Life Cycle Assesment of ICT

Carbon Footprint and Operational Electricity Use from the Operator, National, and Subscriber Perspective in Sweden

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Supporting information is available on the *JIE* Web site

Summary

The use of information and communication technology (ICT) is growing throughout society, and new products and solutions are developed at an increasing rate. To enable environmental assessment of specific ICT products and other products that rely on ICT in some way, a more complete, detailed, and up-to-date study based on real measurements is needed. To date, similar studies have not been readily available or fully comprehensive. This study assessed the overall operational electricity use and life-cycle–based carbon footprint (CF) relating to ICT in Sweden, including activities not commonly addressed previously, such as shared data transport networks and data centers and manufacturing of network infrastructure. Specific, detailed inventory data are presented and used for assessment of the Internet Protocol core network, data transmission, operator activities, and access network. These specific data, in combination with secondary, more generic data for end-user equipment, allow a comprehensive overall assessment. The majority of the ICT network CF is the result of end-user equipment, mainly personal computers, followed by third-party enterprise networks and data centers and then access networks. The parts closest to the user proved to be clearly responsible for the majority of the impact. The results are presented for Swedish ICT networks and for ICT networks in general based on a global average electricity mix.

Introduction

The move toward more information and communication technology (ICT) in various sectors of modern society is rapid. Introduction of new devices, or new designs of old devices, is making it possible for people and things to be always available or accessible. Use of ICT networks, which is necessary for the connection of devices and transmission of data, forms a vital part in the growing use of products and services in society. Consequently, life cycle assessments (LCAs) of different products and services performed during the past 10 years have demanded an inventory of data regarding ICT. There are several databases providing comprehensive information on conventional transportation infrastructure, such as road systems and railways, and the environmental impacts related to these and all vehicles that use them. In contrast, for electronic distribution, the inventory data are less comprehensive and not as readily available. Some studies have been made for parts of the ICT network system and some on products and services using ICT networks, in which estimates and best available data are used. However, comprehensive studies including user equipment and internet data services (or other managed Internet Protocol [IP] services) are few in number. The physical transmission links (hereafter "data transmission") and the IP edge/metro/core

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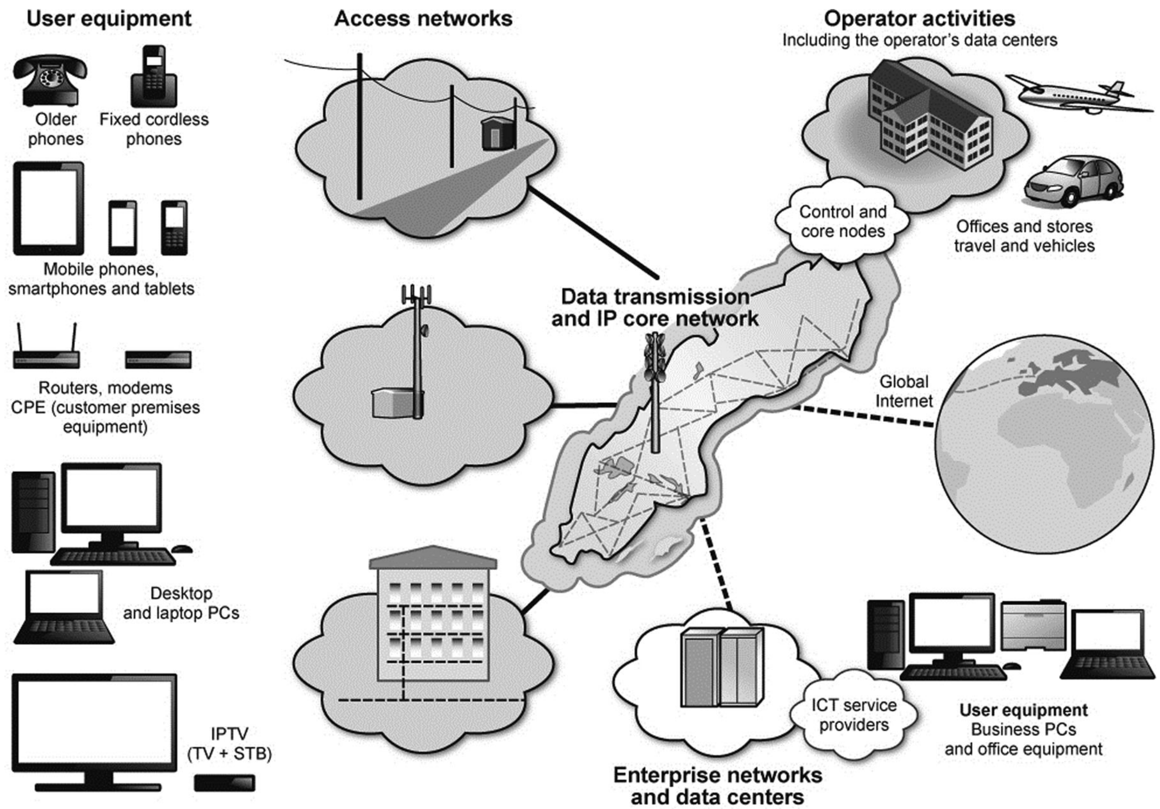

Figure 1 Scope of the study. IP = Internet Protocol; PCs = personal computers; ICT = information and communications technology; STB = set-top box.

switches/routers (hereafter "IP core network") are the least investigated part of the network to date. Some previous studies include detailed examination of parts of the systems (e.g., Faist Emmenegger et al. 2006; Koomey 2011; Lange et al. 2011). There are also less-detailed studies on the national or global level (e.g., GeSI 2008; Malmodin et al. 2010a; GeSI 2012).

In 2009, two companies in the telecom sector, Ericsson and TeliaSonera, joined forces to perform a complete, in-depth LCA study of an ICT network. The study was enabled through the substantial LCA experiences of these companies and life cycle inventory data gathered and refined over many years. Based on the results, the present study assessed the overall operational electricity use and carbon footprint (CF) related to the ICT network with a life cycle perspective. This assessment included activities previously not commonly addressed, such as shared data transport networks and data centers as well as manufacturing of network infrastructure. The most significant parts of the network relating to operational electricity use and greenhouse gas (GHG) emissions were identified. The results are presented from three main perspectives: for a telecom and network operator (hereafter "operator"); nationally for Sweden; and related to different subscriber services. In addition, the results are recalculated using a global electricity mix to better illustrate the impacts of ICT networks from a global perspective. This article expands on results presented at NorLCA (Malmodin and Lundén 2011).

Methodology

Definition of Information and Communications Technology

The term ICT network is used here to denote communication networks from the core network to the end-user equipment. It covers mobile and fixed access networks (including broadband) and data transmission and IP core networks. The term ICT also includes user equipment connected to the networks, such as phones, personal computers (PCs) and modems, enterprise networks, data centers, and operator activities (see figure 1). It matches the scope for ICT recently used by GeSI (2012) and the scope used in a previous study (Malmodin et al. 2010a), which also describe how ICT is defined in relation to entertainment and media products and services, and recently another study (Malmodin et al. 2013) that discuss the Organisation for Economic Cooperation's (OECD's) definition of ICT.

In this study, primary subscription services (i.e., the possibility to communicate by speech and data) are seen as an integral part of the sector. ICT includes the system generally referred to as "the Internet," although it is difficult to allocate a specific share of the results to the Internet because of its complex infrastructure and usage practices. As an example, all PCs and servers and their total usage are seen as part of ICT and no share are allocated to other sectors or usage.

Results are presented here for both the actual ICT network itself and also for the "extended ICT network," in which end-user equipment and third-party enterprise networks and data centers are included, which, also short, can be denoted ICT.

Life Cycle Assessment of Information and Communications Technology in General

By using a life cycle perspective, the environmental impact throughout the whole system from cradle to grave is considered. For ICT networks, this means that the energy used for operating the network, but also the manufacturing and maintenance of infrastructure and equipment and their end-of-life treatment (EoLT) are included.

Performing an LCA of an ICT network is very complex. Because the telecommunication and Internet services are globally connected and some national nodes are accessed by many operators, description of a national ICT network is complicated in terms of both scope and allocation. How this was handled in the current study is described in the following sections.

Scope of the Study

The case study performed covered TeliaSonera's actual ICT network and its connected Swedish customers in the extended network, including its share of impact from international data traffic network equipment and third-party enterprise networks and data centers. The functional unit was 1 year of network operation. In addition, the impact was calculated in relation to specific primary subscription services, including subscriptions for mobile and fixed voice or broadband connections.

All networks included and calculations made were based on 2009 data, except measurements of user equipment in Swedish households in 2008 (Zimmermann 2009), TeliaSonera operator activities in 2007 (TeliaSonera 2008), and data traffic in Sweden in 2010 (PTS 2011). Manufacturing and construction-related LCA inventory data were normalized to 1 year of operation (2009) using relevant lifetime estimates. Earlier LCA studies performed at Ericsson and TeliaSonera on various parts of the ICT network in Sweden were used as the main data source for embodied emissions (see the supporting information on the Journal's website). Based on observations, energy and manufacturing data change slowly year by year, despite the rapid increase in data traffic. This argues for the estimates being appropriate also for 2010 when using data traffic measurements from the same year.

