European operators report the emissions of their data center operation (Lundén et al., 2022). Some other operators also report their data centers, and some can be estimated based on market data. The remaining operators' data centers are then estimated based on these data sources. Note that internal networks in all data centers are included in *Data centers*. Cable-TV operators with both TV and fixed broadband subscriptions have been split based on number of subscriptions. The fixed broadband part is included in *Networks*. CPE related to fixed broadband connections in personal homes are included in *User devices* (residential use). Total resulting electricity consumption and GHG emissions for network operations are 247 TWh and 155 Mtonne CO_2e, as shown in Table 2. These figures include 14 TWh electricity generated by diesel generators for off-grid sites. Diesel GHG emissions are included as scope 1. Our estimate for off-grid is somewhat higher than an estimate from GSMA (GSM Association, 2020), but the total values are in line with the similar data collection (GSM Association, 2021).

The embodied carbon footprint for networks is estimated to 30 Mtonne CO_2e for 2020. It is based on the network equipment part of all electronic equipment manufacturing estimated to 23 Mtonne CO_2e (6% of 387 Mtonne) in Lövehagen et al. (2023a, 2023b). Thereof are 12 Mtonne CO_2e allocated to mobile, and the rest to other parts based on revenue. In addition, GHG emissions related to the

Table 1
ICT subscription data for 2020 and 2015 as a reference.

	Mid 2015 (million)	Mid 2020 (million)	Source	2015 as in (Malmodin & Lundén, 2018)
Fixed telephony (voice)[a]	1069	914	ITU, 2022a	1070
Mobile subscriptions [b]	7049	8237	ITU, 2022b	7090
Of which is mobile broadband	2992	5921	ITU, 2022c	2950
Fixed broadband (lines)	783	1185	ITU, 2022d	785
ICT total subscriptions [b]	8901	10,336		8955

[a] Includes fixed-telephone lines, voice-over-IP (VoIP) subscriptions, fixed wireless local loop subscriptions, ISDN voice-channel equivalents and fixed public payphones. The VoIP subscriptions is estimated to be 500 million.

[b] Not including Internet-of Things/machine-to-machine subscriptions. IEA, 2020a, 2020b, 2020c these are estimated to about 1500 million (Ericsson, 2022), compared to 350 million in 2015 (Malmodin & Lundén, 2018).

Table 2
Annual Electricity Consumption (AEC) and GHG emissions for network operations in 2020.

Network operator's regions	AEC (TWh)	Use stage GHG (Mtonne CO_2e)	Collected data subscription coverage [a]
Europe-30	31	9	80%
US	35	21	90%
China	59	47	100%
Korea and Japan	18	12	80%
India	20	20	100%
Rest of World	84	47	55%
Network operations total (rounded)	247	155	

[a] Derivation of the coverage percentage is available in (Supplement sheet 7).

infrastructure itself, e.g. construction of new mobile base station sites and new deployment of fixed cables/lines, antenna towers, fixed cable ducts, all buildings, from larger site buildings down to all smaller cabinets, have been estimated to about 10 Mtonne CO_2e based on an estimate of number of new fixed broadband deployments and network sites in 2020. From these about 3 Mtonne CO_2e is considered enterprise networks (section 4). A full description is available in the Supplement (sheet 11). Satellites used for telecommunication has been estimated to 0.8 Mtonne CO_2e and these are all considered embodied emissions (see Supplement sheet 12). The uncertainly in this estimation is large and its impact is investigated in the sensitivity analysis.

In Table 3 the data are split on the four main network access types. The allocation of electricity used for core networks, access network and offices/stores etc. is based on the corresponding shares for European networks in 2018 provided in Lundén et al. (2022, Table 6). The allocation to fixed broadband and fixed telephony is calculated using the electricity per subscription and the number of subscriptions globally (excluding VoIP subscriptions). The remaining is allocated to mobile networks. A detailed description is available in the Supplement (sheet 13). Table 4 shows the impact of four main network access types per subscription. Note that in previous studies by the authors (e.g. Malmodin & Lundén, 2018), most of the embodied GHG emissions were based on LCA studies and were equally distributed over an estimated lifetime of 10–20 years (depending on type of equipment). In the present study they are based on annually reported and extrapolated GHG emissions without depreciation over lifetime, which are typically higher as networks are still expanding globally.

