Challenges **2015**, *6*, 117-157; doi:10.3390/challe6010117

OPEN ACCESS

challenges

ISSN 2078-1547

www.mdpi.com/journal/challenges

Article

On Global Electricity Usage of Communication Technology: Trends to 2030

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Academic Editor: Andreas Manz

Received: 27 February 2015 / Accepted: 22 April 2015 / Published: 30 April 2015

Abstract: This work presents an estimation of the global electricity usage that can be ascribed to Communication Technology (CT) between 2010 and 2030. The scope is three scenarios for use and production of consumer devices, communication networks and data centers. Three different scenarios, best, expected, and worst, are set up, which include annual numbers of sold devices, data traffic and electricity intensities/efficiencies. The most significant trend, regardless of scenario, is that the proportion of use-stage electricity by consumer devices will decrease and will be transferred to the networks and data centers. Still, it seems like wireless access networks will not be the main driver for electricity use. The analysis shows that for the worst-case scenario, CT could use as much as 51% of global electricity in 2030. This will happen if not enough improvement in electricity efficiency of wireless access networks and fixed access networks/data centers is possible. However, until 2030, globally-generated renewable electricity is likely to exceed the electricity demand of all networks and data centers. Nevertheless, the present investigation suggests, for the worst-case scenario, that CT electricity usage could contribute up to 23% of the globally released greenhouse gas emissions in 2030.

Keywords: communication networks; consumer devices; data centers; data traffic; electricity usage; electricity efficiency; electricity intensity; greenhouse gases; voice traffic

1. Introduction

With recent explosive growth in markets for new Communication Technology (CT) devices—smartphones and tablets in particular—and the transition of the television (TV) from a basic receiver into a digital media center and entertainment hub, these 'digital' consumer devices now dominate global sales of consumer electronics. [1]. The Internet-of-everything paradigm is also happening [2], which means that most electronic devices will be connected. Although not exactly new [3–6], the Internet-of-everything is widely believed to be coming in the following years [7]. Now, devices, such as humidifiers and heat pumps, are sold with integrated smartphone control [8].

Since 2009, several emerging technologies have initiated broad and disruptive impacts across the CT sector:

(i) cloud computing promises efficiency of scale, both in terms of capital and operational costs [9–12];
(ii) high-speed wireless access networks promise near-ubiquitous network access [13–15]; and
(iii) thin-client solutions, such as smart-phones and tablet devices [16].

At the same time, strong improvement in electricity efficiency have been made both from processing [9,17,18] and storage standpoints [19,20].

Despite these improvements, electricity usage is increasing [21,22], and as The New Climate Economy pointed out, the investments made in the next 15 years will determine the future of the planets' climate system [23]. The investments in electricity and CT infrastructure will be especially important. On the other hand, providers of CT Services hope that the overall global electricity usage, and thereby some of the eco-environmental impacts, will be reduced once new smart solutions [24] are implemented. Widely seen, the so-called enabling effect of CT, is thought to be large [25–28].

A key goal of this work is to outline a framework for evaluating future electricity growth patterns, including renewable electricity.

Electricity usage from CT is here divided into four principle categories:

(i) consumer devices, including personal computers, mobile phones, TVs and home entertainment systems;
(ii) network infrastructure;
(iii) data center computation and storage; and lastly
(iv) production of the above categories.

Regarding production impacts, left out amongst others are these devices:

- printers and multi-function devices;
- digital and video cameras;
- music players and similar digital media and stand-alone video player devices;
- network connected white goods;
- smart thermostats;
- home energy management;
- security systems;
- satellites;

- personal drones;
- robots;
- driverless automotives; and
- portable batteries, “power banks”.

While the excluded categories are not currently a significant contributor to electricity usage, compared to the ones included, some of them and others might emerge over the coming decade.

Neither is transport of CT devices included, nor end-of-life treatment, as well as diesel generators used as back-up power in off-grid situations [29–31] The present investigation focuses primarily on electricity usage of cradle-to-gate production of a number of CT devices and infrastructure for networks and data centers, and their use-stage electricity. Production is important, as has been shown by previous studies [32–34], and the upstream eco-environmental impact can be estimated by applying new standards for life cycle assessment (LCA) from European Telecommunication Standards Institute (ETSI) [35,36]. We also exclude resource usage, chemical usage, other energy sources apart from electricity as well as generation of electronic and other waste, preventing an overall sustainability evaluation.

Numerous studies in the area of estimating the global or national electricity and greenhouse gas (GHG) footprints of the entire CT Sector have been carried out, mainly between 2008 and 2014 [21,22,37–55].

All of the above shows a growing trend toward 2020 for one or several of the following: power usage, electricity, primary energy or release of GHG emissions related to CT. However, the GreenTouch consortium stands out, predicting a 90% reduction of electricity usage by communications networks between 2010 and 2020 [48].

To date, University of Ghent [37,41,49,50]; Ericsson with partners [38,39,45,46,53]; Global e-Sustainability Initiative [21]; National University of Ireland, Galway [40,43,54]; University of Melbourne/Centre for Energy Efficient Telecommunications [42,52]; Alcatel Lucent/Bell Labs [55]; the European Commission/Öko-institute on Europe [22]; and various Japanese organizations in Japan [44,51] are the leading the research groups evaluating CT energy use.

Moreover, University of Zurich and the Swiss Federal Laboratories for Materials Science and Technology are amongst the leading organizations describing the overall sustainability footprint of Information CT (ICT) [56]. Apart from the above, a large number of publications shown below, in sub-clauses for each sub-category, have addressed different parts of the electricity and GHG footprint of CT.

Our main additions to the above body of literature are predictions for 2030 CT electricity footprints and its related GHG emissions. Moreover, we include the voice aspect of wireless communication, which electricity usage is modeled in more detail than before.

The main question we seek to answer in this paper is whether future consumer CT infrastructure can actually slow its overall electricity usage, and related GHG emissions, until 2030. Also, considering the growth of data and produced devices, we suggest which electricity efficiencies would be necessary to keep the electricity usage at reasonable levels until 2030.

Elsewhere, the research aims to confirm and revisit earlier projections of the electricity footprint towards 2020.

Next follows the description of the overall methodological approach. Then follows the modeling of the four main categories of the overall analysis; consumer device use, networks use, data centers use and production. Three scenarios for 2010–2030 electricity usage of CT: best, expected, and worst, are included in each. For each category a description of assumptions and modeling approaches is done leading to results. Then the results are discussed and the conclusions drawn, followed by recommendations for the next steps.