Operational electricity use and overall GHG emissions related to ICT networks and the operator's activities were assessed. The GHG emissions included both use stage and embodied emissions. The embodied carbon emissions for any equipment are defined as the total life cycle carbon dioxide equivalent (CO_2-eq) emissions associated with manufacturing, transportation, and EoLT for that equipment (i.e., all emissions except those related to its operational energy use). All relevant GHG emissions are included, for example, GHG emissions related to cement production (construction of infrastructure) and use of fluorinated gases (electronic component manufacturing).

As illustrated in figure 1, the ICT network system studied was comprehensive. The subsystems included in the study were:

User equipment:

- Basic mobile phones and more advanced smartphones, fixed (cordless) phones, PCs/terminals, office equipment, televisions (TVs) used together with IPTV subscriptions. Additional equipment, such as personal data storage and audio peripherals, were excluded because they were defined as entertainment and media products (Malmodin et al. 2010a).
- Home network equipment or customer premises equipment (CPE), for example, modems, routers and gateways, and set-top boxes (STBs) used together with IPTV

Access networks:

- Second-generation (2G; global system for mobile communications [GSM]) and third-generation (3G; wideband code division multiple access [WCDMA]) mobile radio access networks, public switched telephone networks (PSTNs), digital subscriber line (xDSL), cable TV, fiber optic cable to the home/curb, and so on

Control and core nodes (allocated to each service):

- PSTN voice, 2G and 3G mobile core networks, voice-over IP (VoIP)

Operator activities and operator data centers:

- Offices and stores (energy), internal data centers, business travel, service vehicles (own and third-party services), and activities required for operation and maintenance of the ICT networks, to serve the subscribers, and so on

Data transmission and IP core network:

- A large number of different types of transmission link elements (copper, fiber optics, radio links, and so on), IP edge/metro/core switches/routers, including all supporting infrastructure for cooling, power, and so on
- International data transport, IP core networks and data centers, routers and fiber optic links, and submarine fiber optic cable systems for data traffic outside Sweden/European Union, and so on

Third-party enterprise networks and third-party data centers:

- Enterprise networks (local area network; LAN) with access and aggregation switches and routers
- Servers, storage, and routers and switches in data centers, including all supporting infrastructure for cooling, rectifiers, and back-up systems

For a more detailed description of ICT network subsystems and their function, see appendices S3 and S5 in the supporting information available on the Web.

Table 1 Summary of average end-user equipment operational electricity consumption figures used in this study and resulting carbon footprint

	In use (million)	*Average long time power (W)*	*Electricity consumption (kWh/year)*	*Total electricity in Sweden . . . (GWh/year)*	*. . . with Swedish–global mix (kt CO_2-eq/year)*
Fixed phone	5.4	0	0	0	0
Cordless phone	5.4	3	27	146	9 to 88
Mobile phone	10.5	0.3	2.7	28	2 to 17
PC	8.5	25	218	1,850	111 to 1,110
Modem	2.5	9	79	198	13 to 129
Router	1.2	9	79	95	6 to 57
Gateway	0.35	11	96	34	2 to 20
TV	0.35	24	210	74	4 to 44
Set-top box	0.35	7	61	21	1 to 13

Note: Swedish electricity mix = 0.06 kg CO_2-eq/kWh; global electricity mix = 0.6 kg CO_2-eq/kWh.
PC = personal computer; TV = television; W = watt; kWh = kilowatt-hour; TWh = terawatt-hour; kt = kilotonne (metric); CO_2-eq = carbon dioxide equivalent.

The network studied contained all functions that can be expected from an operator offering all modern ICT services for both the private sector and business customers, including machine-to-machine services and seamless cloud functionalities for fixed and mobile operations. All parts of the TeliaSonera ICT network physically located in Sweden were included, as were core network interfaces toward the international backbone network. Impacts outside Sweden related to international traffic to and from Sweden were included and shared between original and terminal networks. TeliaSonera equipment installed on the premises of other operators was included by use of site- and equipment-specific information, whereas equipment installed by other operators on TeliaSonera premises was excluded.

Top-down and Bottom-up Approaches

Electricity consumption is, in general, measured on site level and includes all installed equipment, and, for this reason, there are no measured figures available per function or device. However, by combining available measurements with data sources, such as internal experts, own measurements, and estimations, weighed together with information on facility locations, equipment type, equipment age, and so on, figures per service with relatively good accuracy were obtained. See appendices S3 and S4 in the supporting information on the Web.

Thus, top-down and bottom-up data collection approaches were used to quantify the network equipment and the energy use of the ICT network. The top-down data collection included energy measurements on site level from seven large data/telecom centers, 15 office locations, 58 stores, and approximately 11,000 fixed and mobile sites in Sweden.

The bottom-up data collection approach used databases containing information on more than 100,000 network equipment entities. Per equipment type, this information was combined with supplier information regarding electricity use values validated by short-term measurements. The aggregated value was compared against measured long-term (top-down) site electricity use values and adjusted accordingly. Energy-use data for supporting infrastructure, such as cooling equipment and rectifiers for all-access network equipment, were collected from internal sources. The data collection differed depending on available sources and is described below. All findings were compared and combined with findings from previous internal LCA studies.

Allocation in Information and Communications Technology Networks

The ICT network is complex and is used for different purposes and by a number of users. An implication of this is that part of the energy use and GHG emissions (e.g., in the case of shared support systems such as the core network) need to be allocated to different activities. How this was done here is described in the *Data from a Subscription Perspective* section. Another complexity associated with ICT networks is that they often host multiple network equipment entities, which may belong to different operators. To avoid allocation between operators, top-down energy measurements of complete sites and bottom-up aggregation of equipment energy models were used (see below). Common site infrastructure, such as cooling, rectifiers, and back-up systems, was allocated to each network equipment type based on its actual energy use or, when this was not available, based on internal expertise. In some cases, equipment (e.g., top lights to mobile access and old transmission links to PSTN access) was allocated only to the major ICT network equipment for reasons of simplicity, even though they were shared, to a minor extent, with others.

Operator activities were allocated between fixed and mobile network-based services using number of employees and internal business information.

Data Collection and Calculations

This section describes the data collection process and presents some figures characterizing user equipment (summarized in tables 1 and 2) and the network (summarized in

Table 2 Summary of average end-user equipment manufacturing carbon footprint figures used in this study

	Put on market (million/year)	*Manufacturing CF (kg CO_2-eq/device)*	*Total manufacturing CF (kt CO_2-eq/year)*
Fixed phone	0	5	0
Cordless phone	0.8	15	12
Mobile phone	3.5	24	84
PC	2.1	375	790
Modem	0.5	15	7.5
Router	0.2	20	4
Gateway	0.08	50	4
TV	0.05	300	15
Set-top box	0.07	25	2

Note: PC = personal computer; TV = television; CF = carbon footprint; kg = kilogram; CO_2-eq = carbon dioxide equivalent; kt = kilotonne (metric).

table 3). The main data used in the study can be found in the supporting information on the Web, where network elements and abbreviations used are also explained.

User Equipment

One key challenge in this study was to find representative figures for the energy use and the embodied CF of a number of user equipment categories reflecting the current use of ICT in Sweden. Typical user equipment per subscription was estimated for the whole of Sweden and the same values were used for TeliaSonera subscriptions.

Based on number of PCs sold and in use in Sweden every year, it was clear that PCs would play a major role for the ICT networks studied. Therefore, PCs are used here as an example to illustrate how calculations were made for user equipment. Further information and calculations regarding other equipment categories are presented in the Supporting Information on the Web, where all references to the LCA studies used are also listed.

According to some 20 LCA studies, the embodied CF of a PC is between 200 and 800 kilograms (kg) CO_2-eq for a desktop computer and between 100 and 400 kg CO_2-eq for a laptop. The two most important reasons for the range of values are the type of PC studied (from inexpensive small basic to expensive large high-end) and the age of the data. Based on the LCA studies reviewed, a number of LCA models for the average embodied carbon footprint and electricity consumption for the main PC types were established; see figure 2 and appendix S2 in the supporting information on the Web. Standard peripherals, such as keyboard and mouse, were included, but other peripherals, such as external storage, speakers, and gaming peripherals, were not. Extra monitors and docking stations for office laptops were included in the study as separate equipment.

Table 3 Summary of network site/node data used in this study

		Per average network site		*Per average subscription (/sub)*	
Site/node type	*Unit*	*Electricity use and CF per year*	*Manufacturing CF per year (lifetime)*	*Electricity use and CF per year*	*Manufacturing CF per year*
PSTN access line (including physical line manufacturing and construction)	kWh	10,200		18	
	kg CO_2-eq	6,100	2,950 (10 to 40 years)	11	5.3
PSTN exchanges and core sites (including building)	kWh	113,000		5.3	
	kg CO_2-eq	68,000	43,000 (10 to 20 years)	3.2	2
2G/3G base station site (including infrastructure, e.g., towers and shelters)	kWh	8,300		23	
	kg CO_2-eq	5,000	1,750 (7 to 20 years)	14	3.5
Fixed broadband (DSLAM equipment only, not including existing line/site)	kWh	3,420		31	
	kg CO_2-eq	2,100	120 (7 to 10 years)	19	1.1
Data center (only TeliaSonera's own equipment in own data centers)	kWh	5,300,000		0.5	
	kg CO_2-eq	3,180,000	477,000 (5 to 20 years)	0.3	0.044
				Per average data traffic (/GB)	
Data transmission and IP core network (including cables)	kWh	20,500		0.08	
	kg CO_2-eq	12,000	4,000 (5 to 40 years)	0.048	0.016
International submarine cable system	kWh	3,200,000		0.02	
	kg CO_2-eq	3,180,000	7,400 (5 to 20 years)	0.013	0.031

Note: Data are per year, which means the embodied carbon footprint has been normalized by lifetime for network equipment and supporting infrastructure. See appendix S1 in the supporting information on the Web. Use of carbon footprint is based on a global electricity mix (0.6 kg CO_2-eq/kWh).
CF = carbon footprint; PSTN = public switched telephone network; kWh = kilowatt-hour; kg = kilogram; CO_2-eq = carbon dioxide equivalent; 2G = second generation; 3G = third generation; DSLAM = digital subscriber line access multiplexer; GB = gigabyte; IP = Internet Protocol.