4. Enterprise networks

Apart from networks managed by operators, there are numerous enterprise networks or LANs/WLANs. ILO and IEA estimate the global workforce that use a PC and could possibly telework to about 20%, corresponding to 660 million workers out of 3.3 billion (ILO, 2020; IEA, 2020a, 2020b, 2020c). However, there are probably more workers supported by enterprise networks, e.g., in manufacturing and health care, and based on figures for commercial PC sales and average lifetime, 800 million workers supported by enterprise networks is believed to be a more relevant value. Based on AEC per employee for Ericsson's global enterprise networks (31 kWh), it is estimated that enterprise networks globally for 800 million workers, consume 25 TWh per year. An estimate based on annual shipments of enterprise switches/routers and WLAN access points and their lifetime results in a similar AEC value. With an installed base of about 150 million Wi-Fi hotspots, about 10 million enterprise small cells for mobile 3G–5G coverage, and about 1.5 billion *Ethernet ports*, the total annual electricity consumption is estimated to 25 TWh and the embodied carbon footprint to about 3 Mtonne CO_2e. A full description is available in the Supplement (sheet 9). Note that also public networks in e.g. schools, restaurants, shopping malls, and airports are included. A small share of all residential CPE or Wi-Fi hotspots described in section 6 are used for business purposes and/or are open for public or *guest* use. It is not believed that those have been left out in the present study, but there is an uncertainty about the

Table 3
Network electricity consumption and GHG emissions for 2020 allocated to network types.

	Total electricity (TWh)	Access network (TWh)	Core network (TWh)	Support activities (TWh)	Use stage GHG (Mtonne CO_2e)	Embodied GHG (Mtonne CO_2e)	Total GHG (Mtonne CO_2e)
Total networks [a]	247	215	17	15	153	31	184
Mobile networks [b]	161	146	6	9	101	17	118
Fixed broadband	60	48	8	4	38	14	51
Fixed telephony [c]	23	22	0.7	0.7	14	(0) [d]	14
Allocated to enterprise [a]	3		2	1			

[a] Business customers are allocated 3 TWh from core networks (2 TWh) and support activities (1 TWh) and the related use stage GHG emissions (1.6 Mtonne CO2e).
[b] All active mobile networks, 2G-5G, including satellite communication.
[c] All technologies, copper and fiber based.
[d] No embodied emissions have been allocated to fixed telephony as hardly any new fixed telephony networks were built during 2020.

Table 4
Annual electricity consumption and network GHG emissions per subscription (sub) 2020.

	Use stage electricity (kWh/sub)	Use stage GHG (kg CO_2e/sub)	Embodied GHG (kg CO_2e/sub)	Total GHG (kg CO_2e/sub)
Mobile networks	20	12	2	14
Fixed broadband	51	32	11	43
Fixed telephony [a]	25	16	0	16
Total average (rounded)	24	15	3	18

[a] Including VoIP. VoIP telephones uses a fixed broadband connection but are typically grouped together with PSTN fixed telephones. In total 914 million subscriptions (ITU, 2022b). VoIP uses only a small part of a fixed broadband connection, but no fixed broadband electricity consumption/GHG have been allocated to VoIP. An estimate is that there are about 500 million fixed telephony subscriptions and an allocation excluding the VoIP subscriptions would lead to an electricity of 46 kWh/sub and 29 kg CO_2e/sub, still allocating no embodied emissions to fixed telephony.

Table 5
Datacenter Annual Electricity Consumption (AEC) per geographical region estimation.

	AEC (TWh)	AEC share of global
US	65–80	~35%
Europe-30	35–50	~20%
China	45–60	~25%
Rest of World	35–50	~20%
Data centers electricity total	210	100%
Data centers operation total incl. support activities	223	

allocation between enterprise and user devices. Enterprise networks also use part of the core networks and supporting activities that is included in the networks part in the present study. As described in the footnotes to Table 3, about 3 TWh is reallocated from networks to enterprise networks as they are business customers connected to operators' core networks.

5. Data centers

For data centers, two data sets are applied and combined to arrive at the estimate used in this paper. These are i) a recalculation of Masanet et al. (2020) based on a revised number of installed servers and ii) an estimate based on extrapolation of data collected from company reporting.

Masanet et al. (2020) estimated the use stage electricity consumption of all data centers globally to 205 TWh in 2018 (up from 194 TWh in 2010) using a model based on leading market statistics from Cisco and IDC, together with bottom-up modelling of servers, storage, and networks, and estimates of infrastructure overhead like cooling and power supply/back-up. Masanet et al. (2020), referring to a current trend analysis, estimate data centers electricity use to 196 TWh for 2020, not including supporting activities. The key data used to estimate global data center operations are number of new servers shipped globally each year. The number of new servers is around 12 million per year 2018–2020 (MIC, 2021), but data varies between sources and therefore the development of server shipments are summarized in the Supplement (sheet 8). The installed base of servers estimated in the present study is about 5% higher than in Masanet et al. (2020), therefore the total data center electricity consumption is estimated to be 210 TWh (196 TWh + 5% rounded upwards).