2. Materials and Methods—Approach

The Overall Methodological Approach Consists of the Following Steps:

- *Setting of the modeling framework leading to total electricity used per year:*
  - Consumer devices production and use: A framework is set up that includes the kind of consumer devices to be included, the units of these consumer devices produced each year from 2010 to 2030, their lifetimes, their production electricity per unit, their average annual electricity usage, and the annual electricity efficiency improvements to be achieved year by year in production and use.
  - Fixed access networks (FAN) use: FAN consists of Fixed access wired and Fixed access Wi-Fi. A framework is set up based on the expected annual growth of fixed access wired data traffic and fixed access Wi-Fi data traffic between 2010 and 2030 and the improvements of electricity efficiency to be expected year by year from 2010 to 2030, and assumed known values for the 2010–2012 electricity of the defined FAN scope. The same framework is applied to both fixed access types.
  - Wireless access networks (WAN) use: A framework is set up based on the annual growth of voice traffic; the growth of mobile data traffic; electricity used per traffic unit for each of voice; second-generation (2G) wireless telephone technology data, third generation (3G) data, fourth generation (4G) data and fifth generation (5G) data; share of the before mentioned technologies of the total wireless traffic year by year from 2010 until 2030; and improvements of electricity efficiencies to be achieved year by year.
  - Data centers use: A framework is set up based on expected annual growth of global data center Internet Protocol (IP) traffic between 2010 and 2030, electricity used per traffic unit, and improvements of electricity efficiencies to be achieved year by year.
  - Networks and Data center production: The estimation is based on the share of the use-stage electricity of the life cycle electricity of networks and data centers. The production electricity is correlated fully to the use-stage electricity.
  - Global electricity: The estimation is based on a known starting value for 2010 and an annual growth rate for non-CT electricity. CT electricity (E_{CT}) grows according to the present investigation.
  - Renewable electricity: The estimation is based on known starting value for 2010 and an annual growth rate.
  - GHG intensity of the global electricity mix: The estimation is based on a combination of GHG intensities of (annually changing) shares of non-renewable and renewable electricity.

- GHG global emissions: The estimation is based on a 2010 starting value of 46 Gigatons and a 2% annual growth rate until 2030, for non-CT GHG emissions. CT electricity GHG emissions grow according to the present investigation.

- *Data input:* Collecting and extrapolating the data to be inserted in the modeling tool, in this case Microsoft Excel. The details are found in the Supplementary Materials file.
- *Data calculation:* Produce the numbers and graphs.
- *Data analysis:* Make a check to determine the reasonableness of the results.

The normalization basis adopted here, for the quantification of electricity efficiency/intensity, is traffic expressed as TWh/ExaByte (EB), whereas previous studies have used bases such as subscriber and household for the electricity calculations [57,58]. Joules/bit [59], bits/Joule [60,61], and bits per second per Watt [62] are also popular. One joule per bit corresponds to 2,652 TWh/EB.

3. Consumer Devices Use Stage—Results

For the devices, no best, expected or worst numbers of produced units are set, *i.e*. all scenarios use the same estimations. However, the production electricity numbers, lifetimes, and use electricity numbers are all assumed to be different. Different annual improvements of 1% (worst) [68,69], 3% (expected) [68,69] and 5% (best) [49,68,69] are assumed for the electricity usage starting from 2011 until 2030. The annual improvements are applied to both the production electricity and use-stage electricity for all kind of devices. This means the, e.g. for the best-case scenario, the electricity usage will be 64% lower by 2030 than in 2010.

Equation 1 describes the relation between annual electricity use of a category of a consumer device, produced units, lifetime, average annual electricity used per unit, and annual electricity usage reduction for devices:

$$E_{CDU,2010+n} = \left(\sum_{n+1-L}^{n} P_{CD,2010+n} \right) \times E_{CDUu,2010} \times \left(\frac{(100\% - ER\%)}{100} \right)^{n} \quad (1)$$

where

$E_{CDU,2010}$ = Total electricity for annual use of a category of consumer devices in 2010, TWh.

$P_{CD,2010}$ = Units of a category of consumer device (desktops, monitors, *etc*.) produced in one year 2010, millions.

L = lifetime of a category of consumer devices, 1, 2, 3, 5, 7, 8 or 10 years.

$E_{CDUu,2010}$ = Average annual electricity used by a category of consumer device in 2010, MWh/unit/year.

ER = annual electricity usage reduction, 5% (best) [49,68,69], 3% (expected) [68,69], 1% (worst) [68,69].

n = 0,…20.

Equation 1 is used for the use stage of all included consumer devices.

For example, the electricity usage for smartphones in 2025 for best-case scenario using Equation 1: n = 15, L = 1, $P_{CD,2025}$ = 1,774, $E_{CDUu,2010}$ = 0.005, ER = 5% -->$E_{CDU,2025}$ = (1,774) × 0.005 × ((100% – 5%)/100)^{15} = 4.11 TWh.

Further, the electricity usage for TVs in 2017 for expected-case scenario: $n = 7$, $L = 10$, $P_{CD,2017} =$ 2,608, $E_{CDUu,2010} = 0.2$, $ER = 3\%$ --> $E_{CDU,2017} = (2{,}608) \times 0.2 \times ((100\% - 3\%)/100)^7) = 421$ TWh.

Moreover, the electricity usage for TVs in 2030 for worst-case scenario: $n = 20$, $L = 10$, $P_{CD,2030} =$ 3,152, $E_{CDUu} = 0.2$, $ER = 1\%$ --> $E_{CDU,2030} = (3{,}152) \times 0.2 \times ((100\% - 1\%)/100)^{20} = 516$ TWh.

In the case that data on produced units before 2010 are not available, 2010 data are used (see clauses 3.1.1–4).

3.1. Desktops, Monitors, Laptops

The number of annually produced desktops is all in all expected to decline between 2010 and 2030 from around 146 million to around 100 million units due to changed consumer behavior and competition from other types of personal computers [40,43,63,64].

As for monitors, the decline is predicted to be from 160 to 120 million units, following roughly the desktop trend [64].

The laptops produced will, on the other hand, increase in the next years from 200 to 780 million between 2010 and 2020 [65,66]. However, after 2020 a decline to around 130 million in 2030 is assumed, due to competition from other mobile devices [64].

Ranges for the average annual use-stage electricity of the devices are derived from literature [21,67–72].

For the best scenario, seen from a low electricity usage standpoint, the lifetime is set to three years, whereas for the expected and worst, five and seven years are assumed, respectively. ‘Worst’ is meant from the viewpoint of use-stage electricity usage.

3.2. Smartphones, Tablets, Ordinary Mobile Phones, Phablets, Mobile Broadband Modems

The number of annually produced smartphones is expected to rise between 2010 and 2030 from around 350 million to around 3,000 million units [40,43,64–66].

As for tablets, the corresponding increase is predicted to be from 50 to 560 million units [65,66]. The production of ordinary mobile phones, having less functionality than smartphones, will decrease from 1,200 to 350 million units between 2010 and 2030 [66]; phablets will increase from none to 1,600 million [66]; and mobile broadband modems increase from 100 to 900 million [40,43, 64–66].

Ranges for the annual use-stage electricity of the devices are derived from literature [36,43,73–75]. Mobile broadband modems are assumed to be charged separately by the device (e.g. via a laptop) they are connected to. For this sub-category, the electricity usage per device is likely to grow to accommodate improved screen and Central Processing Unit (CPU) technology, and emerging high-speed wireless connections to the network [43].

For the best scenario, seen from a low electricity usage standpoint, the lifetime is set to one year, whereas for the expected and worst, two and three years are assumed, respectively.

3.3. TVs

The number of produced TVs of different sorts is expected to increase slightly between 2010 and 2030 from around 250 million [77] to around 340 million units [77].

One significant change to be expected, as the Internet-of-everything paradigm happens [2], is the switch-over to connected TVs. The trend is likely to grow until the majority of new TV panels feature network connectivity as a standard feature. There is also an active market in add-on High-Definition Multimedia Interface (HDMI) appliances that can provide this connectivity for existing TV panels. [43].