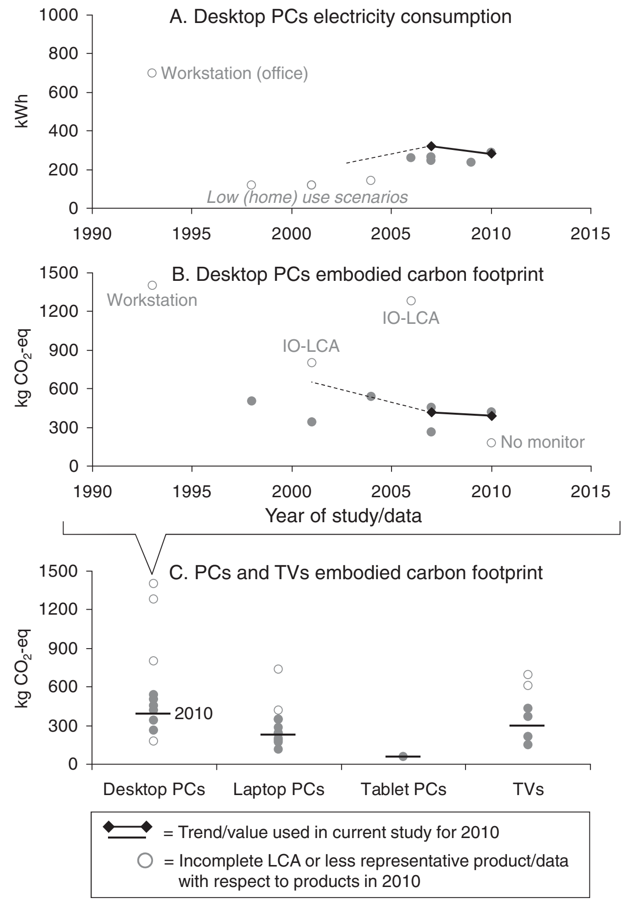

Figure 2 Values for electricity consumption (A) and embodied carbon footprint (B) of desktop PCs based on a number of previous studies. Laptops, tablets, and TVs are also shown in the summary graph (C). Selected relevant values used in the present study are indicated. In diagram (B), 2010 is included to visualize the variations in reported LCA results in that year and to highlight the average figure used in this study. For references to all studies, see appendix S2 in the supporting information on the Web. PCs = personal computers; IO-LCA = input-output life cycle assessment; kWh = kilowatt-hour, kg = kilogram, CO_2-eq = carbon dioxide equivalent.

The electricity consumption of all electrical and electronic equipment in 400 households in Sweden was measured during 2008 (Zimmermann 2009). It emerged that the average electricity consumption for PCs (234 kilowatt-hours per year [kWh/yr]) was similar to the average scenarios and values (240 to 270 kWh/yr) reported in other similar studies, but higher than that stated in earlier PC LCAs (approximately 150 kWh).

The impact on the climate system in households or offices, or the need for extra space to host equipment or even a workplace, which may lead to increased total energy consumption in the home or the office, has not been included. It was seen as higher-order effects not a part of the scope of the study. Also, many studies, such as that of GeSI (2012), believe that the positive higher-order effects related to ICT (e.g., reduced) is far greater than the negative ones.

The total amount of user equipment was mainly based on Swedish Post and Telecom Agency (PTS) subscription statistics (PTS 2008, 2009, 2010, 2011). Sales statistics were used to determine the amount of new products manufactured. The number of PCs in active use was estimated based on the number of PCs in Swedish homes and our own estimates regarding PCs in nonresidential use. The ratio between sold and active PCs is approximately 1:4 and between sold and active mobile phones approximately 1:3. These ratios were used to estimate the life of PCs (4 years) and mobile phones (3 years).

Tables 1 and 2 summarize the user equipment data used. The figures relating to the typical PC refer to a mix of desktop and laptop PCs, with a ratio of 1:1 for offices and 2:1 for homes. The typical mobile phone in table 1 is based on a mix of mobile phones and smart phones, with a ratio of 2:1. It was assumed that one cordless phone and one older analog phone are used per fixed voice subscription.

Access Networks

A key conclusion of previous studies (presented in the Supporting Information on the Web) is that supporting infrastructure makes a significant contribution to the overall impact of access networks, especially when studying a country such as Sweden with low emissions related to operational electricity consumption. The term "supporting infrastructure" is used here to denote all materials, products, and related construction work that are not active network equipment (e.g., manufacturing and construction of fixed cable networks and antenna masts for base stations in mobile access networks).

Even though many of the studies used that relate to supporting infrastructure are rather old, they can still be considered representative. In fact, much of the infrastructure is more than 10 years old and was deployed before the studies were made. Activities such as manufacturing of cables, digging cable trenches, raising steel lattice antenna masts, and so on, are based on mature techniques, which are not changing as rapidly over time as, for example, design and manufacturing of ICT equipment. Further, the estimated lifetime of such equipment is long (e.g., 40 years for cable trenches and 20 years for antenna masts). The embodied CF for all infrastructure divided by its estimated lifetime was included in annual emissions in the present study in order to take the full life cycle into account.

Fixed Access Network

The fixed access network structure is quite complex and includes many different access technologies, for example, PSTN (see appendix S5 in the supporting information on the Web for more acronyms used).

Traditional PSTN telephone communication, where the telephone is powered from a local exchange (LX) by a fixed copper cable-based network, is the most common access technology. In the LX system, the copper cable is connected to a line interface card and then further to an LX. In the TeliaSonera network in Sweden, the LXs are conventional digital automatic cross-connection equipment stations. The total volume of such sites is less than 200 in Sweden. Traffic volumes for PSTN are reported annually (TeliaSonera 2008).

VoIP is the IP-based fixed telephone system that, in the long run, will replace conventional PSTN. The usage is still limited, but the network equipment already exists and increased customer volumes will only increase the need for hardware and the electricity consumption to a limited extent. VoIP requires fixed broadband access.

Fixed broadband access by xDSL communication over copper cable is the most common solution in Sweden to achieve high-capacity data streams up to 20 megabits per second (2009). To achieve xDSL communication either by asymmetrical digital subscriber line or very-high-bit-rate digital subscriber line, there is a need for a digital subscriber line access multiplexer (DSLAM) or similar equipment, which distributes the broadband signal to the end customer. The DSLAM can supply many customers and the electricity consumption varies, depending on broadband capacity, distance to the customer, and quality of the copper wire. On the end-user side, there is a need for a modem that converts the xDSL signal to a data stream that, in normal cases, is distributed on a local fixed or wireless local LAN network. Fiber optic cable to the home network also exists, but volumes were quite low in 2009.

The supporting infrastructure is mainly made up of cable ducts and trenches. The average distance to an LX in Sweden is approximately 2 km. On average, approximately 33 lines share a physical cable deployment, approximately two thirds of which is outside buildings in cable ducts. TeliaSonera has made an extensive LCA study of manufacturing and construction of fixed copper networks, including all active equipment as well as supporting infrastructure (see appendix S1 in the supporting information on the Web). According to that study, the embodied carbon footprint is 5.3 kg CO_2-eq for the physical line itself and approximately 2 kg CO_2-eq for active equipment and sites per average fixed line and year. The DSLAM described above, which is needed to enable fixed broadband in existing copper access networks, has an embodied footprint for its active equipment of approximately 1.1 kg CO_2-eq per new fixed broadband line.

Mobile Access Network

The mobile network was divided into radio access and mobile core networks. Different methods were used to collect electricity consumption figures for these parts.

The radio access network consists of base stations, including transmitters and receivers. There are two parallel systems: 2G (GSM) and 3G (WCDMA). The TeliaSonera 3G network in Sweden is shared with another operator, a fact that was taken into account in the calculations. Measured electricity-use data were available for 36% of the base station sites. Based on these and a bottom-up approach regarding installed network equipment and different site sizes, a model was created to estimate electricity use for all base stations.

The mobile core network consists of mobile switches, subscriber databases, base station controllers, and so on. Energy-use calculations were based on bottom-up energy models, including energy figures from vendors for each node type.

For transmission between base stations and core networks, several technologies, such as radio link and fixed broadband communication, are used. Energy figures for transmission per site were based on an average of the different technologies.

