Worldwide electricity consumption of communication networks

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Abstract: There is a growing research interest in improving the energy efficiency of communication networks. In order to assess the impact of introducing new energy efficient technologies, an up-to-date estimate for the global electricity consumption in communication networks is needed. In this paper we consider the use phase electricity consumption of telecom operator networks, office networks and customer premises equipment. Our results show that the network electricity consumption is growing fast, at a rate of 10 % per year, and its relative contribution to the total worldwide electricity consumption has increased from 1.3% in 2007 to 1.8% in 2012. We estimate the worldwide electricity consumption of communication networks will exceed 350 TWh in 2012.

OCIS codes: (060.4250) Networks; (000.5920) Science and society; (000.4930) Other topics of general interest.

References and links

1. M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Optimal energy savings in cellular access networks," in "IEEE International Conference on Communications Workshops," (2009), pp. 1–5.
2. W. Vereecken, W. Van Heddeghem, M. Deruyck, B. Puype, B. Lannoo, W. Joseph, D. Colle, L. Martens, and P. Demeester, "Power consumption in telecommunication networks: overview and reduction strategies," IEEE Commun. Mag. **49**, 62–69 (2011).
3. K. Hinton, J. Baliga, M. Feng, R. Ayre, and R. Tucker, "Power consumption and energy efficiency in the internet," IEEE Netw. **25**, 6 –12 (2011).
4. A. P. Bianzino, C. Chaudet, D. Rossi, and J.-L. Rougier, "A survey of green networking research," IEEE Commun. Surv. Tutorials **14**, 3–20 (2012).
5. M. C. Parker, "Roadmapping ICT: an absolute energy efficiency metric," IEEE J. Opt. Commun. Netw. **3**, A49–A58 (2011).
6. D. Kilper, G. Atkinson, S. Korotky, S. Goyal, P. Vetter, D. Suvakovic, and O. Blume, "Power trends in communication networks," IEEE J. Sel. Topics Quantum Electron. **17**, 275 –284 (2011).
7. J. Baliga, R. Ayre, K. Hinton, and R. Tucker, "Energy consumption in wired and wireless access networks," IEEE Commun. Mag. **49**, 70 –77 (2011).
8. M. Pickavet, W. Vereecken, S. Demeyer, P. Audenaert, B. Vermeulen, C. Develder, D. Colle, B. Dhoedt, and P. Demeester, "Worldwide energy needs for ICT: the rise of power-aware networking," in "2nd International Symposium on Advanced Networks and Telecommunication Systems, 2008. ANTS '08.", (2008), December, pp. 1–3.
9. M. Webb, "Smart 2020: enabling the low carbon economy in the information age," The Climate Group (2008).
10. J. Malmodin, A. Moberg, D. Lundn, G. Finnveden, and N. Lvehagen, "Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors," J. Ind. Ecol. **14**, 770–790 (2010).
11. S. Lanzisera, B. Nordman, and R. Brown, "Data network equipment energy use and savings potential in buildings," Energy Efficiency **5**, 149–162 (2012).
12. "The Carbon Disclosure Project," `https://www.cdproject.net/en-US/Pages/HomePage.aspx`.
13. "World population prospects: the 2010 revision," UN Population Division (2011). `http://data.un.org/Data.aspx?q=population&d=PopDiv&f=variableID%3a12`.

