The Global Footprint of Mobile Communications: The Ecological and Economic Perspective

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ABSTRACT

This article quantifies the global carbon footprint of mobile communication systems, and discusses its ecological and economic implications. Using up-to-date data and life cycle assessment models, we predict an increase of CO*2* equivalent emissions by a factor of three until 2020 compared to 2007, rising from about 86 to 235 Mto CO_2e, suggesting a steeper increase than predicted in the well-known SMART2020 report. We provide a breakdown of the global carbon footprint, which reveals that production of mobile devices and global radio access network operation will remain the major contributors, accompanied by an increasing share of emissions due to data transfer in the backbone resulting from rising mobile traffic volumes. The energy bill due to network operation will gain increasing importance in cellular business models. Furthermore, technologies to reduce energy consumption are considered a key enabler for the spread of mobile communications in developing countries. Taking into account several scenarios of technological advancement and rollout, we analyze the overall energy consumption of global radio access networks and illustrate the saving potential of green communication technologies. We conclude that, conditioned on quick implementation and alongside other "classical" improvements of spectral efficiency, these technologies offer the potential to serve three orders of magnitude more traffic with the same overall energy consumption as today.

INTRODUCTION

> "After its invention, the telegram took 90 years to spread to four-fifths of developing countries; for the cell phone, the comparable diffusion was 16 years." R. J. Samuelson, *Washington Post*.

Rarely have technical innovations changed everyday life as fast and profoundly as the pervasive use of personal mobile communications. Over the last two decades, mobile wireless services grew from being niche market applications to globally available components of daily life. The first mobile phone call using the Global System for Mobile Communications (GSM) took place in 1991 in Finland, and just 15 years later there were over two billion GSM users. Today the total number of mobile subscriptions in the world has passed 4 billion, more than half the population of the planet. By comparison, there are only about 1.3 billion fixed line subscribers worldwide. To date, the number of people accessing the Internet amounts to only 1.8 billion worldwide, which is roughly one fourth of the global population.

The driving force behind this rapid development was the growing importance of connectivity for socio-economic interactions. In addition — according to the International Technology Roadmap for Semiconductors (ITRS) — processing power and storage capacities of mobile devices have doubled approximately every 18 months; this is referred to as "Moore's Law." This prodigious growth rate in turn renders the use of ever more powerful information and communication systems, and devices attractive to the mass market. In order to be able to transport an exponentially increasing amount of (available) data to a user within an acceptable amount of time, the data transmission rates in both the wired Internet and wireless networks, including cellular, local area, and personal area networks, have been rising at approximately the same speed — by about a factor of ten every five years, as illustrated in Fig. 1 for the wireless case.

The increasing demand for wireless services and ubiquitous access, however, comes to the mobile communications industry at the price of a sizable carbon footprint. The whole information and communication technology (ICT) sector has been estimated to represent about 2 percent of global CO_2 emissions, a fraction comparable to that of global aviation, and about 1.5 percent of global CO2 equivalent (CO_2e) emissions[1] in 2007 [1, 3]. This study estimates the corresponding figure for mobile networks to be 0.2 and 0.4 percent of the global CO_2e emissions in 2007

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[1] *CO_2e is the concentration of CO_2 that would cause the same level of radiative forcing as a given type and concentration of greenhouse gas. Note that these figures include emissions from the whole life cycle, not only emissions related to operation.*

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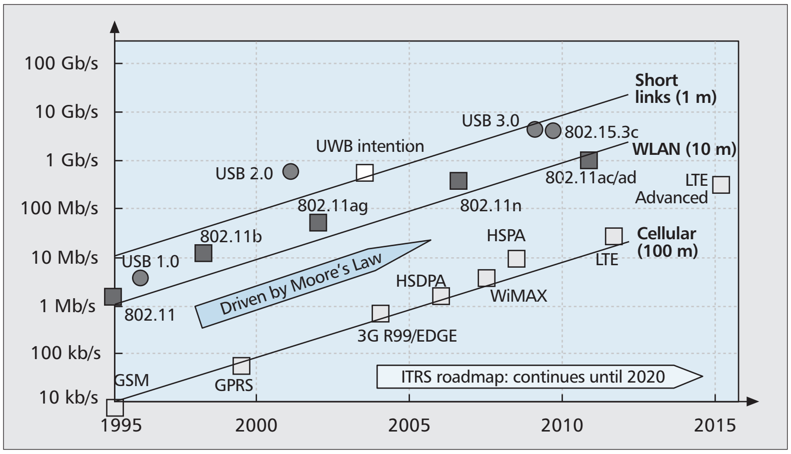

Figure 1. *Growth in wireless data rates follows approximately Moore's Law increasing by a factor of 10 every five years [2].*

and 2020, respectively. While the overall ICT footprint will less than double between 2007 and 2020 [5], the study presented in this article predicts that the footprint of mobile communications might almost triple within the same period, reaching more than one third of the present annual emissions of the entire United Kingdom.