Ericsson has made an extensive LCA study of manufacturing and construction of mobile networks and all base station sites, including all active equipment as well as supporting infrastructure (see appendix S1 in the supporting information on the Web). The supporting infrastructure is mainly made up of antenna masts and site housings, but also includes power installations, battery backup, and climate equipment. According to that study, the related carbon footprint is approximately 2.1 kg CO_2-eq per mobile subscription and year, mainly the result of the supporting infrastructure and antenna towers.

Transmission and Internet Protocol Core Network

The transmission and IP core network parts of the ICT network are complex. A simplified version of the ICT network is illustrated in figure 1 and in appendix S3 in the supporting information on the Web. Different methods and different in-house competences were used here to collect information on different network elements. As a general rule, internal inventory data were used. All active (i.e., power-consuming) network elements were identified and divided into categories, as presented in appendix S4 in the supporting information on the Web.

The transmission and IP core network equipment is spread out across many locations and its energy use is included in total electricity consumption figures for different sites. For data transmission and IP core network, each equipment type was identified and nominal energy figures from suppliers were used. In some cases, especially for network core routers, these figures were verified by energy measurements. Some measurements showed a large difference (+100%/–50%), compared to specifications by suppliers. However, because the aggregated nominal electricity consumption in total was in the same range as measured, the overall figures and their distribution between network parts were assumed to be good estimates.

Electricity consumption for each equipment type was calculated by multiplying the amount of equipment by the typical electricity consumption. To this figure, electricity for backup and cooling was added. The back-up and cooling figures were based on in-house estimates made by infrastructure experts. Measurements were made for verification. Most figures were also verified through comparing calculated electricity figures with real electricity consumption figures per site.

The data transmission and IP core network have been the least studied network part in previous LCAs of ICT. Therefore, this part is described in more detail in a separate article (Malmodin et al. 2012), which also describes how the TeliaSonera core network data can be extrapolated to model the corresponding overall Swedish core network parts. A submarine optical cable system, which is used for data traffic across the Atlantic, was included based on an LCA of sea cable-laying operations (Donovan 2009).

Operator Activities and Operator Data Centers

To install, maintain, and operate an ICT network, there is a need for human resources, machines, and energy. Human resources are associated with energy use in offices and stores, business travel, service vehicles, and commuting and were modeled based on measurements of TeliaSonera activities in Sweden. Impacts from operator activities were included within the system boundaries, both when performed by internal personnel and when outsourced (Malmodin et al. 2010b).

TeliaSonera's annual report (2008), written in accord with the Global Reporting Intiative standard Scope I, II, and, partially, III (TeliaSonera), was used as the basis for all internal and external contractor work performed, including use of vehicles and other machines, transport and travel.

Data centers containing servers for business support systems, operations support systems, and so on, were allocated to this category. The seven largest data centers in TeliaSonera Sweden cover almost 80% of the total number of internal servers relevant to this study. Five of these (>70% of total server volume) were studied in depth (i.e., manufacturer information, equipment types, supporting infrastructure, and so on). Equipment in these data centers was categorized as servers, storage, or other information techonology (IT) equipment. For these categories, LCA studies, such as Hermann (2008), Google (2011) and Weber (2010), provided information on the embodied CF. This information was combined with electricity consumption figures from suppliers. Site-specific supporting infrastructure data (cooling, uninterruptible power supply [UPS], rectifiers, and so on) were collected from each data center and combined with estimates made by internal experts. All this information was used to validate the total electricity consumption.

For the remaining server volume, a rough estimate of equipment composition (mainly numbers and types), together with extrapolated figures from the more detailed assessment, were used to allocate overall electricity consumption to the specific equipment.

Third-Party Enterprise Networks and Third-Party Data Centers

For third-party data centers (e.g., Google and Facebook, but also including all servers in enterprise networks), the total operational energy use in Sweden was based on Koomey (2011) because of the lack of good server sales data for Sweden. The number of active servers was estimated based on the global ratio between estimated active servers and PCs globally and the number of PCs in Sweden. Approximately the same ratio was found between global domain name system registrations globally and in Sweden, as well as approximately the same ratio also for data traffic volumes and colocation data center count. The data from Koomey (2011) were used, which include a factor of 1.3 to include storage and network equipment and then a factor of 1.8 to include cooling and power systems (power usage effectiveness factor), as defined by The Green Grid (2011). TeliaSonera's share was based on number of subscriptions and share of enterprise customers.

The energy use of enterprise LAN network equipment in Sweden was estimated to be 74 gigawatt-hours (GWh), based on 35 kWh per active LAN PC (based on internal studies) and 2.1 million LAN PCs (see section S6.5 in the supporting information on the Web). Based on internal studies, it was estimated that the server-to-PC ratio in enterprise networks was approximately 1:10, compared to an overall ratio of approximately 1:30. The energy consumption for a service such as Google is rather low, at 2 kWh per average user and year (Google 2012), whereas it is far higher for average total enterprise network data services (>200 kWh).

Approximately 35% of all access data traffic was estimated to be to and from data centers. Based on the same data traffic measurements in IP core networks in Sweden, it was estimated that approximately one quarter of the data centers are located abroad (e.g., Google and Facebook) and that one quarter of the data centers in Sweden serve customers abroad. In practical terms when studying Sweden, this means that one quarter of the data centers were modeled using a global average electricity mix. It was also assumed that approximately 50% of this international data traffic proceeds through a long-distance submarine fiber optic connection, based on Donovan (2009). See appendix S5 in the supporting information on the Web for more information about the data traffic model developed for Sweden.

The embodied CF for servers and other network equipment was based on the same LCA studies described in the operator sections. Electricity consumption in the use stage typically represents approximately 90% of the total CF for such network equipment (see appendix S1 in the supporting information on the Web). To what extent offices and travel activities (similar to TeliaSonera operator activities) are included in used LCA data for network equipment is not fully known. Ericsson includes offices and travel related to the design, manufacturing, sales, and so on, in LCA of its products and services, but it represents typically only approximately 1% of total life cycle energy or CF.

Data Extrapolation to Sweden and Recalculations to Illustrate Global Conditions

The data gathered for TeliaSonera were extrapolated to estimate values for the overall Swedish ICT networks. Each network part was scaled individually using best available information (see appendix S4 in the supporting information on the Web). End-user equipment data were available on the national level, as previously described.

For operator activities, it was assumed that, per subscription, other operators in Sweden have as many employees and stores, travel as much, and have as many vehicles servicing the networks as TeliaSonera, if PSTN maintenance specific for TeliaSonera is excluded.

As a result of Sweden's relatively low GHG-emitting electricity mix (0.06 kg CO_2-eq/kWh), which is based mainly on hydro and nuclear sources, use stage results were recalculated for a global average electricity mix (0.6 kg CO_2-eq/kWh) to make the results more relevant for non-Swedish conditions. The emission factors for electricity consumption are based on LCAs of electricity production, including fuel supply chain and construction of power plants and the grid itself (including losses), which is described in Malmodin and colleagues (2010a).

In many other ways, Swedish ICT networks are believed to correspond rather well to global conditions. In brief, the geographical density (subscriptions per square kilometer [km^2]) of mobile subscriptions is slightly lower, but the density of fixed subscriptions is somewhat higher. The number of mobile subscriptions per area in Sweden is of the same order of magnitude as the global average, at 27 and 33 subscriptions/km^2, respectively (based on ITU [2011]). The number of fixed subscriptions per area in Sweden is higher than the corresponding global average, at 18 and 11 subscriptions/km^2, respectively. The voice and data traffic is higher per subscription in Sweden, but this is not crucial for the extrapolation. The average outdoor temperature in Sweden is approximately 5°C, compared with a global average of approximately 15°C. Because of this fact, free air cooling is used more frequently in Sweden. Overall, the energy use related to climate is lower in Sweden.

Data from a Subscription Perspective

The subscription perspective was calculated for the Swedish and global results, but not for TeliaSonera, because parts of the key data were only publicly available on the national level (e.g., data traffic and sales statistics).

The recalculations from total network values to subscription were generally straightforward (e.g., total results for PSTN network were divided by PSTN subscriptions). Dedicated PSTN and mobile transmission links were first related to PSTN and mobile networks, respectively. However, whereas the access equipment for PSTN and xDSL is dedicated to subscriptions, the physical line itself is shared. Several alternative allocation principles may be applied (e.g., one line per subscription or based on share of data traffic). Using data traffic would be consistent with the allocation choice used for other network and transmission components here. However, this would allocate nearly all the line impact to broadband subscriptions. Such an allocation seems unreasonable, because approximately three quarters of the PSTN lines deployed have no broadband equipment connected. Also, in the future, all households will probably have xDSL (or another broadband connection), but no active PSTN. The data for the physical line construction is approximately a decade old, when there were about as many more active PSTN lines as there are new broadband lines today. Therefore, the full impact of an average physical line was allocated to both PSTN (approximately 10% of the total PSTN impact; see section S6.1 in the supporting information on the Web) and broadband connection (only approximately 1% of the total broadband impact; see section S6.5 in the supporting information on the Web).

Data centers were allocated 50/50 between propriety enterprise networks ("intranet") and the public Internet based on typical server-to-PC ratios for enterprise networks. The Internet part was then allocated to different subscription services based on data volume, including also enterprise network PC Internet data volume. Data transmission and IP core networks were allocated to different subscription services based on data volume.