Ongoing is a substantial improvement in electricity performance of individual TV panels due to a transitioning to Light Emitting Display (LED) based displays [77]. Internet Protocol (IP) TV is also expected to demonstrate improved efficiency [78]. Emerging technologies such as field emission display [79] offer potential for continued improvements. The electricity efficiency improvements have made researchers question the strong eco-environmental focus on the use phase [80].

For the best scenario, seen from a low electricity usage standpoint, the lifetime is set to eight years, whereas for the expected and worst, ten years is assumed.

3.4. TV peripherals

The present category comprises set-top boxes, game consoles, Digital Versatile Disc (DVD), Blue-ray players and Audio/Video (A/V) TV peripherals. The sales of these devices are assumed to follow closely TV sales.

A constant relation of produced TV peripherals per TV unit is assumed: 38% set-top-boxes, 20% game consoles, 30% A/V receivers, and 35% DVD/Blu-ray players [68]. This means that in 2010, around 95 million set-top boxes were sold, and in 2030 128 million.

For the best scenario, seen from a low electricity usage standpoint, the lifetime is set to eight years, whereas for the expected and worst, ten years is assumed.

The average electricity use of high definition games consoles was previously estimated at 102 kWh/console/year [81], and used here for 2010. Moreover, the total electricity consumption of video game consoles in the United States was around 16 TWh (330 kWh/console/year) in 2010 [82]. This number can be compared to the estimation for the current global usage, 40–50 TWh for game consoles in 2010.

Below in Figure 1 is shown the global electricity demand for consumer devices use stage. The details for Figure 1 are shown in the Supplementary Materials file, sections “Cons Dev Best”, “Cons Dev Expe” and “Cons Dev Worst”.

TVs and TV peripherals make up around 70% of the total scores shown in Figure 1. As of 2013, Alcatel-Lucent estimated that worldwide usage of personal computers, printers, smartphones, mobile phones and tablets, excluding TVs, used 39 GigaWatt ≈ 341 TWh [55], which is close to our modeling for the expected scenario for this equipment.

4. Networks Use Stage—Results

Networks can be simply divided into a core backbone and a local access network. Tucker *et al*. argued that the network should be divided into core network, metro/edge network, access network, content distribution network and data centers [42]. Optical networks are important as they form the actual ‘core’ network handling all bulk data traffic [83]. However, from a traffic and electricity sense, the data centers, which handle the majority of bulk data traffic, are separated (see clause 5). Strategies and trends for reducing electricity usage in communications networks have been presented [84–86], and the absolute electricity usage is also well researched [41,49,50,87].

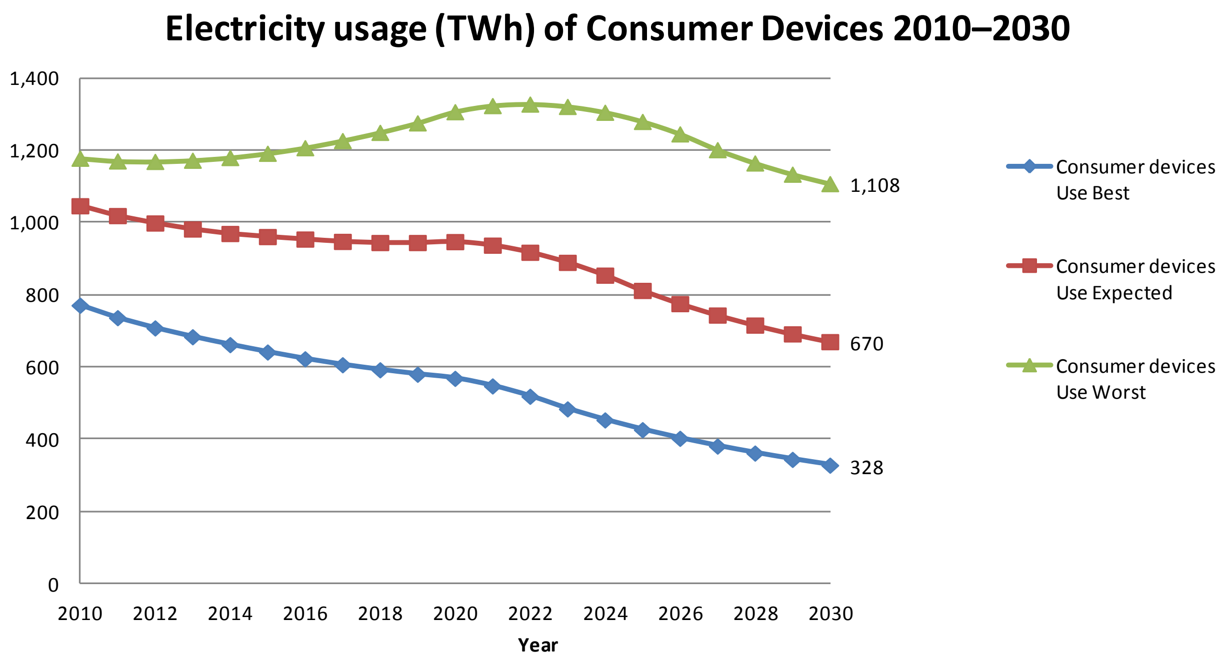


Figure 1. Global electricity demand of consumer devices 2010–2030.

4.1. Fixed Access Wired and Wi-Fi Networks—Results

The core network, metro/edge network, content distribution network, wired access network, customer premises equipment and wireless local area networks, are regarded here as one primary entity called fixed access networks (FAN). FAN is divided into two parts, fixed access wired and fixed access Wi-Fi. Fixed access Wi-Fi is here regarded as customer premises equipment and their 2010–2012 electricity usage is based on [41]. The FAN infrastructure will continue to expand, as it has in the past, and its electricity efficiency will be essentially static [43]. The growth in electricity usage over the next few years is estimated from the growth in total fixed access wired and fixed access Wi-Fi network data traffic, respectively [88]. The optical backbone network is responsible for the majority of the consumed electricity, especially at high traffic loads [89].

Addis *et al*. proposed optimization models to minimize the electricity usage of IP networks [90]. Several other previous studies exist focusing on overall electricity usages in transport and optical networks [91–96].

Migration towards higher data rates, *i.e.*, from 10 Gbit/s to 40 Gbit/s, is assisting in improving the overall electricity efficiency of the optical transport network [91]. Van Heddeghem *et al*. presented a quantitative survey of the power saving potential in IP over Wavelength Division Multiplexer backbone networks [97]. They concluded that the reduction potential, for the electricity efficiency, between 2010 and 2020 is 2.3 to 31 times [97]. Based on Cisco's traffic data [88], we expect that the total annual fixed access traffic will rise six to nine times between these years, from 320 to 1,900 or 3,000 EB, and then rise further to 13,000 or 48,000 EB until 2030 (Traffic details available in the Supplementary Materials file, section "Traffic").