In addition to minimizing the overall footprint of mobile communications, there is a strong economic incentive to reduce energy consumption of mobile networks. Considering the rising energy consumption of mobile networks, which is driven by complexity and increasing number of base station sites on one hand and steadily increasing energy costs on the other, it becomes clear that energy cost is critical for the operational expenditures (OPEX) of mobile telecom providers.

In the following, we present valuable insights into life cycle analysis (LCA) and carbon footprint modeling of mobile communication networks, trends, and figures of the global footprint of mobile communication until 2020, as well as a breakdown of the footprint into major contributors such as the operation of radio access networks (RANs) and manufacturing of mobile devices. In the second part of this article, we predict the RAN energy consumption according to different scenarios — depending on the energy efficiency of base station sites and adoption of technological advances in real networks — and discuss the impact of RAN energy consumption on operator revenue models.

The results of this study are calculated using the most reasonable assumptions on models and their parameters available today, which in certain cases might be subject to changes in the future.

A GLOBAL VIEW ON MOBILE COMMUNICATION NETWORKS

Before turning our attention to the footprint and energy consumption of mobile networks, this section presents a discussion on global statistics and future trends with regard to mobile subscriptions, traffic, and network infrastructure. Estimates of key figures for the years 2007, 2014, and 2020 are summarized in Table 1. Estimates up to 2014 are based on projections from analysts Gartner and ABI Research [1, 4]. Estimates of characteristic figures for the period 2015 to 2020 are based on modeling and extrapolation of current trends conducted as part of the EARTH project [9].

MOBILE SUBSCRIPTIONS

A fundamental driver of the overall carbon footprint of mobile communications is the number of worldwide mobile subscriptions. According to statistical surveys, the number of mobile subscribers worldwide increased between 2000 and 2009 with a compound annual growth rate (CAGR) of 24 percent from about 500 million to over 4 billion. As depicted in Fig. 2, there are expected to be about 1.4 billion and over 2 billion broadband subscriptions in 2012 and 2014, respectively. The number of GSM subscriptions decreases rapidly after 2014. A "peak GSM" (in terms of number of subscriptions) is expected to occur around 2012. The total number of subscriptions is expected to grow to about 6 billion in 2014 and tends to reach global penetration of 100 percent after 2020, which means that the number of subscriptions matches the number of inhabitants. If the relevant population age group of 10–65 years is taken into account, a *quasi-100 percent penetration* can already be expected during 2012.

MOBILE TRAFFIC DEMAND

Besides a growing subscriber base, data traffic is becoming more and more dominant in mobile networks. For the first time in history, the volume of worldwide mobile data traffic exceeded that of voice traffic in December 2009. In 2020, mobile data is expected to dominate all mobile traffic with a decreasing share of voice and is predicted to account for more than 10 percent of all IP traffic in 2020, mostly due to a proliferation of smartphones and data subscriptions for laptops. The most influential type of application will be video streaming, whose share of mobile data traffic is expected to increase from 40 to almost 66 percent between 2009 and 2014, and might easily break the 90 percent barrier in 2020. While data traffic volume skyrockets, voice traffic will increase only very moderately, and represent a decreasing share of less than 5 percent of all mobile traffic in 2014 and below 1 percent in 2020.

MOBILE NETWORK INFRASTRUCTURE

With respect to the network infrastructure, about 3.3 million radio base station (RBS) sites (including all standards) were in operation in 2007 [4]. The number of actual physical sites is of course lower as more than one standard and more than one operator can be located at the same site. For instance, many third-generation (3G) sites have been built at preexisting 2G sites. It is estimated that there were about 4.6 million sites, counting all standards in 2009, located at 3.6 million actual physical sites. The total number of radio base station cabinets delivered in 2009 was more than 5.5 million.