For the second data set, electricity and GHG emissions data were collected from annual reporting of 37 data center operators and estimated for three additional data center operators by comparing with companies of similar sizes (all companies listed in the Supplement sheet 2). Moreover, electricity for data center services by network operators, subtracted from the networks category (see section 3) were added. These sources added up to 123 TWh including offices and supporting activities. The share of electricity used by data centers was estimated for companies with other major business areas (e.g. Amazon, Alibaba, Microsoft, Apple, and Huawei) as well as other companies where the data center share of the electricity consumption is reported or estimated to 90–100%. The total data center electricity based on collected and estimated data, after these modifications, is 116 TWh (excluding supporting activities, offices etc.) and corresponding 41 Mtonne CO_2e use stage GHG emissions. The derived relationship between the data center electricity consumption and the total electricity consumption including supporting activities are used for extrapolation of the 210 TWh estimated above based on Masanet et al. (2020). The resulting total electricity consumption including supporting activities is 223 TWh. The global average electricity grid emission factor is used to calculate the additional GHG emissions, resulting in a total of 95 Mtonne CO_2e. Table 5 shows an attempt to allocate the data centers electricity consumption to geographical areas. All collected data, estimates and calculation are transparently available in the Supplement (sheet 6, 10).

The total embodied carbon footprint of data center equipment in 2020 is estimated to 30 Mtonne CO_2e. This includes 23 Mtonne CO_2e representing the data center hardware (estimated as 6% of 387 Mtonne CO_2e of the electronics industry emissions from Lövehagen et al. (2023a, 2023b) and, in addition, the embodied GHG emissions related to data center buildings and other non-electronic infrastructure, estimated to about 7 Mtonne CO_2e based on number of new servers, estimate of such emissions per server and a benchmark against various sources. A full description is available in the Supplement (sheet 11).

Table 6
Use stage electricity and GHG emissions for user devices and displays.

User devices	TEC (kWh/year)	Installed base (million)	Use stage electricity (TWh)	Use stage GHG emissions (Mtonne CO_2e)	Embodied GHG emissions (Mtonne CO_2e)
Smart phones	3	5800	17	9	65
Feature phones	1	1950	2	1	6
Tablets	6	800	5	3	16
Laptop PCs	25	1150	29	16	46
Desktops PCs	150	550	83	44	25
PC monitors	50	1100	55	30	14
CPE	100	1185	119	64	6 [a]
Extended CPE	80	95	8	4	
Fixed wireless access	60	65	4	2	17 [b]
Fixed phones	10	914	9	5	
PC peripherals	–	3400	–	0	
Wearables	0.5	500	0.3	0.1	
Headphones	0.1	2000	0.2	0.1	
Smart speakers	20	320	6	3	
VR headsets	3	19	0.1	0.03	
Public displays	200	20	4	2	
Projectors	200	25	5	3	
Commercial displays	600	10	6	3	
Total			351	189	195
Reduction of user devices used in the ICT industry			−6	−3	
Total			345	186	195

[a] CPE and Extended CPE.
[b] Embodied GHG emission sum for fixed wireless access, fixed phones, etc. to commercial displays.

6. User devices

User devices cover both traditional user devices used for communication like phones and computers, but also IoT devices as specified in Fig. 1. The electricity consumed by user devices during operation is difficult to assess because of the uncertainties in the number of active devices (a k a the installed base) and in the typical electricity consumption per device. The uncertainty in numbers of active devices is associated with such as difficulties in acquiring data for the commercial lifetime of devices. To mitigate this, different sources have been collected and reasonable values for numbers of devices in use have been chosen. For some products, total annual electricity values have been published. For others, the energy consumption for charging and stand-by is presented by the manufacturer. These are then combined with estimated average annual usage time derived by other studies. Table 6 shows the chosen representative values for the different user devices. The references and rationale for all choices are presented in the Supplement (sheet 14–16).