Regarding metrics for electricity used per data traffic, 0.08 kWh/GB for Swedish data transmission and IP core networks, has been proposed [98], which corresponds to 0.08 TWh/EB. Coroama *et al*. estimated 0.2 kWh/GB, or 0.2 TWh/EB, for transporting the video signal of a virtual conference on a network path between Switzerland and Japan [99], and Verizon [100] indicated 0.15 TWh/EB in 2009 and 0.13 TWh/EB in 2010. Verizon have set targets to increase its network efficiency to achieve below 0.08 TWh/EB by 2020 [100], *i.e*. around 6% decrease per year. We later use 5% improvement for FAN and data centers worst-case scenario (see Equations 2 and 9). Recently Schien and Priest suggested 0.02–0.18 kWh/GigaByte (GB) for digital services in 2014 for metro and core network scopes, which excluded consumer devices, other types of FAN other than metro/core and WAN [101].

Telecom Italia reported values of their Eco-Efficiency indicator in bits/Joule, 1,298, 2,157, 2,524 and 2,828 for 2010–2013 [60,61]. This is translated to 1.97, 1.18, 1.02 and 0.91 TWh/EB in 2010–2013. Telecom Italia reported for a mix of FAN, WAN and data centers, however, the achieved annual efficiency improvements of more than 22% are noticeable. We later use 22% improvement for WAN best-case scenario (see clause 4.1.2).

Hence, we assume that FAN electricity intensity is in the order of magnitude of 0.1–0.2 TWh/EB in 2012.

From 2012 to 2030 the overall electricity efficiency is expected to improve by 15% per year in the best scenario, by 10% in the expected and by 5% in the worst-case scenario [43]. We set 196 TWh as baseline for 2012 for fixed access wired and 51 TWh for fixed access Wi-Fi [41]. For 2010 and 2011, data are adapted from Lambert *et al*. [41,49] based on the growth rate from 2007–2012. Equation 2 describes the relation between fixed data traffic, electricity efficiency and electricity usage from 2013 to 2030:

$$E_{F,2012+n} = \left(\frac{TF_{2012+n}}{TF_{2011+n}}\right) \times E_{F,2011+n} \times \left(\frac{(100\% - EE\%)}{100}\right) \tag{2}$$

where

$E_{F,2012}$ = electricity usage fixed access wired or fixed access Wi-Fi networks in 2012, TWh

$E_{F,2011}$ = electricity usage fixed access wired or fixed access Wi-Fi networks in 2012, TWh

TF_{2012} = fixed access wired + fixed access Wi-Fi data traffic or fixed access Wi-Fi data traffic in 2012, EB

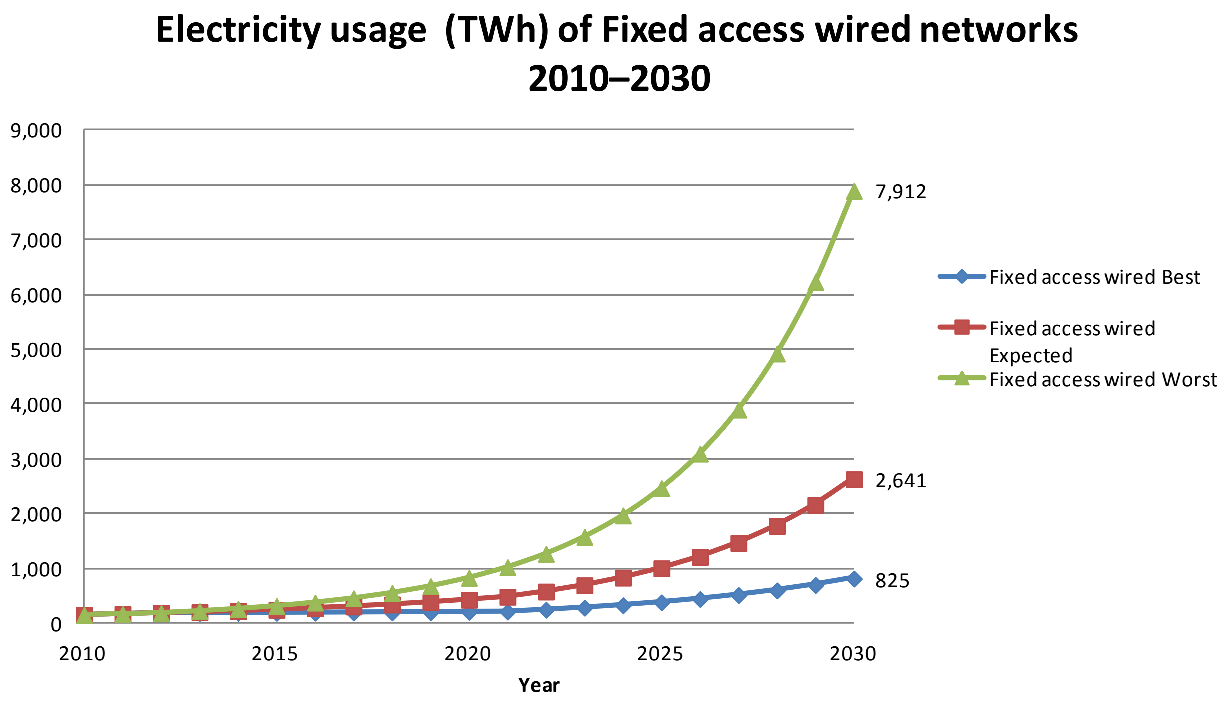
TF_{2011} = fixed access wired + fixed access Wi-Fi data traffic or fixed access Wi-Fi data traffic in 2011, EB

n = 1,2,3…,18

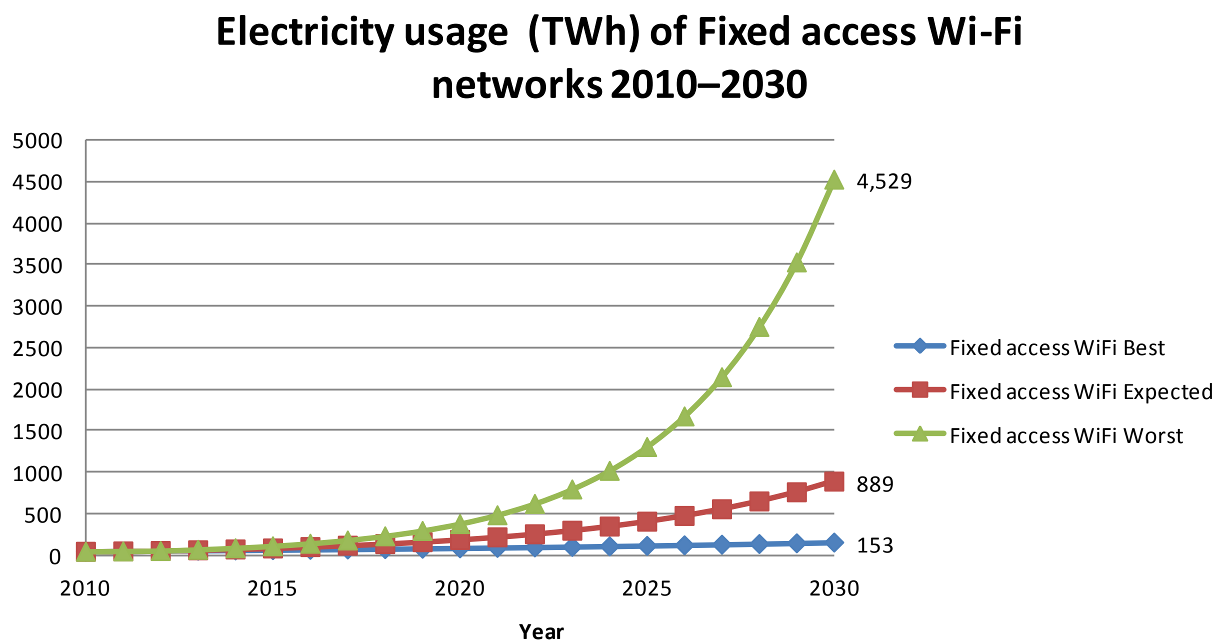
EE = annual electricity efficiency improvement, 15% (best) [42], 10% (expected) [43], 5% (worst) [43]

From 2022, for EE only, 5% is assumed possible for all scenarios as we except it will become more difficult to improve the electricity efficiency via Moore's Law [102,103].