In addition to the proliferation of low-power base stations with a dedicated backhaul connection, future mobile networks will be characterized by an increasing number of home base stations, called femto cells, which require an

	2007	2014	2020
Total subscriptions (millions)	2950[a]	5600[a]	7600
3G+ data subscriptions (millions)	30[c]	700[c]	1600
Total mobile phones sold (millions)	1150[a]	1400[a]	1700
Share of smartphones in total sales/in use (%)	9[a]/7	29[a]/24	33/33
Laptops and netbooks sold (millions)	23[a]	280[a]	510
Worldwide base station sites* (millions)	3.3[b]	7.6	11.2
Average power consumption per site (kW)	1.7	1.3	1.1
Total global RAN energy consumption (TWh)	49	84	99
Share of diesel generated power in total RAN power (%)	9.5	11.3	13.2
Mobile data, including voice as data (million Tbytes)	0.8[c]	45[c]	493–753
Share of mobile data in total mobile traffic (%)	37.5[c]	98[c]	99.6
Share of mobile data traffic in all IP traffic (%)	0.9[c]	5[c]	11–17
Mobile data per average subscription (Gbytes)	0.3	8	65–100
Mobile data traffic per 3G+ data subscription (Gbytes)	5[c]	27[c]	120–184
Average data traffic per base station site (Mb/s)	0.062	1.5	11–18
Total emissions (Mto CO$_2$e)	86	170	235

[a] Gartner Research [b] ABI Research [c] Cisco Visual Networking Index, * per site and standard, actual site count is less but sites require more power due to collocation

Table 1. *Statistical data and projections of global mobile network characteristics for the years 2007, 2014, and 2020.*

If only the actual modem part is allocated to be a part of the mobile network, which seems reasonable, the carbon footprint due to manufacturing and operation of M2M communication will be small, even for a vast number of existing devices in 2020.

additional broadband connection for backhaul. According to Berg Insight, there could be about 12 million femto cells with about 70 million users on a regular basis in 2014. A rough extrapolation suggests about 100 million femto cells with about 500 million users in 2020. The effect of additional femto cells on the carbon footprint is discussed later.

MACHINE-TO-MACHINE COMMUNICATION

Currently there are about 75 million machine-to-machine (M2M) subscriptions worldwide, which are projected to triple until 2014 with a CAGR of 26 percent, a growth rate similar to that of mobile subscriptions in recent years. Optimistic predictions envision 50 billion connected devices by 2020. Despite the potential for rapid growth, we expect M2M communication to have only a marginal impact on the overall carbon footprint of mobile communications. Due to low activity levels and small capacity per link requirements, M2M data traffic is expected to be small compared to traffic originating from human users and their video demands. Assuming an average of 50 bytes/min/device and 10 devices/person on the planet (which yields over 75 million devices by 2020), the M2M traffic is less than 0.3 Gbytes/person — negligible compared to the estimated 100 Gbytes data traffic per person in 2020. Additionally, if only the actual modem part is allocated to be a part of the mobile network, which seems reasonable, the carbon footprint due to manufacturing and operation of M2M communication will be small, even for a vast number of existing devices in 2020. An exception might be video cameras (e.g. for security applications) sending real-time video. Here, the key question is to what extent mobile networks will carry such traffic, which is beyond the scope of this study.

CARBON FOOTPRINT OF MOBILE COMMUNICATIONS: THE ECOLOGICAL PERSPECTIVE

Assessing the ecological impact of mobile communications requires the study of a series of factors related to production, operation, and distribution of mobile communication networks

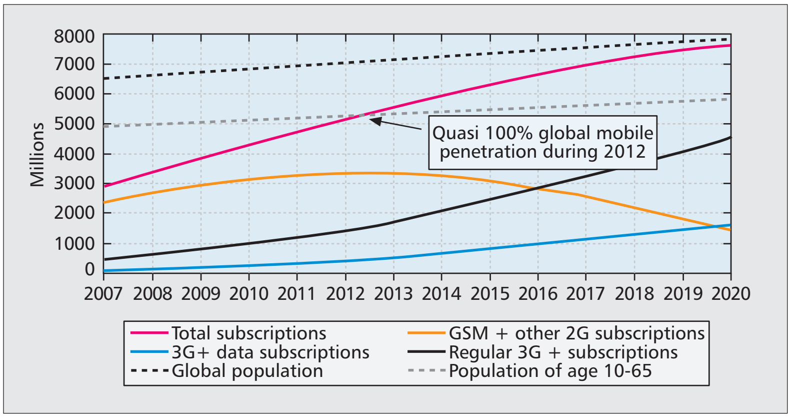

Figure 2. *The number of global mobile subscriptions projected until 2020. "Regular 3G+ subscription" refers to subscriptions for regular phones and smartphones. "3G+ data subscription" refers to subscriptions for mobile broadband modules used only in laptops.*

and services. A key factor of interest is the overall carbon footprint measured in CO_2 equivalent emissions (CO_2e) calculated with the Global Warming Potential (GWP-100) indicator defined by the International Panel on Climate Change (IPCC) [6]. In mobile communications, a large part of the carbon footprint stems from electricity consumption during operation and manufacturing, that is, from the production and distribution of electricity; from the extraction, production, and distribution of fuels consumed; from the construction and operation of the power plants and the grid; and, finally, from all related waste treatment.