Results and Discussion

The Information and Communications Technology Network: Operator and National Perspective

The TeliaSonera actual network consumes approximately 0.42 terrawatt-hours (TWh). This includes access networks, data transmission, and IP networks, but excludes TeliaSonera customers' colocated equipment. It can be noted that the old public fixed access network (i.e., PSTN) represents almost 25% of this (figure 3) because it has quite high, constant electricity consumption. This includes traditional PSTN network nodes and concentrators. There is potential to decrease the overall energy use by replacing old with new technology (i.e., by using IP-based PSTN solutions). This is also true for the mobile network. Thus, in new markets, where state-of-the-art technology can be applied from the start, the energy use may be lower than the average presented here. However, it is worth highlighting the in-built conflict between choosing to invest in expensive, but modern, IP-based solutions and relying on older, perfectly working, but not as energy-efficient, solutions that are in operation subsequent to investments made more than 15 years ago.

Another way of presenting the operational electricity of the TeliaSonera actual network (excluding offices) is: network equipment, 65%; cooling, 19%; rectifier/UPS, 12%; and others 4% (see appendix S4 in the supporting information on the Web).

User equipment, third-party data centers, and enterprise networks consume 1.5 TWh. Together with the energy of the actual network, this results in 1.9 TWh for TeliaSonera, its connected Swedish customers, and accessed third-party equipment in the extended network (figure 3). Note that number of PCs and their electricity consumption is not modeled, but based on actual measurements in 400 Swedish households for a whole year (Zimmerman 2009). These measurements showed high "on-time" (5 hours/PC/day) and high electricity consumption (240 kWh/PC/year). It is also worth mentioning that customer premises equipment (CPE) in people's homes consumes slightly more electricity than the mobile and fixed broadband access networks altogether.

To reduce the total electricity consumption of ICT, the focus should primarily be on PCs, data centers (servers), and CPE, where the largest potentials are. New energy-efficient laptops and tablets have the potential to lower the consumption of user equipment in the future as their share of user equipment grows. Electricity consumption should also be an important aspect when access network nodes are added or modernized. The core network's consumption is, on the other hand, low, in comparison to its importance.

The overall CF of TeliaSonera's extended network during 1 year is equal to 0.65 million metric tonnes (Mt) CO_2-eq (figure 4). This is mainly the result of the end-user equipment and, more specifically, their manufacturing (0.37 Mt CO_2-eq), because the electricity used in manufacturing is highly fossil based, unlike the Swedish electricity mix used for operation. Other important contributors are construction and

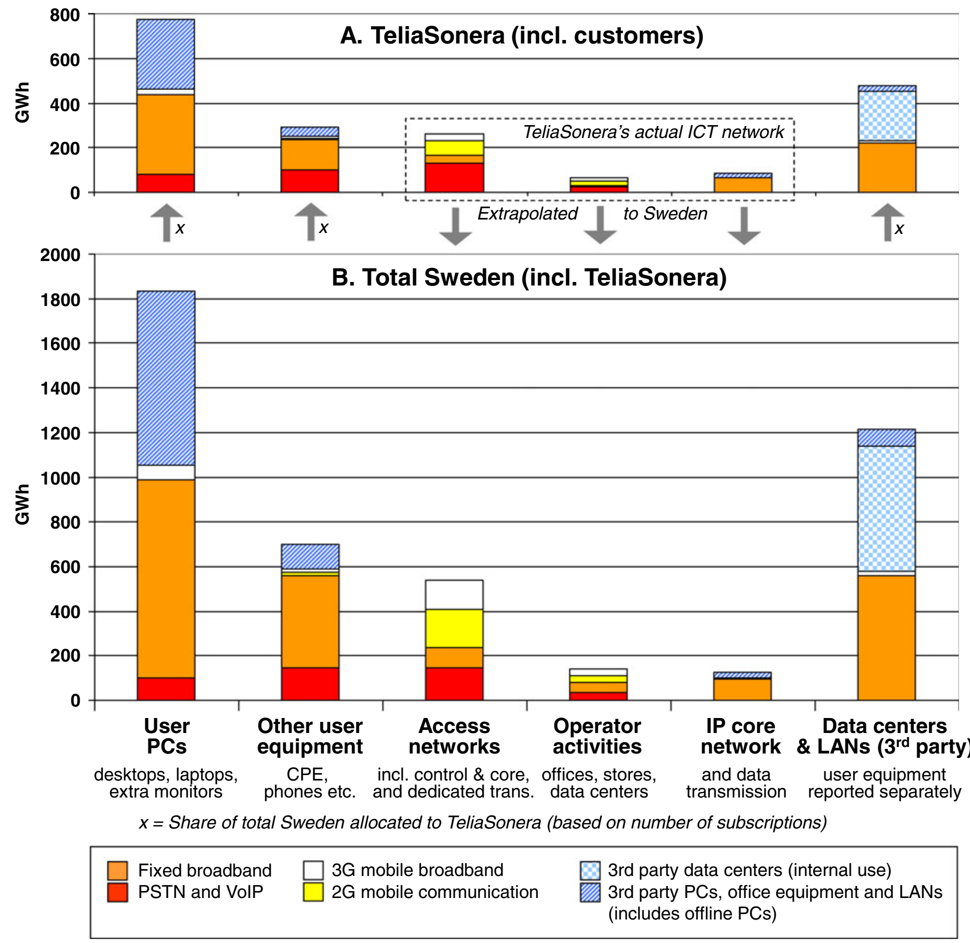

Figure 3 Operational electricity use for (A) TeliaSonera, its connected Swedish customers in the extended network, and (B) the overall Swedish ICT extended network. GWh = gigawatt-hour; ICT = information and communications technology; IP = Internet Protocol; LAN = local area network; CPE = customer premises equipment; PSTN = public switched telephone network; VoIP = voice-over IP; 2G = second generation; 3G = third generation.

manufacturing of access networks supporting infrastructure and third-party data centers and enterprise networks. The majority of the GHG emissions related to TeliaSonera's operations are the result of the combustion of fuels for transportation and travel and heating of office facilities.

The CF of the Swedish ICT extended network is an estimated 1.5 Mt CO_2-eq, which is 1.2% of the overall Swedish CF, including international transport and embodied emissions from imported products, excluding exported products (Peters and Solli 2010), or approximately 160 kg per citizen. The main parts of the footprint are the same as for TeliaSonera's extended network.

In the scenario where the Swedish electricity was changed to the global average, the result was clearly higher emissions (figure 4), and, in this case, operation of user equipment was the major reason, followed by operation of third-party data centers and enterprise networks and manufacturing of end-user equipment.

In Sweden, there is currently a high level of ICT penetration, and if the current networks are regarded as sufficient, the Swedish ICT CF will not grow and could even decrease in the future as end-user devices and networks become more efficient. However, on the global level, the number of customers, subscriptions, and end-user devices will increase, especially in the mobile sector, and thus the overall global CF of ICT will increase (Malmodin et al. 2013). Depending on developments in Sweden, this may be the case there, too, if the number of devices used continues to increase.

An increased ICT footprint should be related to a possible larger decrease in the footprint of other sectors if ICT solutions, in practice, replace other activities or products or make them more efficient. This is crucial in enabling ICT to provide for sustainable development.

The Subscription Perspective

The energy use of ICT services differs between different services provided. The results from a yearly subscription perspective are presented in figure 5. In Sweden, the average mobile subscription uses 23 kWh of operational electricity and the average fixed subscription including common shared data transmission uses 45 kWh. The electricity use per mobile subscription is