14. "Global ICT developments, 2001-2011," ITU World Telecommunication / ICT Indicators database (2011). http://www.itu.int/ITU-D/ict/statistics.
15. W. Van Heddeghem, F. Idzikowski, W. Vereecken, D. Colle, M. Pickavet, and P. Demeester, "Power consumption modeling in optical multilayer networks," Photonic Netw Commun **24**, 86–102 (2012).
16. J. Koomey, "Growth in data center electricity use 2005 to 2010," http://www.analyticspress.com/datacenters.html (2011).
17. K. Kawamoto, J. Koomey, B. Nordman, R. Brown, M. Piette, M. Ting, and A. Meier, "Electricity used by office equipment and network equipment in the US," Energy **27**, 255–269 (2002).
18. "World broadband statistics: Q4 2007," Point-Topic (2008).
19. "World broadband statistics: Q4 2011," Point-Topic (2012).
20. "The little data book on information and communication technology," The World Bank / ITU (2007-2012).
21. B. Urban, V. Tiefenbeck, and K. Roth, "Energy consumption of consumer electronics in U.S. homes in 2010." Fraunhofer Center for Sustainable Energy Systems (2011).
22. C. Cremer, W. Eichhammer, M. Friedewald, P. Georgieff, S. Rieth-Hoerst, B. Schlomann, P. Zoche, B. Aebischer, and A. Huser, "Energy consumption of information and communication technology (ICT) in Germany up to 2010: summary of the final report to the German federal ministry of economics and labour," (2003).
23. "Global energy statistical yearbook 2012," Enerdata (2012). http://yearbook.enerdata.net/world-electricity-production-map-graph-and-data.html.
24. "Co2 emissions from fuel combustion - highlights," IEA (2010).
25. A. Fehske, G. Fettweis, J. Malmodin, and G. Biczok, "The global footprint of mobile communications: the ecological and economic perspective," IEEE Commun. Mag. **49**, 55 –62 (2011).
26. S. Phillips, S. L. Woodward, M. D. Feuer, and P. D. Magill, "A regression approach to infer electricity consumption of legacy telecom equipment," SIGMETRICS Perform. Eval. Rev. **38**, 61–65 (2011).
27. J. Baliga, R. Ayre, K. Hinton, W. V. Sorin, and R. S. Tucker, "Energy consumption in optical IP networks," J. Lightwave Technol. **27**, 2391–2403 (2009).

1. Introduction

In recent years the energy efficiency of communication networks has received a lot of research attention. Various strategies have been proposed to reduce the power consumption of both mobile and fixed networks on all levels, from the access network to the core [1–4]. In most studies, potential energy savings of proposed innovations are expressed relative to the power consumption of current technologies, e.g. in [5], energy efficiency improvements from applying different techniques are stated as reduction factors (expressed in dB) compared to a baseline consumption. In order to assess the global impact of these savings in absolute numbers, an estimate is required for how much electricity present-day networks consume as a whole.

Most studies on the energy consumption in networks focus on specific network scenarios (particular technologies, bit rates, ...) rather than worldwide averages. Kilper et al. [6], for example, determine the power per bit rate by adding up the power of all the equipment in the network that is used to deliver a given service on a mean transaction basis. The access equipment considered is that of a Passive Optical Network (PON). This provides state-of-the-art estimates, which are useful for future projections, but which are probably not realistic for present-day networks. Baliga et al. [7] use a similar bottom-up approach to estimate the electricity consumption per user for different access technologies. Although this approach is very useful when comparing different technologies, it is less suitable to get an idea of the global energy consumption in the network, since it is nearly impossible to consider every technology in use, every user profile and every topology.

Often-cited values for the footprint of communication networks and ICT in general date from five to ten years ago or are extrapolations based on these values. Our previous report [8] on the worldwide energy needs for ICT was based on data from 2007. In the Smart2020 report [9], which studied both the footprint of ICT and its enabling effect to reduce emissions, the network section of the analysis was based on reported energy consumption values of telecom providers in 2002. These values were then extrapolated based on the expected increase in subscriptions in 2002-2020. Another extensive study on greenhouse gas emissions and operational electricity use in ICT by Malmodin et al. [10] also provided estimates for 2007. In the past five years,

the electricity consumption in networks was likely transformed by fiber rollout, smart devices requiring mobile internet access and rapid customer base growth in emerging markets.

The contribution of this paper is twofold: (a) we present a top-down analysis of the total global electricity consumption in communication networks, and (b) we base our results on recent data (2007-2011) to get an updated estimate for the network share of worldwide electricity consumption in 2012. We consider three components of communication networks: telecom operator networks, office networks and customer premises equipment. Note that we consider electricity consumption in the use phase only, we do not consider the electricity used to manufacture or dispose of equipment. Our calculation method for telecom operator networks is similar to the approach used by Malmodin et al. in [10]. We extend their approach by adding a representative sample selection, where we try to match the relative subscription ratios for different services in our sample to the worldwide ratios. We discuss the methodology used for operator networks in detail in section 2, along with the results of our calculations. In section 3 we consider the electricity consumption of office network equipment. The numbers in this section are mainly based on previous research by Lanzisera et al. [11], but we change the scope to avoid overlap with telecom operator equipment. We also exclude data centers since we consider these as end devices rather than network equipment. Finally, customer premises equipment used to access the network is discussed in section 4. The equipment considered includes modems and WiFi routers, but excludes end-user equipment such as set-top boxes, TVs and PCs.