As shown in Figure 2a,b, the electricity usages for the FAN wired and Wi-Fi are set to increase, in all three scenarios, as the fixed access wired data traffic, and fixed access Wi-Fi traffic, grow faster than the likely electricity efficiency improvements. The details for Figure 2a,b are shown in the Supplementary Materials file, section "WAN FAN Wi-Fi".



(**a**)



(**b**)

Figure 2. **(a)** Global electricity demand of fixed access wired networks 2010–2030. (**b**). Global electricity demand of fixed access Wi-Fi networks 2010–2030.

Figure 2a,b are opposing predicted potential reductions by GreenTouch between 2010 and 2020 [48]. On the other hand, as of 2013 Alcatel-Lucent estimated that worldwide telecommunication networks, excluding service core data centers, but including wireless access networks, on average, used 31.9 GigaWatt ≈ 279 TWh [55], which is close to our modeling for all scenarios.

4.2. Wireless Access Networks—Results

The second component of networks is that of the wireless access network (WAN) capable of gradually higher data rates, but in parallel they have potential to increase electricity usage substantially [43]. The modeling of the wireless electricity usage is done in more depth than for the consumer devices, fixed networks and the data centers, as several clear trends are identified between different radio technologies.

Gozalvez estimated that 85% of the world's population will be covered by 3G mobile Internet in 2017 and that 4G coverage will reach 50% in the same timeframe [104]. Ericsson predicted that mobile data traffic will grow by around 30% annually between 2013 and 2019 [105]. The European Union research project *Mobile and wireless communications Enablers for the Twenty-Twenty Information Society, METIS* [106] predicted a 1,000 mobile data traffic data growth from 2015–2030, *i.e*. 58% Compound Annual Growth Rate (CAGR), which is the same growth as Cisco predicted for 2014–2019 [107].

Based on these predictions, we assume 58% CAGR from 2015–2020 and then three different rates for 2020–2030, 40%, 50%, and 60% for best, expected, and worst, respectively.

Part of the mobile data traffic growth is driven by Machine-to-Machine [108] and Internet-of-everything applications, which will generate a vast amount of data, implying a major technical challenge for WAN [109]. Another trend is utilizing the close synergy between cloud computing, software defined networking (SDN), and network function virtualization (NFV). A convergence of cloud computing, SDN, and NFV are likely to form the 5G platforms for big data [109]. In SDN architecture, network control is detached from the forwarding hardware, and resides as a logically centralized control program that install rules in forwarding hardware (switches/routers) [110]. In summary, the synergy trend is envisaged to improve the electricity efficiency.

The general problems and opportunities regarding electricity usage of WAN have been widely discussed [111–116].

Many have presented ideas and implementations of electricity savings in mobile networks [117–124]. Frenger *et al.* demonstrated that it will be possible to save 60% of absolute electricity usage in WAN from 2013–2020 [125].

For example, massive Multiple Input Multiple Output (MIMO) systems offer significantly better electricity efficiencies than traditional 5G deployment [126].

The electricity usage of WAN has also been specifically studied [39,127–129].

Lambert *et al*. assumed 105 TWh for worldwide WAN in 2012 [41], and Scheck assumed 125 TWh in 2013 [130]. These estimations are not far from our best-case scenario for these years, 116 and 96 TWh, respectively.

Moreover, an exergy analysis of WAN has been carried out, highlighting lifetime and production of consumer devices [131].

Useful electricity efficiency metrics for 2G, 3G and 4G mobile networks have been reported by several authors [48,53,117,132]. Huawei measurements of traffic and electricity usage in field WAN confirm the best-case scenario electricity efficiencies, especially for voice traffic. Nevertheless, the electricity efficiencies are hugely dependent on how well the networks are utilized.

Below we have defined a generic efficiency improvement function for 2010–2030, which applies to all radio technologies when they are introduced.

4.2.1. 2G/3G Voice Traffic

Here, for the first time, the electricity usage associated with voice traffic is separated, enabling a more sophisticated modeling of the electricity usage than previous studies [39,41,45,49,50].

This is important, as including voice in the model prevents an overestimation of the potential electricity efficiency increase, especially until 2020. The total *voice* traffic is assumed to be constant (absolute value) from 2010 to 2030 [105]. Equation 3 describes the relation between voice traffic, electricity intensity (*EI*), electricity efficiency improvement (*EE*) and electricity usage (*E*) from 2010 to 2030:

$$E_{Voice,2010+n} = VT_{2010+n} \times 12 \times EI_{V,2010} \times \left(\frac{(100\% - EE\%)}{100} \right)^{n} \quad (3)$$

where

$E_{Voice,2010}$ = electricity usage in 2010, TWh

VT_{2010} = voice traffic per month in 2010, EB

n = 0,1,2,3…,20

$EI_{V,2010}$ = electricity intensity voice traffic in 2010, 5 (best),7 (expected),14 (worst), TWh/EB

EE = annual electricity efficiency improvement, 30% (best) [42,125], 22% (expected) [42,60,61], 10% (worst) [100]

From 2022 only 5% is assumed possible [102,103]. The electricity intensity in 2010, for best-case voice traffic, is based on Huawei internal measurements in field WAN for 2014 (2.1 kb/J = 1.22 TWh/EB), which are extrapolated backwards to 2010. The expected- and worst-case electricity intensities in 2010 are based on iterations, which, in combination with mobile data traffic intensities, lead to a reasonable total WAN electricity usage in 2010 [41,130].

4.2.2. Mobile Data Traffic

Starting from 0.32 EB/month [133], the *total mobile data* traffic is assumed to rise 66% per year between 2010 and 2017 [133], 58% per year between 2017 and 2020 [107], and then by 40% [105], 50% [133] and 60% [133] annually between 2020 and 2030, for the best, expected- and worst-case scenarios, respectively.