There are several sources of double counting. User devices used by data center, network operators, and manufacturing companies' employees are double counted as they are included in both the company data already accounted for in other categories and all user devices derived in this section. The total number of employees in all these ICT companies are estimated to about 30 million, and for user devices the average electricity consumption and emissions per employee to about 200 kWh/year and about 110 kg CO_2e. To avoid double counting, the resulting about 6 TWh and about 3 Mtonne CO_2e have been subtracted in the total user devices estimate in Table 6. The most common user devices for communication are feature phones, smartphones, tablets, laptop and desktop PCs and the related PC displays and CPEs. For these user devices the total embodied GHG emissions for 2020 are estimated to about 180 Mtonne CO_2e (Lövehagen et el., 2023a). The rest of the ICT devices in Table 6 has an embodied GHG emission of 17 Mtonne which is calculated from the 'Other ICT devices' allocation in Lövehagen et al. (2023a, 2023b) and a removal of payment terminals and other Internet of

Table 7
IoT devices' use stage electricity and GHG emissions.

IoT	TEC (kWh/year)	Installed base (million)	Use stage electricity (TWh)	Use stage GHG emissions (Mtonne CO_2e)	Embodied GHG emissions (Mtonne CO_2e)
Smart meters	13	1100	14	8	2.6
Smart home devices	7	1000	7	4	2.5
Payment terminals fixed	25	100	2.5	1.3	3.4
Payment terminals mobile	4	80	0.3	0.2	
Surveillance cameras	5	825	36	22	3
All other IoT/M2M	5	3000	15	8	2.4
Total		6095	75	43	13

Things (IoT) or Machine to Machine (M2M) as these are included in Table 7. The emissions per key product can be found in Supplement (sheet 17). The ICT sector includes surveillance cameras, and other devices that can be labeled as IoT/M2M, e.g., smart meters, smart home devices, and payment or point-of-sales (POS) terminals according to ITU L.1450. For smart meters, lights and IoT modules in other sectors, only the communication module is included, whereas for payment terminals and smart plugs the whole device is included. Table 7 presents the use stage electricity and GHG emissions as well as the embodied GHG emissions of IoT devices. A full description is available in the Supplement (sheet 18).

7. End of life

End-of-life treatment is included indirectly through the materials model of the ICT and entertainment and media sector in Lövehagen et al. (2023a, 2023b), that is based on Malmodin et al. (2018). A resulting value for the material use of about 45 Mtonne CO_2e is used representing *a reasonable recycling scenario*. If, for those metals that can be recycled with existing systems, only recycled metals were used as input materials, and 100% of these metals were recycled at end of life, the GHG emissions related to the use of materials would be about 30 Mtonne CO_2e ("best case"). If only virgin material was used as input and no materials were recycled at the end-of-life stage, the carbon footprint would be about 65 Mtonne CO_2e ("worst case"). Note that many materials (e.g., plastics and ceramics) cannot be recycled today, and that the collection and recycling processes themselves often use fossil fuels, which the relatively high carbon footprint for the "best case" recycling scenario shows. Many metals with a high monetary value like copper, silver and gold can be recycled at very high rates, even if they are included and mixed with many other materials in electronics. Common construction metals like steel and aluminum can also be recycled to large extent, but other metals contaminating the recycled metal typically lead to down-cycling of the metals into lower quality alloys. However, the effect of this may be limited at this point as the use of these metals are low (<1% of global use), and the need for basic alloys is large in e.g., the building and construction sector where material requirements are lower. An important source of uncertainty is that the end-of-life treatment will take place in the future and conditions may change. The modelling assumes today's conditions, in the future further materials may be recyclable.

8. Results and discussion

8.1. ICT sector total

The total use stage electricity, related GHG emissions and embodied emissions are summarized for the different parts of the ICT sector in Table 8. User devices represent the majority of the GHG emissions (about 57%), with almost equal parts relating to embodied and use stage GHG emissions, as shown in Figs. 3 and 4. The ICT sector represents about 1.4% of the global GHG emissions including land use effects presented by UNEP (2022). As 2020 was a special year for the world (because of the COVID pandemic) a comparison is also made to 2019 but the percentage only varies slightly (1.41% of 54 Gtonne CO_2e in 2020, compared to 1.35% of 56.4 Gtonne CO_2e in 2019 (UNEP, 2022)). The ICT sector's share of electricity consumption is about 3.9% when comparing to global electricity consumption figures from Enerdata (23,584 TWh in 2020, 23742TWh in 2019) (Enerdata, 2023a, 2023b).