2. Telecom operator networks

2.1. Scope and methodology

Many studies on the electricity consumption in communication networks use a bottom-up approach, where the electricity consumption of individual components of the network is summed to estimate the total consumption (e.g. [6, 7]). The approach we propose is top-down: we start from the total electricity consumption of a number of telecom providers and based on these numbers we estimate the worldwide electricity consumption in communication networks.

A similar approach was used by Malmodin et al. in [10]. Based on data from a number of telecom operators, they determined the average electricity consumption per mobile subscriber and per fixed subscriber. Multiplying these values with the worldwide subscription numbers and summing the results provided them with an estimate for the worldwide electricity consumption in telecom operator networks.

Assigning electricity consumption to specific services — Unfortunately, it is very difficult to assign the power consumption of an operator to different services. Sometimes a distinction between the electricity use of mobile and fixed network equipment is made, but then it is still unclear which part of the fixed network is used to transport data for mobile end-users (this problem was also recognized in [10]). Additionally, we want to make a distinction between fixed broadband and fixed telephony in our study, since we believe the power consumption per user for these services can differ significantly. Attributing the power consumption of the fixed network to broadband and telephone services is even more difficult than for the mobile-fixed case since these two services often share a physical medium. We could try to determine the average per-subscriber electricity consumption for each service (mobile access, fixed broadband and fixed telephone) by fitting the calculated power consumption $p_i = \sum_{services} subscribers_{service} \times p_{avg,service}$ for each operator i to their reported power consumption and subscription numbers. This approach is however complicated by the fact that incumbent operators often lease parts of their networks to other operators. This means that the number of customers connected to a network is not necessarily the same as the number of subscribers reported by the operator. Consequently, $p_{avg,service}$ will differ significantly among operators. In the approach we propose, we aggregate the subscriptions and electricity consumption of differ-

ent operators to cancel the effect of leased lines as much as possible.

Introduction of a representative sample — In order to avoid having to assign the power consumption of the operators to different services, we use a subscription-based representative sample. The number of mobile, fixed broadband and fixed telephone subscriptions in this sample have the same relative ratios as the worldwide subscription numbers. This allows us to extrapolate the power consumption of the sample to a worldwide value using a single scaling factor, since the percentage of worldwide subscriptions covered is the same for each type of service. Due to the nature of our sample, we are still taking into account the differences in power consumption for different services. The drawback of our approach is that we cannot determine the relative contributions of different services to the total network electricity consumption, since we aggregate the electricity consumption for all services.

Selection of a sample of telecom operators — We select the telecom providers in this study based on their size and on the availability of data. We start by listing some of the world's biggest telecom operators in terms of fixed broadband and mobile customer base. For each of these operators, we try to gather the following information: (a) total annual electricity consumption, (b) breakdown of electricity consumption by activity (offices & retail, data centers, network), (c) number of fixed telephone subscriptions, (d) number of fixed broadband subscriptions and (e) number of mobile subscriptions.

Some of these numbers can be found in publicly available financial and sustainability reports on company websites. We contacted operators and consulted various websites (such as the Carbon Disclosure Project [12]) to obtain additional data. Not all of the operators in our initial list disclosed their electricity consumption. Since this information is essential to our calculation we excluded these operators from our sample.

Scope — We are interested in the electricity consumption of operator networks, so we exclude the portion of their electricity consumption that is used in data centers, offices and retail from our calculations (office networks are covered in section 3). For some operators, we found a total electricity consumption but were unable to find a breakdown by activity. In these cases we used a value based on the breakdown for other operators. We found that on average, about 13% of electric power is used in offices and retail, 11% is used in data centers and the remaining 76% is used in the network. Off-grid electricity generation (e.g. by diesel generators for remote mobile base stations) is not included in our results.

Extrapolation to worldwide numbers — Once we have determined the network electricity consumption and subscription numbers for each operator, we need to extrapolate these numbers to obtain an estimate of the worldwide network electricity consumption. As mentioned above, we create a representative sample of operators based on subscription numbers in order to do this. The worldwide subscription numbers for 2011 are given in Fig. 1(a); the numbers for other years can be found in Table 1. Our sample of 11 operators for 2011 is represented in Fig. 1(b) (electricity consumption values for individual operators are not shown as some of these numbers are confidential). When we compare the number of subscriptions in the sample to worldwide numbers, we see that mobile subscriptions are overrepresented in the sample: 31.3% of worldwide mobile subscriptions are covered, while only 21.2% and 20.9% of fixed broadband and fixed telephone subscriptions are covered respectively.