CARBON FOOTPRINT MODELS AND ASSUMPTIONS

To quantify the impending mobile footprint, we consider all generations of cellular mobile networks including all end-user equipment accessing the networks, all business activities of the operators running the networks, and the use of fixed network resources as a result of data traffic generated by mobile network users. An overall carbon footprint model for mobile communications can conveniently be broken down into six categories:

1) *Manufacturing of mobile devices* refers to the manufacturing of mobile terminals including low-end phones, smartphones, and laptops, based on actual sales in the same year and covering all equipment newly deployed that year.

2) *Mobile devices operation* refers to charging of batteries and standby consumption of chargers left plugged in for all mobile phones and smartphones. Here, charging and grid operation for laptops (excluding docking stations), extra monitors, and other peripherals are included.

3) *RAN sites manufacturing and construction* means manufacturing of all electronic equipment as well as site equipment like diesel generators and batteries, as well as construction of site infrastructure such as antenna towers and site housings covering all equipment newly deployed each year.

4) *RAN sites operation* refers to the total electricity consumption of base station sites — control sites as well as core sites. A total site view that includes transmission, cooling, rectifiers, backup power, and so on is used. Diesel consumption for off-grid site operation and backup power is also included.

5) *Operator activities* cover operation of offices, stores, vehicle fleet, and business travel related to all operators' business activities.

6) *Data centers and data transport* refers to the use or allocation of other network resources based on the data traffic generated by mobile network users.

Mobile Devices — We consider three categories of devices accessing the network: regular mobile phones, smartphones, and laptops. Modeling of the footprint of regular mobile phones is based on "cradle to gate" LCA studies of mobile phone manufacturing including the transport to the customers resulting in an average of 18 kg CO_2e/device. The operation is estimated to 2 kWh/year based on charging every 60th hour equal to 40 percent of battery capacity every day and a standby scenario of 50 percent of the remaining time. It must be noted that modern mobile phone chargers have low stand-by power consumption in the order of 0.1 W. According to recent trends, it is reasonable to assume that both the manufacturing and operation emissions remain constant; that is, technological improvements on the component level are used for provision of phones with better performance and more functions. Corresponding values for the category of smartphones are 30 kg CO_2e for manufacturing and 7 kWh/year for operation. The same assumptions and principles used for regular mobile phones also apply to smartphones. Based on a comprehensive review of LCA studies of personal computers, the manufacturing related emissions of laptops can be estimated to 240 kg CO_2e/average device. The electricity consumption of the average annual use can be estimated to be 40 kWh in 2007. Based on current trends, we project that manufacturing and operation emissions of laptops decrease by five percent per year.

Radio Access Networks — Concrete figures of the carbon footprint of site manufacturing and construction for the radio access network (RAN) are based on a complete LCA of network equipment [3]. Figures on emissions and energy consumption due to RAN site operation, operator activities, data center operation, and data transport are based on a broad operator investigation covering networks that service about 40 percent of global subscriptions. In 2007, the RAN electricity consumption per average subscription was about 17 kWh. The construction of new base station sites every year as well as the removal of old site equipment is taken into account throughout the period of study. Surveying existing network equipment reveals that annual electricity consumption of new base station sites decreases about 8 percent on average compared to equipment installed the year before due to technological advances. This average figure is an overall estimate inclusive of all developments in power amplifiers, digital processing, AC/DC conversion, and cooling. It also includes the slow increase of more main-remote and small outdoor RBSs as well as the growing share of 3G base stations. In this regard, the base station model must be seen as an average of the mix of installed product. For predictions until 2020, we assume that the 8 percent/year trend continues over the study period and refer to it as *continuous improvements*. Under these assumptions and taking into account installation of new and removal of old equipment each year, the global average of base station site power amounts to about 1.7 kW in 2007 and reduces to about 1.2 kW in 2020. The study further assumes a roll-out model assuming between 600,000 and 675,000 sites newly deployed, and up to 300,000 sites taken out of service each year.