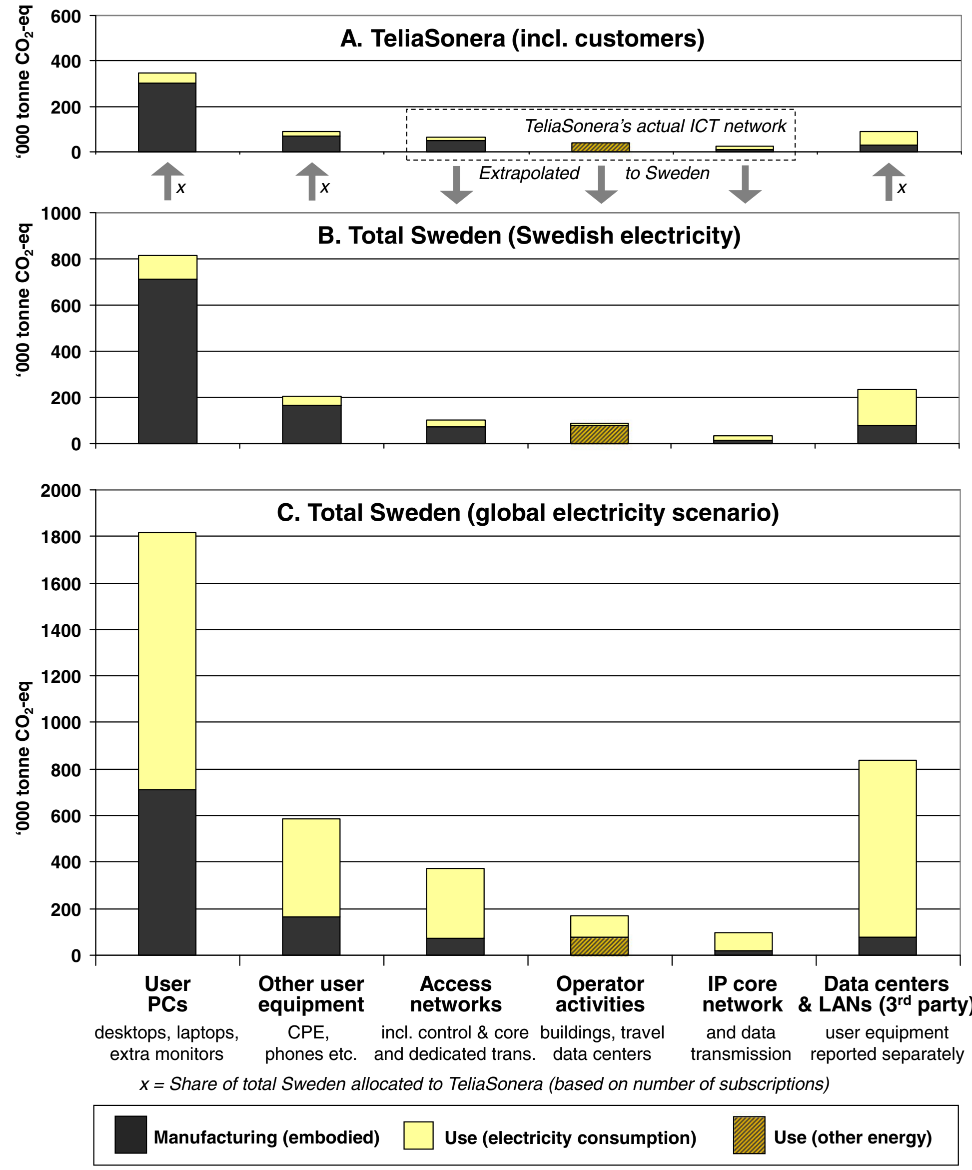

Figure 4 Carbon footprint of (A) TeliaSonera's extended network, (B) the Swedish ICT extended network, and (C) a scenario with global electricity mix. The lighter part of each bar illustrates emissions from operation and the darker part manufacturing, and so on. CO_2-eq = carbon dioxide equivalent; ICT = information and communications technology; IP = Internet Protocol; LAN = local area network; CPE = customer premises equipment.

lower than that per fixed subscription as a result of the number of subscriptions sharing the network. However, it should be noted that a mobile subscription is most often personal, whereas a fixed subscription is often shared by several members of a household. For fixed broadband subscriptions, home network equipment, such as modems and routers, are also included. Because these devices are always on, they contribute to high electricity use.

GSMA (2012) estimated the energy use for mobile subscriptions to be 17 kWh per subscription, relatively close to the results presented here. For fixed subscriptions, the value presented here is even closer to the 50 and 45 kWh per fixed subscription reported by GeSi (2008, 2012). In an earlier study (Malmodin et al. 2010a), the estimated values were 16 kWh per mobile subscription for the global ICT sector and 45 kWh per fixed subscription. Thus, the figures in the present study seem feasible and the results of earlier studies are confirmed by this more detailed assessment. Further, the assumption made that the Swedish ICT network corresponds rather well to global conditions is confirmed.

The yearly emissions of GHG are approximately 15 kg CO_2-eq per subscription year for classic telephony, VoIP telephony, and 2G mobile communications. For 3G mobile communications, the corresponding value is 24 kg CO_2-eq per subscriber and year. The higher figure for the latter is the result of the manufacturing of more advanced smart phones. However, the energy use per average subscription is lower for mobile

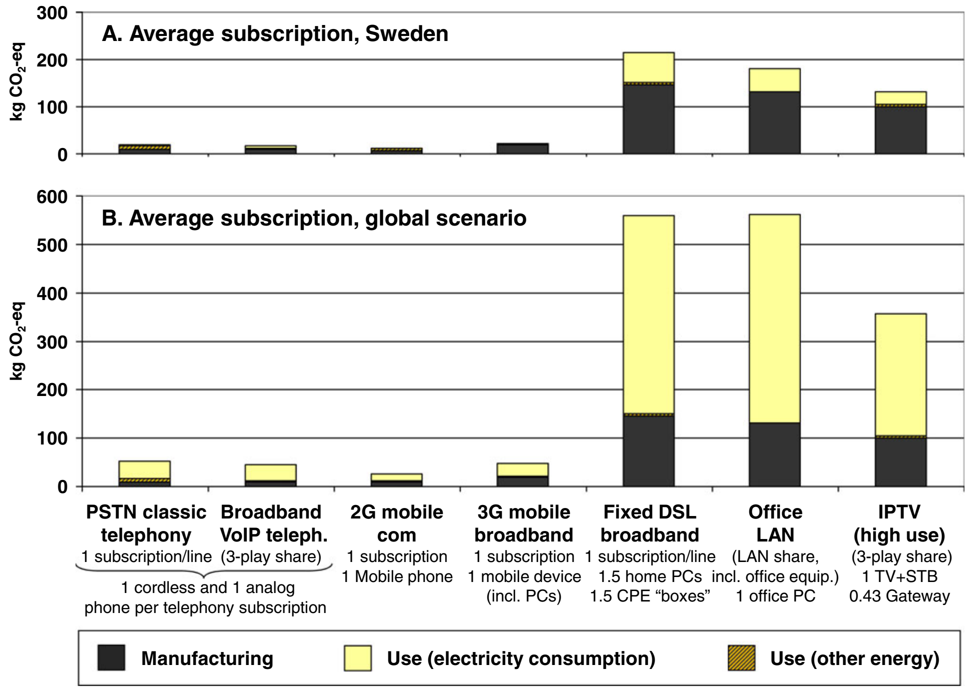

Figure 5 Carbon footprint per average subscription (A) in Sweden and (B) in a global scenario. kg = kilogram; CO_2-eq = carbon dioxide equivalent; PSTN = public switched telephone network; IP = Internet Protocol; VoIP = voice-over IP; 2G = second generation; 3G = third generation; DSL = digital subscriber line; LAN = local area network; STB = set-top box.

telephony than fixed. On the other hand, because fixed telephony subscriptions are often shared between several users, the energy use per user is lower for fixed telephony.

The division into 2G and 3G subscriptions was made only for allocation purposes and was mainly used to differentiate between plain voice and more advanced data services. The subscriptions offered to customers are normally a combination of the two.

Other services give rise to larger footprints. The typical broadband subscription with 1.5 PCs has emissions of 216 kg CO_2-eq per subscriber and year, whereas those of an office LAN subscription (1 PC) are 180 kg CO_2-eq per subscriber and year. The CF of IPTV subscriptions represents a high usage situation (6 hours/day) and corresponds to 130 kg CO_2-eq per subscriber and year, mainly as a result of the TV set itself.

As a result of the electricity mix, the footprints in the global scenario are approximately 2 to 3 times higher, compared to the national (Swedish) perspective. The emissions are slightly higher per office LAN-PC, compared to a residential PC, in the global scenario as a result of higher energy use of supporting data centers.

The results for 3G mobile broadband and fixed broadband are described in more detail below, because these subscription services represent large subscription volumes and relatively large environmental impacts.

Mobile Broadband (Third-Generation) Subscription

With approximately 6.5 million subscriptions in 2010 and the number still increasing, 3G mobile broadband is the most popular subscription type. Figure 6 shows the results for an average 3G mobile broadband subscription in Sweden and in a global scenario. The large dependency on emissions related to electricity production is obvious. For Sweden, manufacturing of user equipment abroad is the main contributor. When using the global electricity mix, the contribution of the base stations to the overall CF is almost as high as the contribution from mobile devices. Whereas the former is mainly a result of operation, the latter is mainly a result of manufacturing.

Fixed Broadband (Digital Subscriber Line) Subscription

The fixed broadband CF varies considerably between users. There can be several PCs and several other pieces of user equipment connected to a single broadband data subscription, and, in addition, devices can be used in different ways. Here, the results are presented per average subscription (1.5 PCs; see figure 7).

The PC is the main contributor to the CF for an average broadband xDSL. In the Swedish scenario, the manufacturing of the PC is the major source of the subscription CF. With a global electricity mix, PC operation and manufacturing are both major sources. There are also significant contributions from CPE and data center operation when using the global electricity mix.