In order to create the representative sample — while keeping the number of subscriptions covered as large as possible — we determine a weight factor for each of the n operators ($n = 11$)

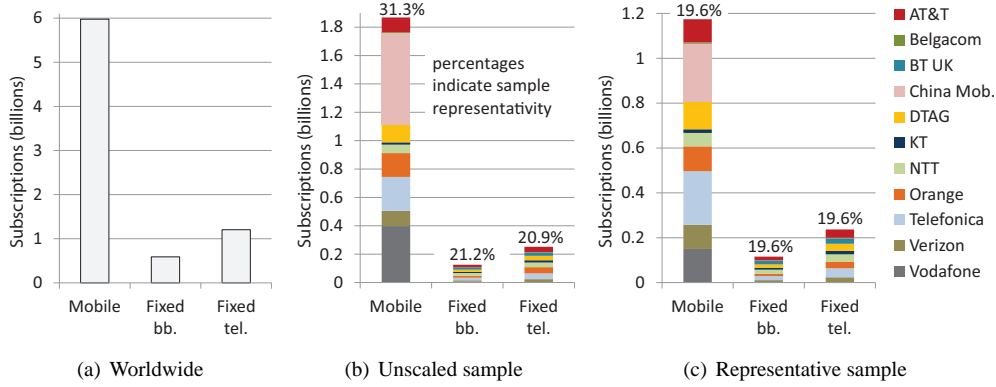(a) Worldwide (b) Unscaled sample (c) Representative sample

Fig. 1. Operator sample selection for 2011: (a) number of subscriptions worlwide, (b) in the unscaled sample and (c) in the representative sample. The percentages are obtained by dividing the number of subscriptions per service in both samples by the worldwide number of subscriptions.

Table 1. Worldwide subscriptions (in millions). Sources: [13, 14]. Numbers for 2012 are extrapolations.

	2007	2008	2009	2010	2011	2012
Mobile subscriptions	3 372	4 034	4 650	5 315	5 975	6 615
Fixed broadband subscriptions	346	409	465	528	590	650
Fixed telephone subscriptions	1 255	1 250	1 249	1 228	1 205	1 182

by solving the following optimization problem:

$$\text{Maximize} \quad M_S(w) = \sum_{i=1}^{n} (w_i \times m_i) \tag{1}$$

$$\text{subject to} \quad \frac{M_S(w)}{M_W} = \frac{B_S(w)}{B_W} = \frac{T_S(w)}{T_W} \tag{2}$$

$$0 \leq w_i \leq 1 \quad (i = 1 \ldots n) \tag{3}$$

where w = vector containing operator weight factors w_i $(i = 1 \ldots n)$

$m_i/b_i/t_i$ = number of mobile/broadband/telephone subscriptions for operator i

$M_S/B_S/T_S$ = number of mobile/broadband/telephone subscriptions in sample

$M_W/B_W/T_W$ = worldwide mobile/broadband/telephone subscriptions (Table 1)

Note that the problem stated above, where we maximize the number of mobile subscriptions in the sample, is equivalent to a problem where we maximize the number of broadband or telephone subscriptions (this follows from the first constraint). We solve the optimization problem for five different years, based on the worldwide and operator subscription numbers for 2007-2011, thus creating a representative sample for each of these years. The representative sample for 2011 is depicted in Fig. 1(c).
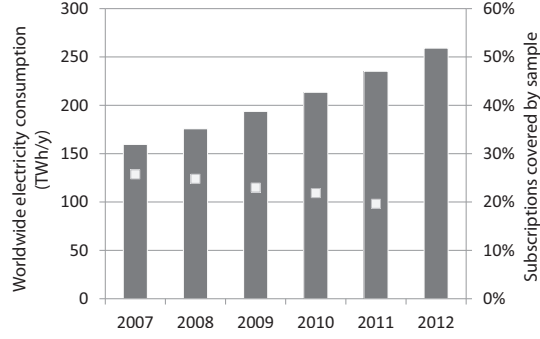
Fig. 2. Worldwide electricity consumption in telecom operator networks (columns, left axis) and sample representativity (markers, right axis).