Femto Cells — The power consumption of a femto cell today is around 10 W, it will be around 6 W in 2012, and it can be assumed that a femto cell in 2020 will still consume about 5 W (if the power consumption for the fixed line connection is also included). An estimated number of 100 million femto cells in 2020 will consume about 4.4 TWh/year, which is less than 5 percent than consumed by the global RAN. Given this rather small impact and high uncertainty of deployment estimates, we exclude femto cells in the RAN energy consumption model. While femto cells consume a rather small amount of energy, their positive impact on data traffic and capacity, resulting in an energy consumption decrease, could indeed be larger, which is, however, beyond the scope of this study.

GLOBAL CARBON FOOTPRINT FORECAST

The estimated development of the global mobile footprint in the period from 2007 to 2020, including end-user equipment, operators' business activities, and data traffic, is depicted in Fig. 3. We would like to emphasize five major observations.

1) According to the projection, the overall carbon footprint of mobile communications increases almost linearly until 2020 with annual increase of 11 Mto CO_2e, an increase equivalent to the annual emissions of the whole of Luxembourg or 2.5 million EU households. The emissions in 2020 amount to more than 235 Mto CO_2e, which corresponds to more than one third of the present annual emissions of the entire United Kingdom. Relative to 2007, the overall carbon footprint will increase by a factor of 2 until 2014 and a factor of 2.7 until 2020. In the event that only minor efficiency improvements of base station sites and end-user equipment occur, the footprint could even increase more than threefold. In contrast, the footprint of the ICT sector as a whole is expected to increase by a factor of only 1.72 during the same 13-year period [5]. Observing the footprint of RAN sites' manufacturing and construction in Fig. 3 suggests that the contribution coming from the so-called *embodied energy* of RANs — as recently considered by some authors — will remain minor compared to RAN operation.

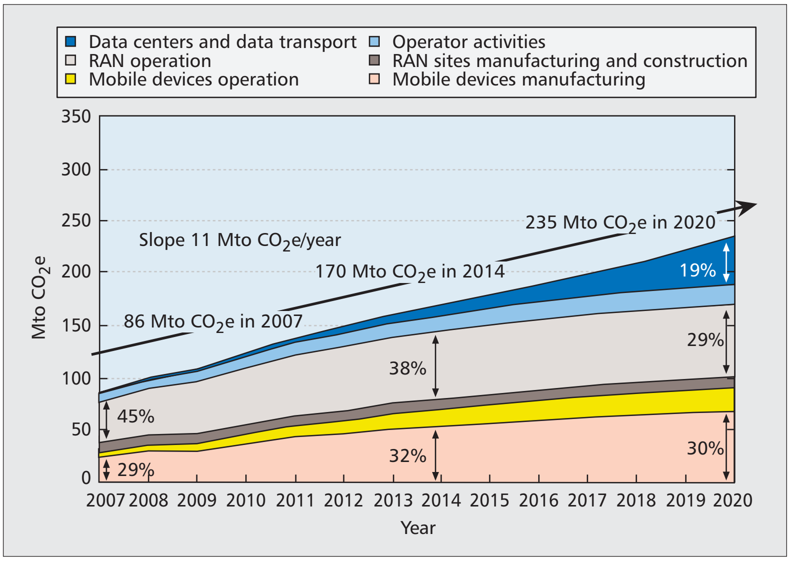

Figure 3. *Global carbon footprint of mobile communications projected until 2020.*

2) Over the whole period of study, individual footprints of RAN operation and production of mobile devices dominate the overall carbon footprint. Accordingly, initiatives aimed at carbon footprint reduction of the mobile communications sector should focus on these two categories. While RAN operation was by far the largest contributor in 2007, mobile device manufacturing will become increasingly important until both have an equal share in the overall carbon footprint in 2020. The reason for this is that smartphones and laptops represent an actively increasing fraction of the devices accessing the network — a trend driven by the demand for advanced wireless services and applications, especially video. Compared to regular phones, smartphones and laptops have carbon footprints almost two times and ten times higher, respectively. This effect is not fully considered in [5], which claims a reduction in the fraction of the footprint due to mobile devices, as further detailed in the next section.

3) The footprint of data centers and data transport will experience the strongest growth among all contributions until 2020 due to a drastic increase in mobile data traffic volume in the coming years. The scenario considered here uses a high data traffic model with a CAGR of 60 percent between 2015 and 2020. Reducing the CAGR of mobile traffic volume to 50 percent during that period would lead to 33 percent less CO_2e emissions from data centers and data transport in 2020.