Triple play is a solution that makes it possible to connect three different services through the Internet connection (i.e., a subscription with broadband data, broadband telephony, and IPTV). Looking specifically at such a solution and its related user equipment, the average CF is presented in figure 8. The CPE has a modem, router, broadband telephony, and IPTV

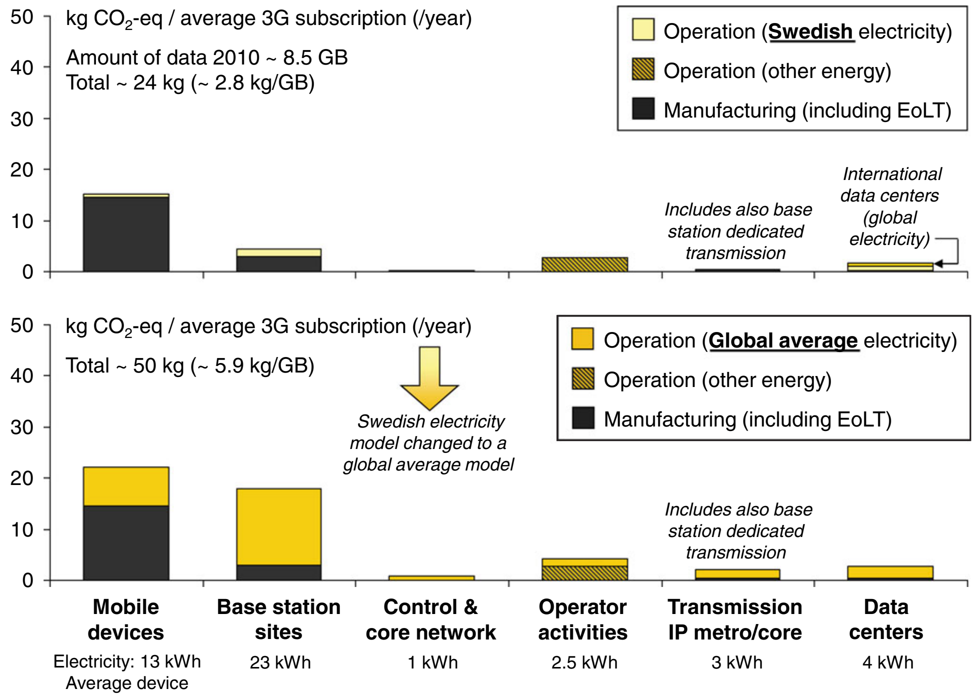

Figure 6 Detailed carbon footprint per average 3G mobile broadband subscription in Sweden and in the global scenario, including figures for operational electricity use at the bottom. Share of emissions for data centers in the top graph is classified as other energy resulting from the international part of the data traffic using another electricity mix. Average home PCs using 3G data subscriptions are also included in the average mobile device. kg = kilogram; CO_2-eq = carbon dioxide equivalent; 3G = third generation; GB = gigabyte; EoLT = end-of-life treatment; kWh = kilowatt-hour; IP = Internet Protocol.

functionality and represents a solution that is emerging and replacing older setups with modems and routers to an increasing extent. The user equipment is represented here by two PCs (one desktop and one laptop), one TV plus STB, and one cordless phone. Mobile phones and other portable media equipment can be connected by CPE WiFi, but this was not considered here. The PCs and TV were based on the same household measurements described earlier (Zimmerman 2009). CPE, STB, and cordless phone were considered to be “always on.”

User equipment dominates the annual CF for the triple-play solution, which, in Sweden, is approximately 380 kg CO_2-eq and, in the global scenario, 1,000 kg CO_2-eq. Because the CPE and network resources are shared by three different services, a more efficient solution is achieved per service.

The Data Usage Perspective

Figure 9 shows details of operational electricity consumption related to different user equipment and network activities. For user equipment, the electricity consumption per amount of data is a typical figure and should only be used as a guideline. To exemplify a PC used for e-mail may consume several orders of magnitude more energy per transmitted data than a PC used for file downloading because of the fact that the energy use of the PC has little dependency on actual data volume. Similarly, CPE and access network electricity consumption shows little dependency on actual data traffic. To avoid this problem, active use time of connected devices may be a better way of allocating CPE energy use to different usages. The CPE’s electricity consumption is nearly the same in active or stand-by state and that is why stand-by energy use should not be overlooked. Electricity consumption per amount of data for the commonly shared data transmission and IP core network are, on the other hand, more useful and provide a good approximation that can be used for most data services. Thus, the figures (figure 9) given are an illustration of energy use per amount of data transmitted, but only the figures for data centers, data transmission, and IP core network can be recommended when modeling electricity consumption.

The figure for data transmission and IP core network (0.08 kWh per gigabyte [GB]) is based on data volumes from 2010 and can be compared to the figure (0.2 kWh/GB) presented by Coroama and colleagues (2013). The latter figure (from 2009) is for a specific point-to-point data flow (not an average for a whole network), which can explain the difference.

The figure for data transmission and IP core network, including CPE and access network, is 0.46 kWh/GB, which can be compared to the 0.17-kWh/GB result presented by Baliga and colleagues (2009). The latter figure is derived from a theoretical model, and even if this is the highest figure presented by Baliga and colleagues (lowest data rate), it seems to be more relevant

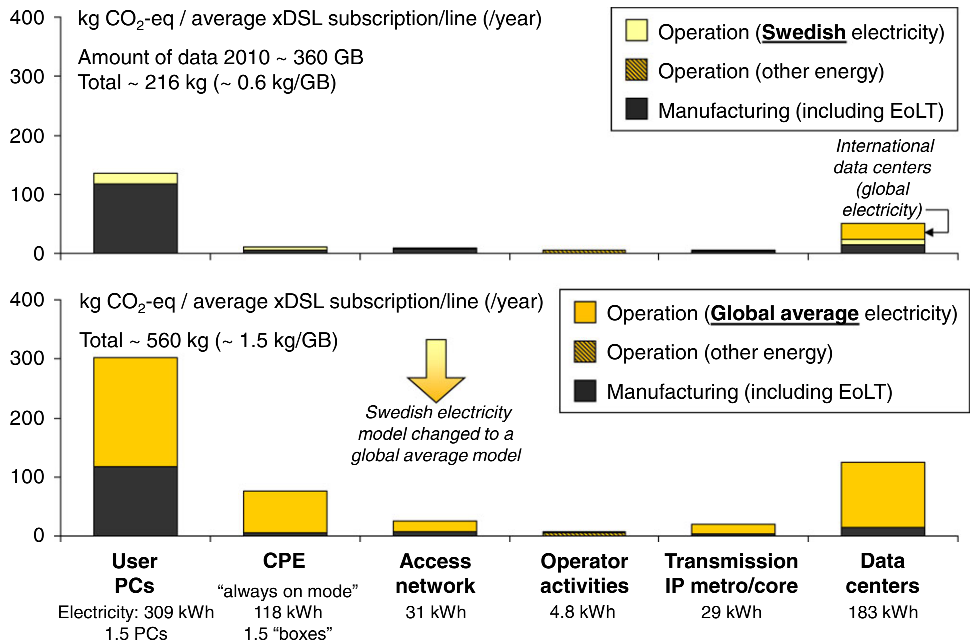

Figure 7 Detailed carbon footprint per average fixed broadband (xDSL) subscription in Sweden and in a global scenario, including figures for operational electricity use at the bottom. kg = kilogram; CO_2-eq = carbon dioxide equivalent; xDSL = digital subscriber line; GB = gigabyte; EoLT = end-of-life treatment; kWh = kilowatt-hour; CPE = customer premises equipment; IP = Internet Protocol.

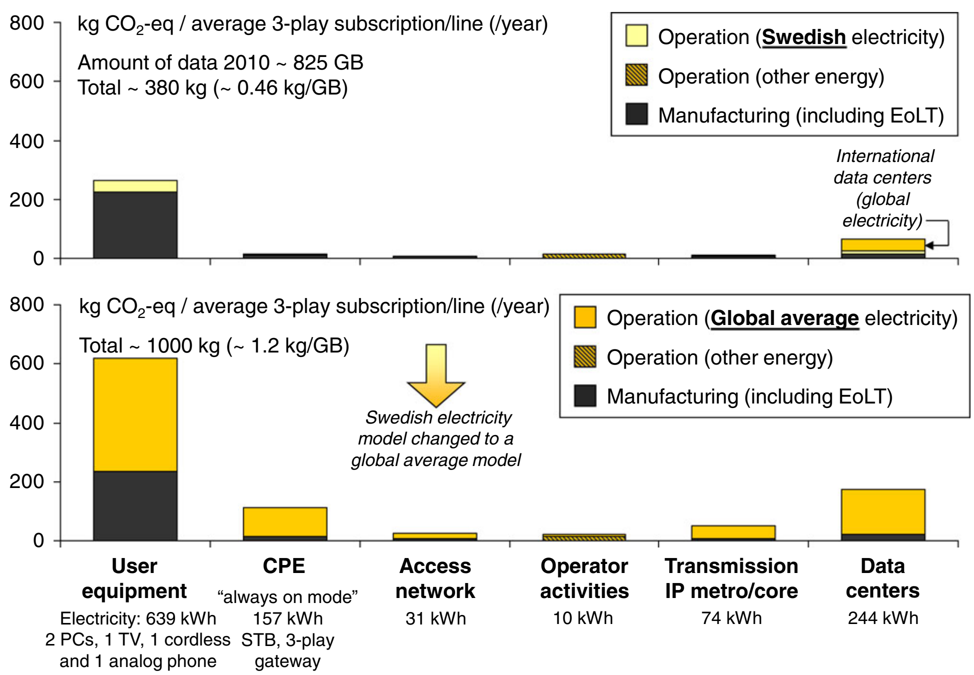

Figure 8 Detailed carbon footprint for the defined triple-play solution. Swedish and global average electricity mixes are indicated and operational electricity use is presented at the bottom. kg = kilogram; CO_2-eq = carbon dioxide equivalent; GB = gigabyte; EoLT = end-of-life treatment; kWh = kilowatt-hour; CPE = customer premises equipment; STB = set-top box; IP = Internet Protocol.

for a more future state-of-the-art network (new equipment, all IP/optical, and low CPE energy consumption).