4.3. 2G Mobile

From 2021 to 2030, the total 2G mobile data traffic is assumed to be constant (absolute value), implying that its share of the total mobile data traffic will decrease rapidly [107]. Equation 4 describes the relation between electricity usage for each year from 2010 to 2030, 2G mobile data traffic, electricity intensity, and electricity efficiency improvement:

$$E_{2G,2010+n} = S2G_{2010+n} \times MDT_{2010+n} \times 12 \times EI_{2G,2010} \times \left(\frac{(100\% - EE\%)}{100} \right)^{n} \quad (4)$$

where

$E_{2G,2010}$ = electricity usage for 2G in 2010, TWh

$S2G_{2010}$ = share of 2G of total mobile data traffic in 2010, %

MDT_{2010} = total mobile data traffic per month in 2010, EB

n = 0,1,2,3…,20

$EI_{2G,2010}$ = electricity intensity 2G mobile data traffic in 2010, 20 (best), 37 (expected) [53], 40 (worst), TWh/EB

EE = annual electricity efficiency improvement, 30% (best) [42,125], 22% (expected) [42,60,61], 10% (worst) [100]

From 2022, for EE only, 5% is assumed possible [102,103]. The electricity usages, for best- and worst-case 2G electricity usage in 2010 are based on iterations, which lead to a reasonable WAN electricity usage in 2010 [41,130].

4.4. 3G Mobile

The total 3G mobile data traffic is assumed to be constant (absolute value) from 2021 to 2030, as 4G and 5G grow [107]. Equation 5 describes the relation between electricity usage for each year from 2010 to 2030, 3G mobile data traffic, electricity intensity and electricity efficiency improvement:

$$E_{3G,2010+n} = S3G_{2010+n} \times MDT_{2010+n} \times 12 \times EI_{3G,2010} \times \left(\frac{(100\% - EE\%)}{100} \right)^n \quad (5)$$

where

$E_{3G,2010}$ = electricity usage of 3G in 2010, TWh

$S3G_{2010}$ = share of 3G of total mobile data traffic in 2010, %

MDT_{2010} = mobile data traffic per month in 2010, EB

n = 0,1,2,3…,20

$EI_{3G,2010}$ = electricity intensity 3G mobile data traffic in 2010, 2.5 (best), 2.9 (expected) [53], 3.5 (worst), TWh/EB

EE = annual electricity efficiency improvement, 30% (best) [42,125], 22% (expected) [42,60,61], 10% (worst) [100]

From 2022, for EE only, 5% is assumed possible [97]. The electricity usages, for best- and worst-case 3G electricity usage in 2010 are based on iterations, which lead to a reasonable overall total WAN electricity usage in 2010 [41,130].

4.5. 4G Mobile

Equation 6 describes the relation between electricity usage for each year from 2010 to 2030, 4G mobile data traffic, electricity intensity, and electricity efficiency improvement:

$$E_{4G,2010+n} = S4G_{2010+n} \times MDT_{2010+n} \times 12 \times EI_{4G,2010} \times \left(\frac{(100\% - EE\%)}{100} \right)^n \quad (6)$$

where

$E_{4G,2010}$ = electricity usage 4G in 2010, TWh

$S4G_{2010}$ = share of 4G of total mobile data traffic in 2010, %

MDT_{2010} = mobile data traffic per month, EB

n = 0,1,2,3…,20

$EI_{4G,2010}$ = electricity intensity 4G mobile data traffic in 2010, 0.5 (best), 0.6 (expected) [53], 1.37 (worst) [43], TWh/EB

EE = annual electricity efficiency improvement, 30% (best) [125], 22% (expected), 10% (worst)

From 2022, for EE only, 5% is assumed possible [102,103]. The electricity usages, for best-case 4G electricity usage in 2010, is based on iterations which lead to a reasonable overall total WAN electricity usage in 2010 [41,130].

4.6. 5G Mobile

5G, which is the next generation radio technology, is thought to use much less electricity per bit than previous generations [134,135].

Mertikopoulos and Moustakas argued that massive MIMO arrays can increase throughput in 5G networks by a factor of 10 or more [136]. Moreover, the target of the *Toward Green 5G Mobile Networks, 5gREEn* project was to reduce the electricity efficiency by a factor of 10 compared to 2013 best practice [137]. Anyway, the share of 5G is assumed to be 1% of mobile data traffic in 2020. Equation 7 describes the relation between electricity usage for each year from 2010 to 2030, 5G mobile data traffic, electricity intensity and electricity efficiency improvement:

$$E_{5G,2010+n} = S5G_{2010+n} \times MDT_{2010+n} \times 12 \times EI_{5G,2010} \times \left(\frac{(100\% - EE\%)}{100}\right)^{n} \quad (7)$$

where

$E_{5G,2010}$ = electricity usage 5G in 2010, TWh

$S5G_{2010}$ = share of 5G of total mobile data traffic in 2010, %

MDT_{2010} = mobile data traffic per month in 2010, EB

n = 0,1,2,3…,20

$EI_{5G,2010}$ = electricity intensity 5G mobile data traffic in 2010, 0.05 (best) [136], 0.06 (expected) [136], 0.137 (worst) [136] TWh/EB.

EE = annual electricity efficiency improvement, 30% (best), 22% (expected), 10% (worst)

From 2022, for EE only, 5% is assumed possible for all scenarios [102,103].

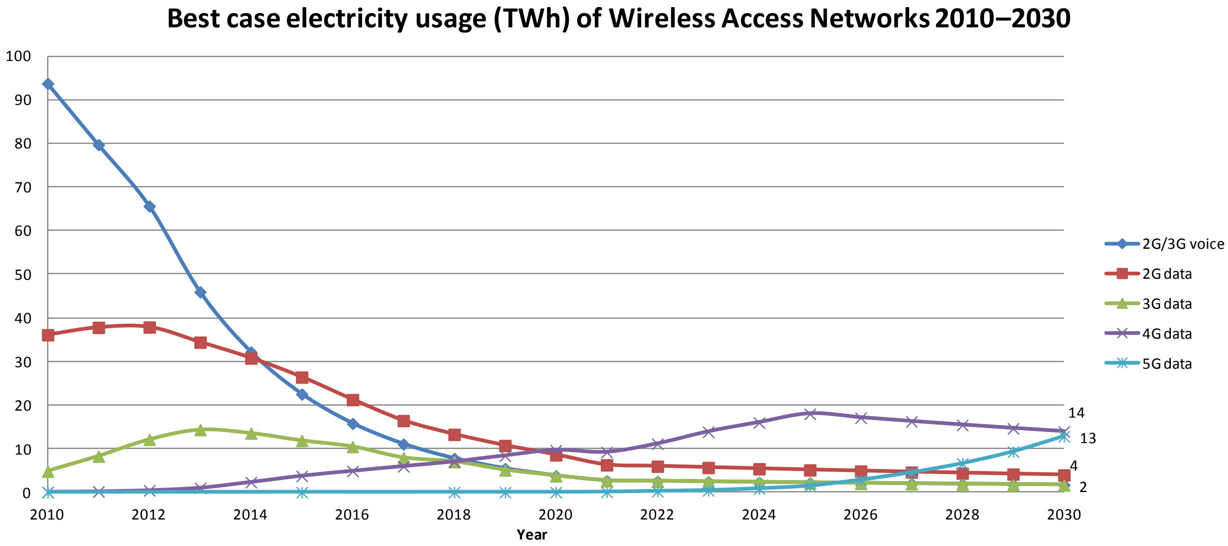
5G did not exist in 2010; however, it is still expected to gain from the efficiency improvements made for the preceding technologies over the period 2010–2020.