4) Combining the estimates presented in Figs. 2 and 3 yields the *carbon footprint per average mobile subscription*, which is predicted to increase just slightly from 28 kg CO_2e in 2007 to about 31 kg CO_2e in 2020, as shown in Fig. 4. The reason is that technological advances, decreasing energy consumption of newly deployed base station sites (8 percent/year), and decreasing operation and manufacturing emissions of laptops (5 percent/year) in particular, keep pace with the growing subscriber base.

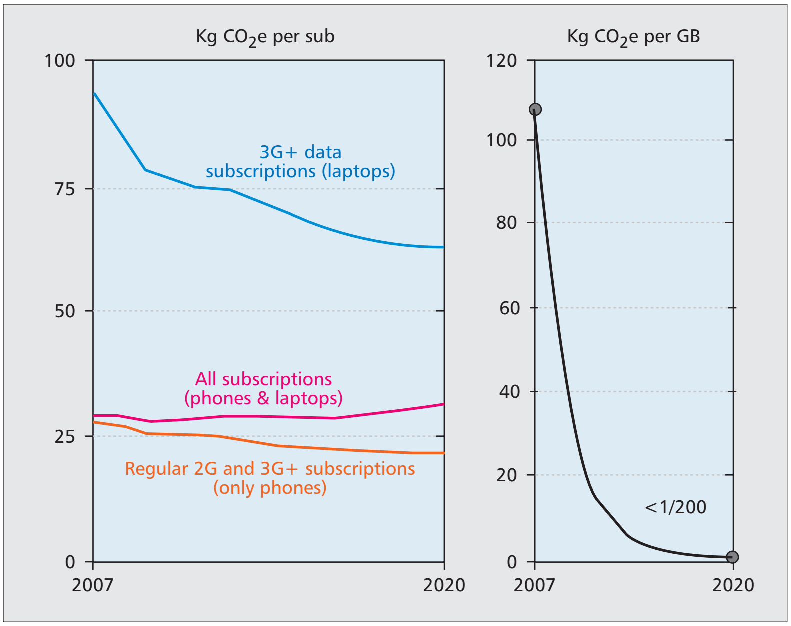

Figure 4. *Global carbon footprint per subscriber and per GB of mobile data traffic projected until 2020.*

5) From 2007 to 2020, the annual data traffic volume per mobile subscription is expected to increase substantially from 0.3 Gbytes/year up to 100 Gbytes/year (Table 1). Interpreting this growth in relation to the estimated emissions, *the carbon footprint per gigabyte of data traffic* will drop quickly from over 100 kg CO_2e/Gbyte in 2007 to less than 0.5 kg CO_2e/Gbyte in 2020, a decrease by a factor of over 200. Similar relations have already been observed for the last decade, where mobile traffic increased by a factor of about one hundred while energy consumption of base station sites per provided capacity dropped by a factor of five. Note that increasing rate demands still lead to increasing energy consumption of the network; however, the growth in rate is much more dramatic than the increase of corresponding energy consumption, and their ratio has only limited significance when observed over longer time periods.

The Mobile Communications Footprint in SMART2020 — The figures on the overall footprint of 86 Mto CO_2e and 235 CO_2e in 2007 and 2020, respectively, as presented here should be understood as an update of those presented in the well-known SMART2020 study [5]. The analysis in [5] is based only on electricity consumption figures for older BS equipment and a network model more suitable for fixed line networks, leading to an overestimation of the mobile footprint for 2007 with 150 Mto CO_2e.

On the contrary, the footprint of 201 Mto CO_2e predicted in SMART2020 for 2020 seems to be underestimated, as the number of mobile subscriptions forecast is assumed to be lower compared to more recent projections in [1]. As mentioned previously, in contrast to this study, the analysis in [5] does not consider the increased footprint of smartphones and laptops compared to regular mobile phones.

Global RAN Energy Consumption: The Economic Perspective

By 2007, for some networks in western Europe, the energy bill due to network operation was as high as the personnel cost to run and maintain the network — one example of the pressing effects of energy consumption (due to network operation) on business models of mobile operators. Unfortunately, future RAN energy consumption is hard to predict accurately, since it depends not only on the availability but also on the adoption and rollout of new technologies. In order to corner-case actual RAN energy consumption, this section details the study of RAN site operation (category 2 in the last section) based on the following five scenarios:

1) There are no significant technological advances that reduce the energy consumption of base station sites after 2012; that is, newly deployed sites after 2012 will require the same average power. This scenario assesses the case where all improvements contribute toward increasing spectral efficiency rather than reducing energy consumption.