To evaluate the overall data quality of the ICT categories, different categories of data have been considered with regards to overall data availability and quality in relation to other items. Moreover, the significance of each item in relation to overall ICT sector GHG emissions has been derived (Supplement sheet 26). In general, the ambition has been to collect the best available data, but most effort has been put into data collection of embodied emissions of user devices (Lövehagen, 2023a), and use stage emissions of networks (Lundén et al., 2022) and data centers, as they are the most significant contributors to the overall ICT sector GHG emissions. For year 2020, the collected measured and publicly reported company data from a high amount of network and data center operators cover about 80% of all fixed and mobile network subscriptions, and an estimated about 55% of data center electricity. Embodied emissions according to Lövehagen et al. (2023a, 2023b) is based on measured and publicly reported company data from 59 companies that cover about 35% of the total embodied GHG emissions for 2020 in the study. In many cases, the collected company reported data for networks, data centers, and embodied GHG emissions have been verified by a third-party auditor. The number of user devices in

Table 8
ICT sector use stage electricity consumption and GHG emissions in 2020.

ICT sector part	Use stage electricity (TWh)	Embodied GHG emissions (Mtonne CO_2e)	Use stage GHG emissions (Mtonne CO_2e)	Total GHG emissions (Mtonne CO_2e)
User devices [a]	421	208	228	436
Networks [b]	247	31	155	186
Data centers	223	30	95	126
Enterprise networks	25	3	13	16
Total [c,d]	916	272	492	764

[a] Including IoT and surveillance cameras.
[b] Including telecommunication satellites.
[c] Rounded values.
[d] These results refer to the reference unit "The overall GHG emission generated by the global ICT sector (as detailed in the scope) over one year (2020). More specifically this refers to one year of operation and embodied emissions associated with the sales volumes of that year.

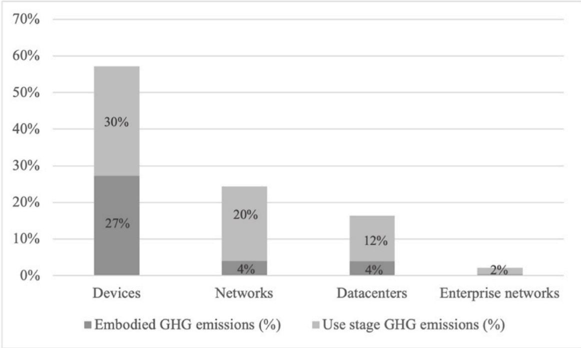

Fig. 3. Total ICT sector carbon footprint 2020.

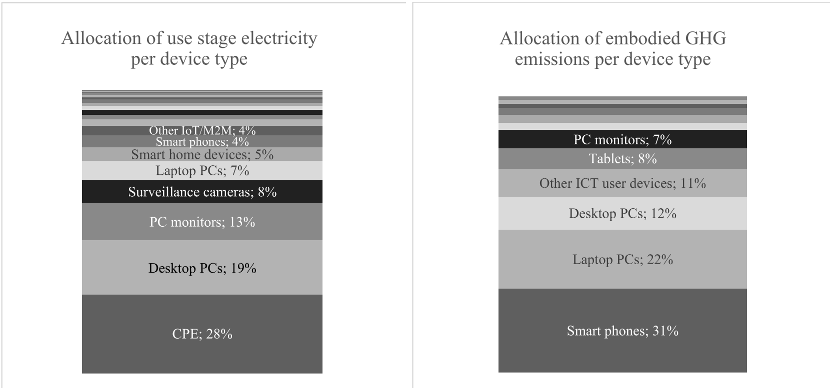

Fig. 4. Allocation of use stage electricity consumption (left) and embodied GHG emissions (right) for user devices. Numbers included only for the most contributing device types.

operation and their average electricity consumption remain a more uncertain part in line with previous studies. In many cases the number of user devices in operation can be derived from subscription numbers, e.g., mobile phones (mobile subscriptions), CPE (fixed broadband subscriptions), and STBs (pay-TV subscriptions). Use time of user devices are surveyed by various ICT and media organizations and their power consumption in various types of use is well communicated by manufacturers today, but to measure user devices over longer time in a large number of households and workplaces around the world is a daunting task. This part will remain more uncertain than other parts also in future studies.

8.2. *Sensitivity analysis*

To investigate the robustness of the total result, a range of sensitivity analyses was performed as shown in Table 9 (Supplement sheet 20). Across these, ICT sector's electricity consumption in the use stage stayed within±5% while the sector's carbon footprint

Table 9
Result of sensitivity analysis.