Equation 8 gives the WAN electricity usage (E_{w2010}), year by year, from 2010–2030:

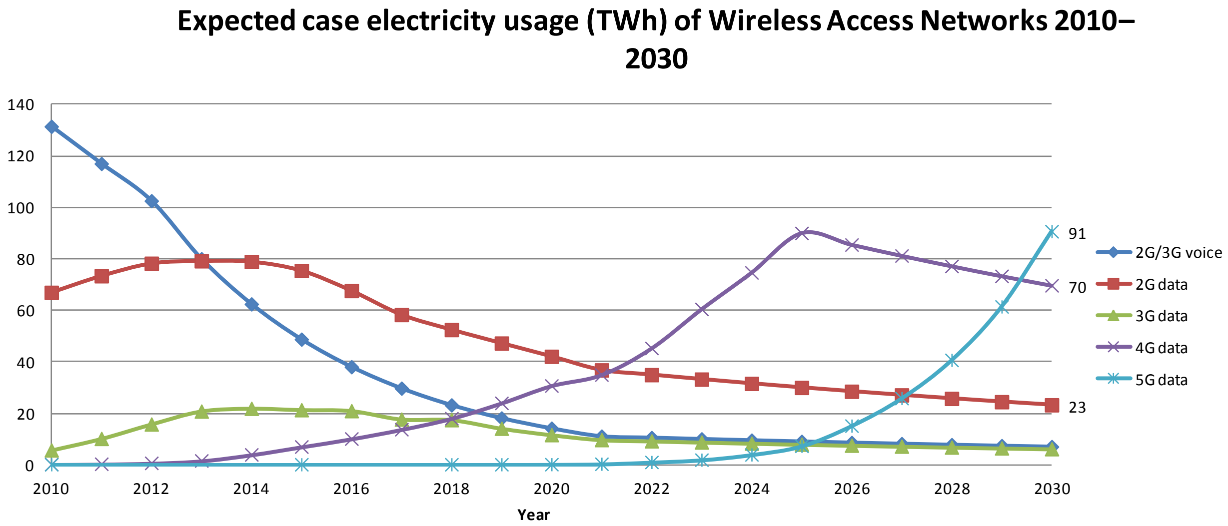
$$E_{w,2010+n} = E_{voice,2010+n} + E_{2G,2010+n} + E_{3G,2010+n} + E_{4G,2010+n} + E_{5G,2010+n} \quad (8)$$

In summary, the electricity usage of WAN from 2010–2030 is given below in Figure 3a–c. The total wireless traffic (voice + data) is 23 EB/year in 2010, 550 EB/year in 2020 and 16,000, 31,000 or 58,000 in 2030, for best-, expected-, and worst-case scenario, respectively.

As shown in Figure 3a–c, the total electricity usages are 130, 26 and 34 (best); 200, 100, and 200 (expected); and 340, 570, and 2,800 TWh/year (worst) in 2010, 2020 and 2030, respectively. The details for Figure 3a–c are shown in the Supplementary Materials file, section “WAN FAN Wi-Fi”.

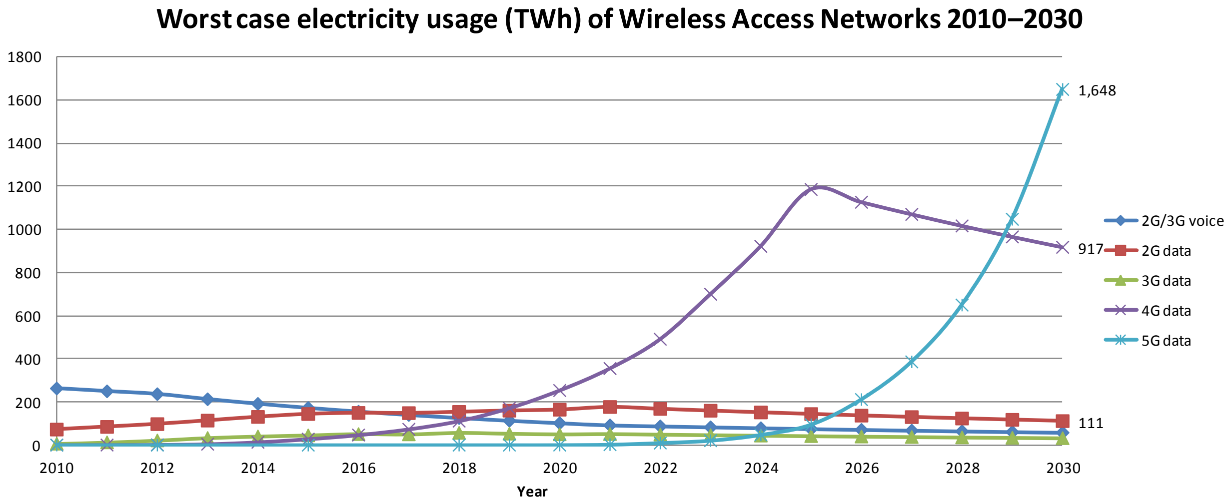


(**a**)



(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. (**a**) Global electricity demand of wireless access networks best-case scenario 2010–2030. (**b**) Global electricity demand of wireless access networks expected-case scenario 2010–2030. (**c**) Global electricity demand of wireless access networks worst-case scenario 2010–2030.

The best-case scenario, for 2010–2020, is similar to was suggested by GreenTouch [48]. Our projection for 2020 expected scenario (98 TWh) is the same as was done by Fehske *et al.* [39]. The reductions shown in Figure 3a are very sensitive to the annual electricity efficiency improvements (*EE* in Equations (3)–(7)).

5. Data Centers Use Stage—Results

In recent years, data centers have been growing from enterprise computing facilities to provide the backbone for Internet growth and, more recently, to emerge as an essential back-end infrastructure for a new generation of thin-client consumer electronics devices. Naturally, the size and scale of these data centers continues to grow and today they are seen as a key element in the next stage of growth for the ICT industry [43]. The traffic handled by the data centers (global data center IP traffic) is here defined as the sum of the "traffic from data center to user", and the "traffic within and between data centers". The "within and between data centers" traffic and growth were estimated by Cisco [138] until 2018, and the 23% annual growth from 2013–2018 is used here toward 2030. Adding the total fixed access and wireless access traffic ("traffic from data center to user"), the global data center IP traffic is expected to grow from 1,400 EB in 2010 to 80,000, 107,000 or 156,000 EB in 2030 [138].

Data center electricity usage was first studied by Koomey [139] and it has been mentioned that data centers used 1.5% of global electricity in 2010 [140]. For 2010, our back-casting estimation is 1%.

Arjona *et al.* measured the electricity usage of data center servers [141,142]. Before the amount of electricity used by data centers has been recognized [143–146]. Measures to handle and reduce electricity usage and CO_2 emissions from data centers have been widely reported [62,147–156].

For 2010, the data center electric usages ($E_{DC,2010}$) for best, expected and worst scenario are calculated by the 2010 global data center IP traffic and three different electricity per data values, 0.135, 0.14 and

0.142 TWh/EB, respectively [43]. Equation 9 describes the relation between electricity usage for each year from 2011 to 2030, global data center IP traffic, and electricity efficiency improvement:

$$E_{DC,2011+n} = \left(\frac{TDC_{2011+n}}{TDC_{2010+n}}\right) \times E_{DC,2010+n} \times \left(\frac{(100\% - EE\%)}{100}\right) \quad (9)$$

where

$E_{DC,2010}$ = electricity usage in data centers in 2010, TWh

$E_{DC,2011}$ = electricity usage in data centers in 2011, TWh

TDC_{2010} = global data center IP traffic in 2010, EB

TDC_{2011} = global data center IP traffic in 2011, EB

n = 0,1,2,3…,19.