The total electricity consumption in open/external data centers related to the user data traffic from access networks through the IP core network is approximately 1 kWh/GB. The total figure, including the whole network, is 1.5 kWh/GB. This overall figure can be compared to an extrapolated figure (3.5 kWh/GB) for 2010 based on Weber and colleagues (2010). The main reason for Weber and colleagues' higher figure is probably the use of older extrapolated data. The electricity consumption share between data centers (2:3) and the whole network (1:3) is approximately the same in both studies. For a

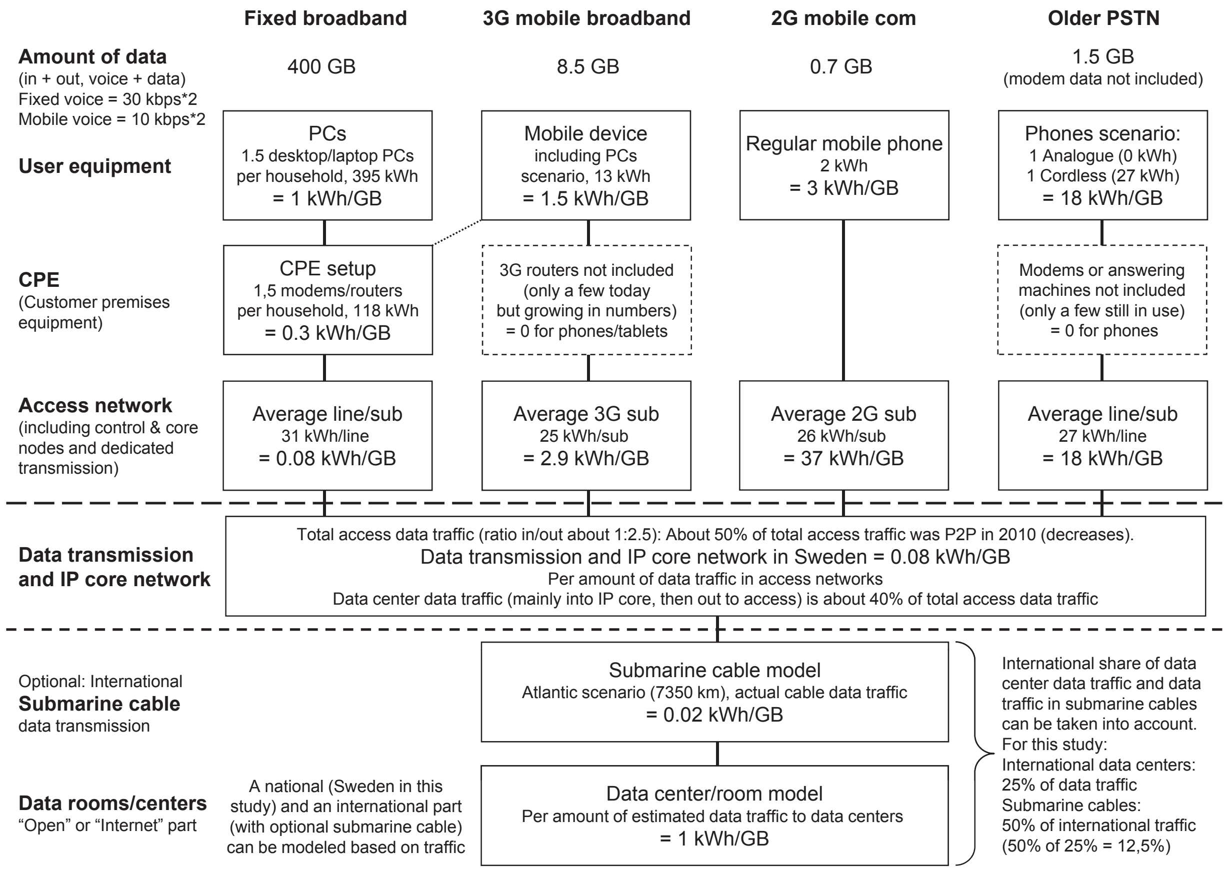

Figure 9 Electricity consumption per data volume (GB) in different parts of the Swedish ICT extended network (data volumes from 2010). A mobile device may access fixed broadband (e.g., through WiFi), as indicated by the dotted line, but this is not taken into account here (all fixed data are allocated to fixed PCs). See also data traffic model for Sweden in appendix S5 in the supporting information on the Web. kbps = kilobit per second; 2G = second generation; 3G = third generation; PSTN = public switched telephone network; kWh = kilowatt-hour; GB = gigabyte; CPE = customer premises equipment; IP = Internet Protocol; P2P = peer to peer.

more detailed description of the data model, energy/data figures, and a comparison to the referred studies above, see appendix S5 in the supporting information on the Web.

To be noted, system boundaries, regional differences in data traffic volumes, and year of measurements or modeling are important when data traffic is studied. Data traffic has increased by approximately 30% per year in Sweden (Lundén and Malmodin 2013) and globally (Cisco 2011) in recent years. In addition, a portion of all nodes are continuously modernized with more energy-efficient hardware resulting in higher data capacity. This needs to be taken into account when energy/data figures are used.

There are large challenges in presenting figures for energy use in relation to data transmissions in the ICT network. The allocation of energy use to different services is not straightforward, but, at present, the general recommendation is to allocate based on the amount of data. Further, the figures change rapidly because the data amounts transmitted increase rapidly, whereas the energy use only changes slowly. Although our results per GB were based on measured energy use and data traffic, this was an average or snapshot of the ICT network conditions in Sweden in 2009/2010. Core data traffic has doubled every 3 years to date (internal TeliaSonera statistics), and this trend is expected to continue, whereas 3G data traffic increased by a factor of more than 200 between 2006 and 2010 (PTS 2008, 2009, 2010, 2011). This needs to be taken into account when using the values presented in figure 9. Further, because those figures are based on average conditions, the results are not relevant for specific conditions, such as very high bit rates and data traffic, as in B2B data traffic, or high-end video conferencing or video streaming. Note also that the amount of data processing and corresponding electricity consumption in a data center is not proportional to the data traffic between a user and the data center. However, the average approach used here concerning average data traffic generated by different subscription services is a good approximation for ICT and data services in general, if applied with caution.

Limitations and Data Quality

The data used in the present study on the network part were based on very-high-quality information (i.e., primary data from the operator and, to a large extent, measured on-site). The data on use of end-user equipment was based on a Swedish study that measured 400 households during 1 year (Zimmerman 2009). Thus, these data are also of high quality. Data on manufacturing of end-user equipment were based on previous LCA studies with varying quality. However, in this study, best estimates based on information from several studies were used and this is probably the largest source to the overall uncertainty of the study. The overall finding, that end-user equipment is the major reason for the overall CF of the ICT network, is valid, but more case studies of generic products are needed for improved data and results in the future. This is especially true owing to the rapid development in ICT-related home and office equipment, where PCs are getting smaller and more energy efficient, whereas, on the other hand, mobile phones are getting larger and more advanced.

There are some uncertainties in the study related to the allocation of energy. Most of the allocations made were in relation to different subscription services and thus there is some uncertainty in the resulting figures per subscription.

This study focused on CF and operational electricity, which are both important aspects for sustainable development. However, there are also other environmental aspects that should be considered, such as toxicological impacts, land use and biodiversity, and so on. Further, matters such as health issues related to raw material extraction and disposal of e-waste are important in relation to the ICT sector. Future studies covering other important aspects would provide more comprehensive life cycle information related to ICT networks.

Conclusions

This detailed and LCA-based study resulted in an estimated total CF of 1.5 Mt for ICT in Sweden, of which 0.65 Mt is attributable to TeliaSonera and its customers. The CF of ICT is approximately 160 kg per person in Sweden, or approximately 1.2% of Sweden's total CF (including transportation and manufacturing abroad of imported goods). The majority of the footprint originates from user equipment, mainly PCs, followed by third-party enterprise networks and data centers, and then access networks. User equipment itself is responsible for more than 50% of the CF, mainly as a result of emissions related to manufacturing abroad.

The yearly CF for an average subscription in Sweden ranges from 15 kg CO_2-eq for classic telephony, VoIP telephony, and 2G mobile communications up to 216 kg CO_2-eq for a fixed (xDSL) broadband subscription. In a triple-play average case, the CF is 380 kg CO_2-eq.

Applying a global electricity mix, the CF is considerably increased and operation contributes a larger share of the overall footprint, but the major impact is still the result of end-user equipment, followed by third-party enterprise networks and data centers and access networks. The yearly CF for an average subscription with global electricity mix ranges from 26 kg CO_2-eq for 2G mobile communications up to 560 kg CO_2-eq for a fixed (xDSL) broadband subscription or a workplace (LAN) PC. In a triple-play average case, the CF is 1,000 kg CO_2-eq.

Energy use and embodied CF per data transmitted can be used as intensity metrics and in LCA studies on transmission and IP core networks. However, when focusing on access networks and end-user equipment, use time is more relevant because the energy consumption and embodied CF is not to the same extent related to transmitted data volume.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides additional information regarding inventory data based on previous LCA studies (appendix S1), user equipment data (appendix S2), ICT network description (appendix S3), ICT network data for TeliaSonera and Sweden (appendix S4), data traffic model for Sweden (appendix S5), detailed results for different primary subscription services (appendix S6), abbreviations and terminology used (appendix S7), and additional references.