Changes to input parameters	Impact on ICT sector	
	Use stage electricity	Total carbon footprint
Emission factors changed to IEA (IEA, 2022a)		+1.3%
Emission factor set to 0.6 kg CO_2e/kWh as in 2015 study (Malmodin and Lundén, 2018a)		+4.9%
Coverage of subscriptions 5 percentage points lower in all regions	+1.8%	+0.9%
Networks, data centers, enterprise embodied emissions +25%		+1.9%
Satellites emissions +50%		+0.05%
Enterprise electricity consumption +25%	+0.7%	+0.4%
Data center electricity +10%	+2.4%	+1.0%
Installed base of smartphones, PCs and PC monitors +25%	+4.5%	+5.6%
TEC of smartphones, PCs and PC monitors +25%	+4.5%	+3.8%
IoT devices embodied emissions +25%		~0%
IoT devices electricity consumption +25%	+4.3%	+0.5%

Table 10
ICT sector footprint development since 2007 and the present study.

	2007	2010	2015	2020
ICT sector total carbon footprint (Mtonne CO_2e)	620	720	730	763
ICT sector use stage electricity consumption (TWh)	710	800	805	916
Carbon footprint per ICT subscription (kg CO_2e/sub)	134	107	81	74
Use stage electricity per ICT subscription (kWh/sub)	153	119	89	89

increased somewhat more (5.6%) at the most. The uncertainty regarding numbers of computers, monitors and smartphones in use globally is large as discussed in section 8.1. Increasing the installed base or the electricity consumption of key user devices (smartphones, laptop and desktop PCs, and PC monitors) by 25% had the largest impact overall. The magnitude of the changes made to the input parameters also indicates the major sources of uncertainties. Embodied emissions are difficult to estimate due to the high number of data sources and uncertainty related to allocation of industry data to products and lifetime uncertainty. However, the increase of 25% to the embodied emissions had no major impact on the total results. Changing the emission factors to IEA factors for the same year (IEA, 2022a) gave no major impact (+1.3% to the carbon footprint), but using the global emission factor from the 2015 study (Malmodin & Lundén, 2018) in all calculations without considering regional differences increased the carbon footprint by almost 5%. Overall, the result is robust to the changes included in the sensitivity analysis. Adding the different analyses together using square-root-sum approach results in a 10% overall impact on the total results. All results of the sensitivity analysis are available in the Supplement file (sheet 20).

8.3. Development over time

The use stage electricity consumption and the total carbon footprint of the ICT sector has increased somewhat since 2015 (Malmodin & Lundén, 2018), see Table 10. This shows that despite the high climate ambition of many ICT companies (GSM Association, 2021; Climate Champions, 2021), the sector is not yet developing in line with the normative decarbonization 1.5°-trajectory outlined by ITU and its partners (IEA, 2020a, 2020b, 2020c, pp. 1–2020). Increased number of ICT subscriptions has led to a decrease in electricity consumption and GHG emissions per subscription 2007–2020, but the decrease has slowed down and electricity consumption per subscription is similar in 2020 vs 2015. The main reason for the decrease is the high growth of mobile subscriptions together with the low network and mobile device electricity consumption per subscription. Note that IoT subscriptions are not included in the number of subscriptions while electricity consumption and GHG emissions related to IoT are included. If excluding the impact related to IoT devices from the total GHG emissions and use stage electricity consumption, the total sector footprint would be lower, as indicated by the dotted lines in Fig. 5.

The estimated embodied carbon footprint of data center and network equipment and all their infrastructure for 2020 in the present study is about 20 Mtonne higher than for 2015 (Malmodin & Lundén, 2018). The main reason is that embodied emissions were depreciated over the life cycle in Malmodin and Lundén (2018) while actual emissions in 2020 are used in the present study.

No data traffic intensity metric has been calculated in contrast to some previous studies by the authors (Malmodin et al., 2010; Malmodin & Lundén, 2018). Global data traffic has increased about 40 times since the first study in 2007 (Cisco, 2015, IEA, 2022b), while the ICT sector's carbon footprint and use stage electricity has stayed almost the same, see Fig. 5. Studies have sometimes assumed that the ICT sector's footprint will grow over time in line with the data traffic growth which has resulted in exaggerated estimates and forecasts. Moreover, allocating electricity consumption and GHG emissions to services or any type of use based on data traffic, e.g., data centers footprints, and without consideration of the electricity consumption needed to keep the system up and running is not recommended. For example, Netflix and Akamai report their data centers and Content Delivery Network (CDN) to consume about 0.5% of data center electricity while their share of global data traffic is 29% (Akamai, 2022; Marwaha, 2021; Netflix, 2021). Without considering these relationships, a simple allocation based on data would result in a value about 50 times too high for their streaming and downloading services.