Once we have solved the maximization problem, we estimate the worldwide network electricity consumption P_W (this includes the consumption of both fixed and mobile networks) by extrapolating the electricity consumption of the representative sample $P_S(w)$ as follows:

$$P_W = \frac{M_W}{M_S(w)} \times P_S(w) = \frac{M_W}{M_S(w)} \times \sum_{i=1}^{n} (w_i \times p_i) \tag{4}$$

where p_i is the network electricity consumption of operator i. From constraint (2) it follows that an extrapolation based on the number of broadband or telephone subscriptions would deliver the same result. The calculation of P_W is performed for each year in 2007-2011. For 2012, we estimate the worldwide electricity consumption by extrapolating the values of the previous years.

2.2. Results

The estimates for the worldwide electricity consumption in telecom operator networks are given in Fig. 2. In 2007, these networks consumed almost 160 TWh. By the end of 2012, at an annual growth rate of 10.2%, their consumption will increase to about 260 TWh per year.

Reliability — As mentioned above, the approach we used for our calculations is based on aggregated numbers rather than individual operators' electricity consumption to minimize the effect of leased and rented lines. This effect may have an influence nonetheless, even though our sample covers at least 19.6% of the worldwide customer base for each year in the considered range (markers in Fig. 2). Another factor that may influence the reliability of our study is the fact that it is based — for the most part — on publicly available electricity consumption values. This may lead to overly optimistic results, since companies that publish these values are typically those that have already made efforts to improve their energy efficiency.

3. Office networks

3.1. Scope and methodology

The scope of this section is the electricity used by network equipment in offices, excluding network equipment in data centers. This includes network equipment in network operator offices but excludes equipment in the telecom network they operate (this was already handled in section 2). We do not consider custom enterprise transport networks, such as those between Google or Amazon data centers. There seems to be a growing trend for such companies to roll out their own fiber networks. While it is hard to map these networks, the total power consumption will very likely be negligible, as optical transport networks consume very little compared

Table 2. Office networks: cooling overhead factors and worldwide electricity use per type of equipment (electricity use estimates are adaptations of the values in [11]).

	Cooling overhead	Electricity use, 2007 (TWh)	Electricity use, 2012 (TWh)
switching - 10/100	1.38	12.7	10.7
switching - 10/100/1000	1.38	5.4	17.5
routers - small & medium	1.75	3.5	4.2
enterprise WLAN	1.00	1.0	2.3
security - small and medium	1.75	5.3	7.7
Total		27.8	42.4

to other network equipment such as modems, IP routers or base stations. For example, the pan-European Géant network and the US NSFNET network consume each in the order of only a few tens of GWh/y [15]. Nonetheless, with the rise of cloud computing, this might become a relevant component to consider in the future.

We base our estimate on a study by Lanzisera et al. [11], which estimates the USA and worldwide electricity consumption of data network equipment in both residential buildings and offices. Their study focuses on IP-based network equipment only, and does not include the electricity used by power or cooling infrastructure. Their annual electricity consumption estimate is based on an average power consumption per device, and uses values for 2008 with forecasts up to 2012, which we have adopted.

We consider only the equipment relevant in office use (based on a selection of the classification in [11]), and in addition we add an estimated overhead for cooling. To estimate this overhead, we start from the approach used for data centers, where the cooling equipment and power provisioning equipment combined typically consume as much as the IT equipment itself. Power provisioning equipment includes uninterruptible power supplies and power conversion devices. The cooling and power provisioning overhead is commonly captured by the so-called Power Usage Effectiveness (PUE) factor being equal to 2, i.e. the IT power consumption needs to be multiplied by 2 to estimate the total power consumption. Since the power provisioning in data centers typically makes up about 1/3 to 1/5 of this overhead, but is in general not applicable to office network equipment, the correction factor to account for cooling only is about 1.75. Since not all switches are installed in cooled locations, we have accounted only half of the cooling factor, which gives an overhead factor of 1.375 for switches.

3.2. Results

The results are shown in Table 2. As can be seen, the worldwide office network equipment is estimated to consume 42 TWh in 2012.

Reliability — There is some uncertainty in the considered cooling overhead factors (which are based on discussions with industrial experts), and whether our selection of Lanzisera's network equipment classification correctly covers office network equipment. Concerning the latter, the power consumption in Table 2 may include some network equipment located in data centers, which are out of our scope. However, based on [16] we estimate the power consumption of network equipment for data center volume servers (without cooling and power provisioning overhead) at 1.48 TWh in 2012. This means that the inclusion of (some) data center network equipment can lead to a maximum deviation of 5% on the total uncooled power consumption.