2) Newly installed BS equipment consumes 8 percent less electricity per year than sites installed in the previous year over the whole studied period. A reduction of 8 percent in electricity needed per year corresponds to the continuous improvements in annual average that can be observed for equipment that is currently deployed and underlies the results presented in the previous section.

3) After 2012, newly deployed base stations consume 50 percent less energy than in scenario 2. This scenario captures potential impact of dedicated initiatives such as the EARTH project to improve energy efficiency of RANs beyond the extrapolated historical efficiency increase. The 50 percent reduction must be seen as per-site-average due to the combined effects of improved hardware as well as better use of the equipment through improved radio resource management, smarter deployment, and so on.

4) Based on the reduced per site electricity consumption of scenario 3, after 2012, all newly installed off-grid sites will be equipped with alternative energy modules (e.g. solar panels and batteries). In addition to the energy coming from a renewable source, diesel consumption with regard to the transportation of diesel to remote sites also decreases.

5) The last scenario assesses the effect of increasing energy efficiency in the base equipment installed, that is, the equipment that is not added or taken out of service during the studied period. More specifically, we assume a progressive swap-out of almost 40 percent of globally installed equipment over the period 2013 through 2020, where old sites are replaced by state-of-the-art equipment (according to scenario 3) each year, taking into account the combined effects of large-scale swap-out of equipment, base station site sharing among mobile operators, site modernizations, and advanced operation techniques.

Besides the specifics of the individual scenarios, we use the models and assumptions laid out earlier.

GLOBAL RAN ENERGY CONSUMPTION FORECAST

Electricity consumption figures for different scenarios are illustrated in Fig. 5, where we project an increase from 49 TWh in 2007 to about 109 TWh in 2020 for scenario 1. The savings resulting from continuous improvements in scenario 2 are below 10 percent since technology expectedly only spreads out slowly into the network via rollout of new sites. Additional energy efficiency related innovations coming from dedicated initiatives yield a reduction of another 10 percent, which is intuitive since we assumed an average efficiency gain per site of 50 percent in scenario 3. Powering new off-grid sites by alternative energy after 2012 in scenario 4 yields a small reduction globally, since the number of newly installed off-grid sites is expected to be small compared to the already existing base of equipment. The accumulated savings coming from new technologies rolled out, according to current considerations on coverage and capacity extension, is projected to be on the order of 15 percent in 2020 compared to the case of continuous improvements.

An additional reduction in global RAN energy consumption can be realized if the base equipment installed is optimized for energy efficiency. In our numerical study, we swapped about 37 percent of equipment in different proportions till 2020 to obtain an overall energy reduction of 50 percent globally in 2020 compared to the continuous improvements. While one has to acknowledge the simplicity of a trend analysis compared to the complexity that swap-outs and modernizations entail in practice, this scenario still illustrates the potential of energy efficiency improving technologies.

The trend analysis presented in Fig. 5 further reveals that a thousandfold increase in bit-per-Joule efficiency as envisioned by current initiatives is indeed within reach for mobile networks.

ENERGY COST AND REVENUE OF MOBILE SERVICES IN MATURE MARKETS

The energy bill due to network operation will gain increasing importance in cellular business models. Assuming a power requirement of 1.7kW on average and 800 subscribers per site with an average revenue per user (ARPU) of $20/mo, and energy costs of $0.15/kWh (common for mature western markets), the annual energy bill can be shown by straightforward calculation to be around 1 percent of the overall network earnings before interest, tax, depreciation, and amortization (EBITDA)! An increase in the number of subscriptions cannot be expected to change the situation in fully penetrated markets. Customer surveys suggest that the share of mobile communication services in the annual expenditure per physical customer is constant; thus, the attainable *revenue per physical person* with wireless services is flat. ARPU, understood as revenue *per subscription*, thus tends to decrease, according to the increase in subscriptions once certain market maturity has been attained.