8.4. Putting the ICT sector footprint in relation to closely related areas

Despite the existence of a standard (ITU, 2018), the set boundaries of the ICT sector differs between studies and sometimes estimates of the ICT sector electricity consumption and GHG emissions are presented together with or including, e.g. televisions, gaming devices, printers, paper media, and cryptocurrency mining equipment. This paper follows the boundaries set by the standard (ITU, 2018), which restricts ICT to information technology (IT) and telecommunication. Borderline activities could often be associated with Entertainment and Media (E&M), but the boundaries of ICT may need to change over time. In the future it might not make sense to distinguish between the E&M sector and the ICT sector. Following this, a coarse estimate has been made to put the ICT sector carbon footprint in relation to other related activities and equipment. TVs, TV peripherals and TV networks are likely the category outside ICT most closely related to ICT. Many other studies include the TV subsector as part of the ICT sector, at least TVs. Set top boxes and gaming consoles are considered as TV peripherals, while audio and camera devices and other portables are grouped into *Other E&M*. This boundary setting is allocated based on hardware regardless of its use and software. This means that e.g. gaming computers are fully allocated to ICT. Fig. 6 shows the footprint of the ICT sector using the boundaries of the present study, together with the footprint of some related equipment categories. For these, the use stage electricity has been estimated for each shown category, e.g. based on

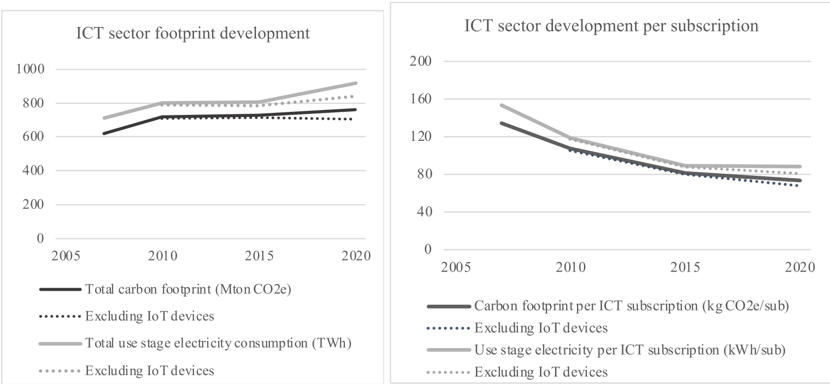

Fig. 5. Development of ICT sector's carbon footprint (left), where the dotted lines show the development without impact from IoT devices in Table 7 and the total ICT sector footprint per subscription (right).

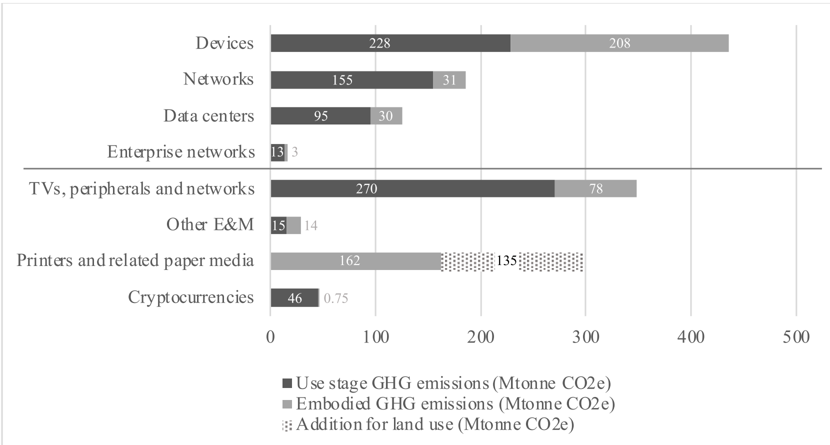

Fig. 6. GHG emissions of ICT sector (above the horizontal line) and related areas.

installed based and average electricity usage, while the embodied emissions are based on Lövehagen et al. (2023a, 2023b) which estimates the total embodied GHG emissions for all electronics and allocates it to various sectors and activities. The background calculation and sources for each category is described in the Supplement (sheet 21–23). The world average electricity grid mix emission factor has been applied for the calculations. Referring to world average electricity mix rather than considering regional or local distributions, or purchase of renewable electricity, could skew the results somewhat, as the sensitivity analysis for the ICT sector indicate (section 8.2). The additional categories presented here also share other sources of uncertainties with the user device category (see section 6). However, a more detailed analysis of non-ICT equipment is beyond the scope of this study.