To get an indication of the reliability of our result, it is instructive to estimate the electricity use of office network equipment per office computer, similar to what was done by Kawamoto

Table 3. Calculation of the office network power consumption per computer based on our results, compared with values from [17].

	Kawamoto 2002 [17] (USA only)	2007 (worldwide)	2012 (worldwide)
Number of computers (desktop + laptop)	60 million [a]	429 million	594 million
Office network equipment power consumption	228.7 MW [b]	3.17 GW	4.84 GW
Office network equipment power consumption per computer	3.8 W/unit	7.4 W/unit	8.1 W/unit

[a] Includes servers, in addition to desktop and laptop computers
[b] LAN routers and switches only; not including cooling and power provisioning overhead

et al. in [17]. These values are reported in Table 3. As can be seen, our estimate for 2012 is 8.1 W/unit and thus about twice as high as Kawamoto et al.'s value in 2002. Three important factors are responsible for this considerable deviation: (a) Kawamoto et al. do not consider the power consumed by network cooling equipment, (b) they include servers in their computer count, however the influence of this inclusion will be minor since servers account for only about 5% of their total number of computers, and (c) they only consider LAN routers and switches; WLAN and security equipment make up 20-25% of the total office network equipment power consumption. If we would not consider cooling overhead and drop the enterprise WLAN and security equipment, our values for 2007 and 2012 would drop to 4.0 and 4.4 respectively, which is in line with Kawamoto et al.'s reported 3.8 W/unit for the USA.

4. Customer premises equipment

4.1. Scope and methodology

In this section, we consider the electricity consumption of residential network access equipment. In order to access the network, every internet subscriber requires a modem. Most users also have a WiFi router installed, often with integrated wired switching and routing capabilities. The modem and WiFi router may also come in a single box. We estimate the worldwide power consumption by multiplying average power consumption values of these residential devices per access technology category with the number of subscriptions per category.

Number of subscriptions — Based on the average number of broadband subscriptions per 100 inhabitants [14] (5.19-8.46 for 2007-2011) and worldwide population data [13] ("Medium variant" for population prospects), we estimate the worldwide number of broadband subscriptions. We distribute these subscriptions over the different technologies using percentages from [18,19]. Based on the percentage of broadband subscriptions (compared to total internet) in [20] we derive the number of narrowband subscriptions. The subscription numbers are given in Table 4. Values for 2012 are extrapolations based on data from previous years.

Power consumption per user — The power per user values for *cable, DSL and FTTH* were adopted from a study by Lanzisera et al. [11]. They assume that few users use a modem without a WiFi router and that this number is comparable to those with multiple WiFi routers (or WiFi repeaters). This assertion is confirmed by data in [21] on the installed base of home network equipment: in 2010, there were 46.4 million modem-only devices and 46.2 million wireless routers installed in USA households. For end-users accessing the internet through *other broadband* technologies such as satellite and fixed wireless access, we assumed a power consumption

Table 4. Customer premises equipment: average power consumption per user, numbers of users and worldwide annual electricity use.

	Power per user (W)	Subscribers, 2007 (million)	Electricity use, 2007 (TWh)	Subscribers, 2012 (million)	Electricity use, 2012 (TWh)
Cable	9.5	74	6.2	123	10.2
DSL	7.1	228	14.2	388	24.1
FTTH	13.0	38	4.3	115	13.1
Other broadband	8.3	6	0.4	24	1.8
Narrowband (dial-up)	2.5	283	6.3	142	3.1
Total		629	31.4	792	52.4

comparable to that of the more common broadband technologies. The end result is not very sensitive to this value due to the small user base. For *narrowband* users we assumed the average power consumption of a dial-up modem from [22]. This value is significantly lower due to the limited time in which the device is active, compared to always-on broadband modems.

4.2. Results

The results are included in Table 4. The power consumption by customer premises equipment totalled 31.4 TWh in 2007 and will total 52.4 TWh in 2012. This corresponds to an annual growth rate of 10.8%.