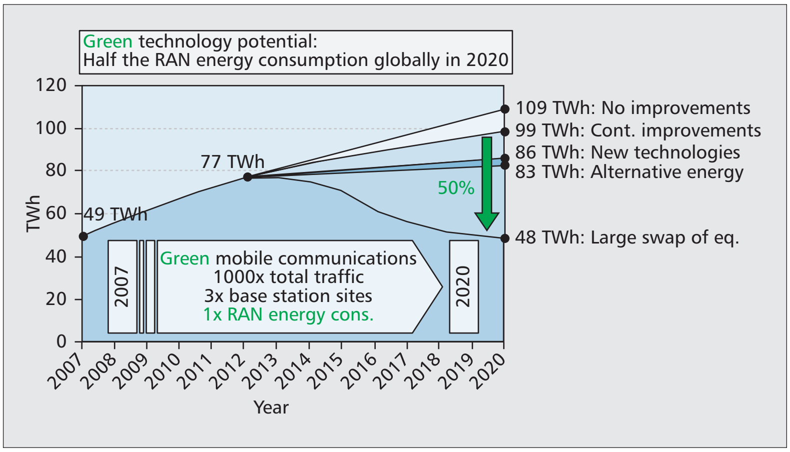

Figure 5. *Global RAN electricity consumption projected until 2020 for different scenarios of RAN development.*

In effect, ARPU is decreasing globally. For instance, Vodafone Germany reports an ARPU shrinking annually by over 6 percent on average from around €30 in 2000 to around €16 in 2009. The hundredfold increase in data traffic per subscriber, as projected in this and other studies (Table 1), cannot be expected to translate into corresponding revenue per user since the revenue per bit will be minute for a majority of future traffic,[2] and the proliferation of flat rate data subscriptions will ultimately bound potential revenue gains of the skyrocketing mobile data volumes. Similar trends can be observed for classical voice traffic, where operators report that revenue per call has dropped by an order of five percent annually over the last few years, and combined flat rates for fixed and mobile connections are becoming standard. Taking into account that quasi-full mobile penetration can be expected *globally* during 2012 (Fig. 2), it becomes obvious that overall network operators' revenues will stay flat in the future, and revenue models are to become more cost-driven.

If we consider the global average energy consumption as a rough estimate for individual network operators, relying on continuing efficiency improvements of 8 percent annually for newly installed sites will double the energy cost by 2020; a 50 percent increase in energy prices by 2020 will most likely triple them!

OFF-GRID SITES AND ALTERNATIVE ENERGY SOURCES IN DEVELOPING COUNTRIES

In order to facilitate the availability and use of mobile communications all around the globe, the exploitation of alternative energy sources for site operation is essential, and highly energy-efficient base station equipment is the key enabler for alternative energy technologies to be applicable. Despite the rapid spread of mobile communications around the globe, as of today there are still about 1 billion people worldwide who do not have access to any telecommunications services. More often than not, the lack of infrastructure (transport and electricity grid) prevents provisioning of cost-efficient access to wireless communications. Part of the reason for the lack of mobile services is that the ratio of energy cost

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[2] *While classical mobile messaging generates revenue on the order of several tens of dollars per megabyte, web browsing related traffic generates average revenue in the range of only several dollars per megabyte. The revenue per megabyte of streaming video services is about two orders of magnitude less, at around $0.01/Mbyte.*

Conditioned on quick implementation and alongside other "classical" improvements of the spectral efficiency of mobile networks, green mobile communication technologies offer the potential to serve three orders of magnitude more traffic with three times the number of sites but the same overall energy consumption as of today.

and revenue, as discussed above for western countries, is much worse when considering an ARPU of $3 dollars/mo and higher energy cost of $0.20/kWh, as is common for developing countries, arriving at an estimate of around 10 percent of overall revenue before interest and tax. Since ARPU increases rather slowly in developing countries, the key here also lies in reduction of electricity cost. If there is no electrical grid to power network equipment, operators have to resort to diesel powered sites more often than not. The transport of diesel to remote sites roughly doubles the cost per gallon compared to the price at the pump, which often makes conventional business models infeasible. Here, alternate energy sources can provide a feasible alternative. However, as of today, the number of RBS sites powered by alternate energy is quite small. For instance, Alcatel-Lucent reported having installed only about 300 solar powered RBS sites globally as of 2009, but envisions a global market potential of more than 100,000 sites in 2012 [8].

SUMMARY AND DISCUSSION

This article quantifies the global carbon footprint of mobile communications, and discusses its ecological and economic implications. We predict an increase of emissions by a factor of three between 2007 and 2020 rising to about 235 Mto CO2e. Production of mobile devices and global RAN operation will remain the major contributors, accompanied by an increasing share of emissions due to data transfer in the backbone.

Energy consumption of RANs will play an increasing role in mobile operators' business models. Technologies to reduce energy consumption of global RANs are a key enabler for the spread of mobile communications in developing countries. Conditioned on quick implementation and alongside other "classical" improvements of the spectral efficiency of mobile networks, green mobile communication technologies offer the potential to serve three orders of magnitude more traffic with three times the number of sites but the same overall energy consumption as of today.

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