8.5. Alignment with ITU standards

The study has used the standard ITU L.1450 (ITU, 2018) as its methodological basis. The ambition has been to follow the standard and the principles of relevance, completeness, consistency, accuracy and transparency as far as possible. A detailed analysis of the standard compliance is available in the Supplement (sheet 24–25). The compliance analysis covered mapping of ICT sector scope, data availability, data quality, data transparency, data age, data sources, use of reported data from actual operations, quality of emission factors, handling of intensities and the actions taken to analyze the uncertainty and sensitivity of the results. Especially it is concluded that the study covers all categories requested by the standard (though sometimes using different terminology and boundaries between them), except for the ICT services category which is excluded due to high uncertainty. Excluding ICT services (except their use of ICT which is covered by other categories) is in line with the approach taken in the decarbonization trajectory developed by ITU and partners (ITU, 2018). The present study also includes additional categories and by that expands the scope beyond the standard to also cover emerging categories of equipment such as VR devices. In particular, the present study includes the optional element of embedded IoT modules. Overall, it is concluded from this self-assessment that the study has a high degree of compliance with the standard with deviations reflected in the Supplement to the best understanding of the authors.

8.6. Implications for policies and future research & development

The main measures to reduce the carbon footprint of the ICT sector is to reduce electricity consumption, both in production ("embodied") and in use, and to transition to electricity from renewable energy sources. Despite great progress in energy efficiency, the sector can further intensify its activities to implement these measures. Policies can support this effort by incentivizing those companies which are not already working to reduce their emissions in line with the science-based trajectory (ITU, 2020) to do so, and can support the transition of all companies by ensuring the access to non-fossil electricity in all countries. Further policy activities that lead to prolonged lifetimes and increased recycling of devices would reduce the embodied footprint.

Continued research within this topic is dependent on the availability and quality of data. Many different data sources are used to cover the whole ICT sector and the more transparently data are presented, the better the quality of these types of studies can become. More focused studies are needed for all parts of the ICT sector on the different life cycle stages covering the embodied emissions, use stage emissions and the end-of-life related impact. Especially, for user devices, statistics on number of devices in use, usage intensity and geographical distribution needs to improve. Similarly, the coarse estimate of the related activities such as E&M could be improved by better data and geographical granularity.

9. Conclusions

ICT sector used about 4% of the global electricity in the use stage and represented about 1.4% of the global GHG emissions in 2020 (Enerdata, 2023a, 2023b; UNEP, 2022). The share of the total carbon footprint is at about the same level as in the 2015 estimate (Malmodin & Lundén, 2018), while the use stage electricity share increased somewhat. Hence, the ICT sector emissions have evolved in line with the rest of the world. In absolute terms, total GHG emissions is about 764 Mtonne CO_2e which is 5% higher than in 2015. Overall, the use stage GHG emissions relating to electricity use represent the majority of the total GHG emissions (~64%). Embodied emissions represent 36% of total emissions and a large part of embodied emissions is also related to electricity use. User devices represents more than half of GHG emissions (~57%) with almost equal parts relating to use and embodied emissions (52% vs. 48%). For networks and datacenters combined, use stage electricity consumption represents about 80% of total GHG emissions.

The GHG emissions per subscription has decreased compared to 2015, to 74 kg CO_2e/subscription, while the use stage electricity consumption has remained constant at 89 kWh/subscription. The difference can be explained by more renewables in the electricity mix overall, and additional renewables used in first datacenter operations but also in network operations. This has also helped to keep the sectors total GHG emissions stable. The related E&M sector is dominated by TVs, TV peripherals, and TV networks, about 350 Mtonne CO_2e in total or 0.65% of global GHG emissions, which is about 12% higher than total GHG emissions for ICT networks and datacenters combined. Despite high ambitions among many ICT companies the sector has not decreased its emissions 2015–2020 in line with the decarbonization trajectory outlined by ITU, GSMA, GESI and the SBTi (IEA, 2020a, 2020b, 2020c, pp. 1–2020), so overall climate efforts need to broaden and increase.

Data availability

All data points, calculations and references are available in the Supplementary material.

CRediT authorship contribution statement

Jens Malmodin: Writing - review & editing, Writing - original draft, Methodology, Investigation, Formal analysis, Data curation. **Nina Lövehagen:** Writing - review & editing, Writing - original draft, Methodology, Investigation, Formal analysis, Data curation. **Pernilla Bergmark:** Writing - review & editing, Methodology, Formal analysis. **Dag Lundén:** Writing - review & editing, Methodology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.telpol.2023.102701.

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