Reliability — The reliability of our results depends strongly on the accuracy of our power per user estimates. Most of our power consumption values are based on averages for the USA, which we extrapolate based on worldwide subscription data per technology category (cable, DSL, ...). However, within these categories there are several subtechnologies (e.g. ADSL2, VDSL,... for DSL). If the relative share of these subtechnologies is different in other parts of the world, the average power consumption per user will also be different. Additionally, we were unable to determine the evolution of the average power consumption per device from 2007 to 2012. Consequently we do not account for shifts between different subtechnologies over time. The shifts between different technology categories — the decrease in narrowband and increase in FTTH being the most notable — were however taken into account, which leads us to believe the general trend in our results provides a good estimate of the evolution in power consumption of customer premises equipment.

5. Total electricity consumption of communication networks

Our results are summarized in Fig. 3. Telecom operator networks make up almost three quarters of the network electricity consumption, the remaining quarter is used by customer premises equipment and office networks. Though our calculation method does not allow us to estimate the relative importance of mobile and fixed infrastructure in telecom operator networks, based on the breakdown provided by a number of operators we expect the contribution of the mobile network to be between 40% and 60%.

The total worldwide electricity consumption in communication networks has increased from 219 TWh per year in 2007 to 354 TWh per year in 2012. This corresponds to an annual growth rate of 10.1%. When we compare this to the total worldwide electricity consumption [23], we see that the share of networks is becoming increasingly important (dotted line in Fig. 3). Where
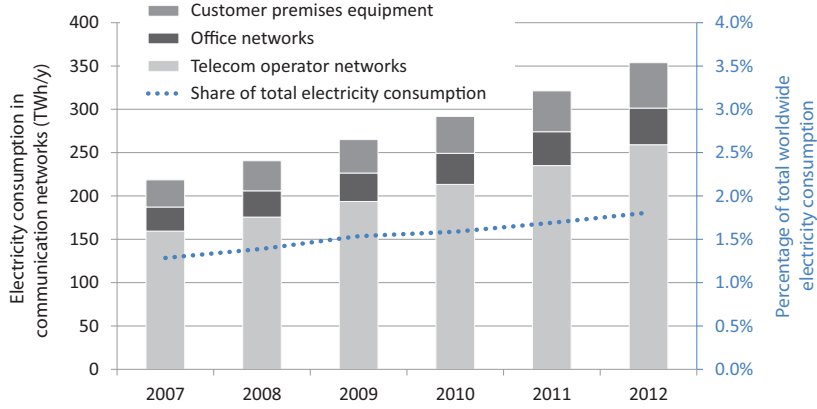
Fig. 3. Worldwide use phase electricity consumption of communication networks (columns, left axis) and share of networks in total worldwide electricity consumption (dotted line, right axis).

communication networks only consumed about 1.3% of worldwide electricity in 2007, their relative contribution has increased to 1.8% in 2012.

6. Comparison with previous studies

To validate our results we list a number of power consumption values from related studies in Table 5. The Smart 2020 report [9] estimate for the use phase carbon footprint of telecoms infrastructure and broadband modems is converted to an electricity consumption value assuming an average worldwide conversion factor of 500 gCO2/kWh [24]. Considering our value for 2012 and the growth rate for 2007-2012, 414 TWh in 2020 seems to be a rather conservative estimate. The calculation in the Smart 2020 report is based on the assumption that the number of mobile, fixed and broadband accounts will reach 7 billion in 2020, whereas our subscription data suggest that the aggregated number of subscriptions has already exceeded 8 billion in 2012 (see Table 1). In the Smart 2020 report itself, the authors note there is a high degree of uncertainty in the telecoms figures.

The 2007 value from Malmodin et al. [10] for operator networks is about 25% lower than our value (assuming offices and retail make up 13% of the value they provide). This difference can probably be attributed to the fact that they used a different sample and did not distinguish between fixed broadband and fixed telephony users in their calculation method. Their value for office networks is similar to our value. For broadband modems their value is significantly higher than our result (which is 25.1 TWh/y). This is due to the fact that they assume relatively high per-user power consumption values (9 W per modem plus an additional 9 W per router, with one router for every two modems).

In a 2011 study by Kilper et al. [6], an estimate is given for the average power per user for mobile and fixed access, core and metro networks (Fig. 5 in [6]). When we add up these per-user values and multiply them by our global subscription numbers (mobile and fixed broadband, see Table 1), we obtain very high values for the mobile network power consumption in 2007 and 2012. Since we do not know the breakdown of the electricity consumption among different services, we do not know the power consumption per mobile user in our results, but we can make a rough estimate based on the electricity consumption and subscription numbers of the two operators in our sample that offer (almost) exclusively mobile services: China Mobile and Vodafone. The electricity consumption for these mobile operators is between 0.75 and

Table 5. Estimates of network power consumption from previous studies [6, 7, 9, 10, 25]. Values between brackets are converted: for the Smart 2020 report the use phase CO2 values are converted assuming 500 gCO2/kWh, Kilper and Baliga's power per user values are multiplied with our worldwide subscription numbers.

Source	Year	Power per user (W)	Worldwide power (TWh/y)	Scope
Smart2020 2008	2020	-	(414)	Telecoms infrastructure and broadband modems
Malmodin 2010	2007	-	139	Operator networks (mobile + fixed + transport), including overhead for offices and stores
Malmodin 2010	2007	-	35	Broadband modems and routers
Malmodin 2010	2007	-	29	Enterprise networks, including cooling and power systems
Kilper 2011	2007	6	(177)	Mobile networks
Kilper 2011	2007	14	(42)	Fixed networks, including CPE
Kilper 2011	2012	14	(812)	Mobile networks
Kilper 2011	2012	19	(108)	Fixed networks, including CPE
Baliga 2011	2012	3.3 - 7.6	(27)	Broadband fixed access, including modems
Fehske 2011	2007	-	49	Radio access network
Fehske 2011	2012	-	77	Radio access network

2 W per user, much lower than the values provided by Kilper et al. This discrepancy can be explained by the fact that the mobile network considered in the study by Kilper et al. is a high-bandwidth LTE network, which is currently only deployed in a relatively small part of the world. Further adoption of wireless broadband access by mobile users can increase the electricity consumption of communication networks significantly in the future. For fixed access Kilper et al. consider state-of-the-art passive optical network equipment that is continuously upgraded each year, which – like their value for mobile networks – provides a good view on the power consumption of possible future deployments but which is not representative for present-day networks. This illustrates the importance of using a top-down approach to obtain reliable estimates for the worldwide electricity consumption, since it is very difficult to assess a worldwide average network deployment scenario.

The per-user power consumption of latest generation broadband access technologies is estimated in a 2011 paper by Baliga et al. [7]. Combining these values for fixed access technologies with our subscription numbers from Table 4 gives us an estimate for the worldwide power consumption in fixed access networks. We would expect this value to be higher than 27 TWh since it covers both customer premises equipment (modems) and part of the telecom operator network (fixed access). This can be explained in part by the fact that Baliga et al. assume lower CPE power consumption values, presumably because they do not include WiFi and routing functionality. Furthermore, they only consider state-of-the-art equipment. Legacy equipment, which is typically less energy efficient, has a significant impact on the energy consumption of operator networks (for example, see [26]).

A recent study by Fehske et al. [25] provides another estimate for the electricity consumption in radio access networks (RANs). Diesel generated power is included in their values and

accounts for about 10% of the RAN electricity consumption. Their estimate amounts to about 30% of our value for operator networks, which is somewhat lower than our estimate for mobile networks (40-60%), this is due to the fact that they do not include data transport in the RAN electricity consumption.

In [27] Baliga et al. estimate the power consumption of the Internet at about 0.4% of electricity consumption in broadband-enabled countries in 2009. This includes the power consumption of core, metro and edge IP networks and modems, but does not include mobile access or fixed (non-IP-based) telephony. This corresponds to about one quarter of our value for the total electricity consumption of the network (including mobile access and fixed telephony) in 2009. For higher access rates Baliga et al. estimate the electricity share of the Internet can increase to 0.8-1.5%.

Overall there is a large spread on the power consumption values we found in literature, which are in some cases higher and in other cases lower than our values. Notably our estimate is higher than the one in the often-cited Smart 2020 report.

7. Conclusion

We have studied the use phase electricity consumption in communication networks, consisting of telecom operator networks, customer premises equipment and office networks. For telecom operator networks, which make up three quarters of the total consumption, we used a top-down approach based on a representative operator sample to obtain a high degree of confidence in our results. According to our calculations, the total worldwide electricity consumption in communication networks will exceed 350 TWh in 2012. This corresponds to 1.8% of the total worldwide electricity consumption. Since the electricity consumption in communication networks is growing at a faster pace (annual growth rate $\approx$ 10% in the interval 2007-2011) than the overall electricity consumption (annual growth rate $\approx$ 3% in the interval 2007-2011), the relative share of communication networks is increasing. These results and the fact that data rates and subscription numbers will most likely continue to grow in the following years confirm the need to invest in more energy efficient network technologies.