EE = annual electricity efficiency improvement, 15% (best) [42], 10% (expected) [43], 5% (worst) [43]

From 2022, for EE only, 5% is assumed possible for all scenarios [102,103].

Data Centers are expected to improve their electricity intensity similarly to FAN. This seems, however, not enough to cope with ≈25% annual growth rate for Global Data Center IP Traffic [138]. Data Centers will use around 3–13% of global electricity in 2030 compared to 1% in 2010. However, the trend of using renewable power is strong [157,158] and likely many data centers can be run GHG efficient, even if they do not find ways to reduce the absolute electricity usage. We believe that CT driven optimization of the electricity systems is a strong trend and a prerequisite for renewable power sources. In Figure 4 below the electricity usages for data centers are shown. The details for Figure 4 are shown in the Supplementary Materials file, section "DataCenters".

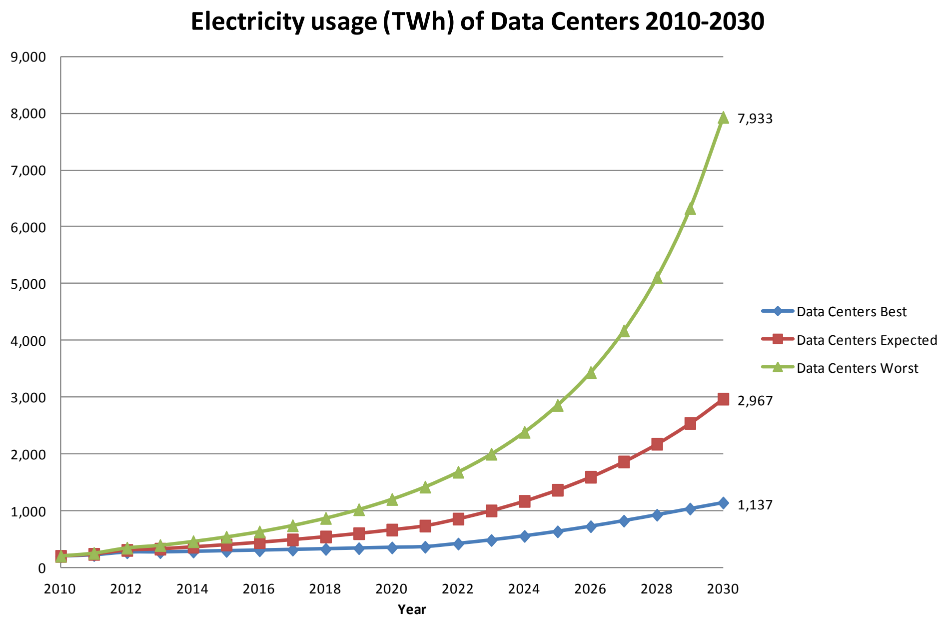


Figure 4. Global electricity demand of data centers 2010–2030.

The worst-case scenario is exorbitant, however not totally unrealistic. However, we are aware that the laws economics will probably prevent it from actually happening. As of 2013, Alcatel-Lucent estimated that service core data centers on average used 37.1 GigaWatt ≈ 325 TWh [55], which is close to our modeling for the expected scenario.

6. Production Electricity for Consumer Devices, Networks and Data Centers—Results

Production is a signification portion of the CT footprint and Vasan *et al*. found reasons to believe it could currently be underestimated in individual LCAs of electronics [159]. Ranges for the production electricity per unit of the desktop, laptop and monitor devices are derived from literature [43,71,160]. Ranges for the production per unit of the phone devices are also derived from literature [43,74,75,161].

The amounts used for producing TVs have been estimated as 250–1,700 kWh/unit [79,162–164].

For set-top boxes and the DVD players, the production electricity is estimated from LCA studies [165] and [166].

Actually, data on the annual amount of produced base stations [43], switches, and servers [167] should be collected, and the cradle-to-gate production electricity should be used to estimate the networks and data center production. Fichter and Hintemann recently started this discussion by estimating the value of the material content of German data centers [168]. Scattered data have been reported about manufacturing of data centers [169,178] and rack servers [170]. LCAs of radio base stations have been presented [171,172], which can be used in further analyses.

Equation 10 describes the relation between produced units, production electricity, and annual production electricity usage reduction for each year from 2010 to 2030:

$$E_{CDP,2010+n} = P_{CD,2010+n} \times E_{CDPu,2010} \times \left(\frac{(100\% - ER\%)}{100} \right)^{n} \tag{10}$$

where

$E_{CDP,2010}$ = Electricity for production of a consumer device category in 2010, TWh

$P_{CD,2010}$ = produced units of a category of consumer device (desktops, monitors, *etc*.) in 2010, millions

$E_{CDPu,2010}$ = production electricity for a category of consumer devices in 2010, MWh/unit

ER = annual production electricity usage reduction, 5% [173], 3% [173], 1% [174]

n = 0,1,2,3,…20

Literature sources are used for the ranges for the relation between production and use stages for FAN [29,175,176], for WAN [39,177] and for data centers [69,178]. Greenhouse Gas Protocol presented a method by which this relation can be used to estimate the production footprint, e.g. electricity usage, starting from the use data for the networks [179].

Equations 11 and 12 describe the relation between production electricity, use-stage electricity, quota between use-stage and production electricity, and annual production electricity usage reduction for each year from 2010–2030, for networks and data centers, respectively:

$$E_{P,networks,2010+n} = (E_w + E_F)_{2010+n} \times \frac{SP_w}{SU_w} \times \left(\frac{(100\% - ER\%)}{100} \right)^{n} \tag{11}$$

$$E_{P,DC,2010+n} = E_{DC,2010+n} \times \frac{SP_{DC}}{SU_{DC}} \times \left(\frac{(100\% - ER\%)}{100} \right)^{n} \tag{12}$$

where

$E_{P,networks,2010}$ = electricity for networks production in 2010, TWh

$E_{P,DC,2010}$ = electricity for data centers production in 2010, TWh

SP_w = share of production in network LCAs, 5% (best) [177], 10% (expected) [39], 15% (worst) [29,175]

SU_w = share of use stage in network LCAs, 95% (best) [177], 90% (expected) [39], 85% (worst) [29,176]

SP_{DC} = share of production in data center LCAs, 5% (best) [178], 10% (expected) [178], 15% (worst) [178,73]

SU_{DC} = share of use stage in data center LCAs, 95% (best) [178], 90% (expected) [178], 85% (worst) [178,73]

ER = annual production electricity usage reduction, 5% (best) [173], 3% (expected) [173], 1% (worst) [174]

$n = 0,1,2,3,\ldots 20$

As a consequence of Equations 11 and 12, Figure 5 below is rather imprecise for data centers and networks, which together here is assumed to constitute a high share of the total in 2030. The details for Figure 5 are shown in the Supplementary Materials file, section "Production".

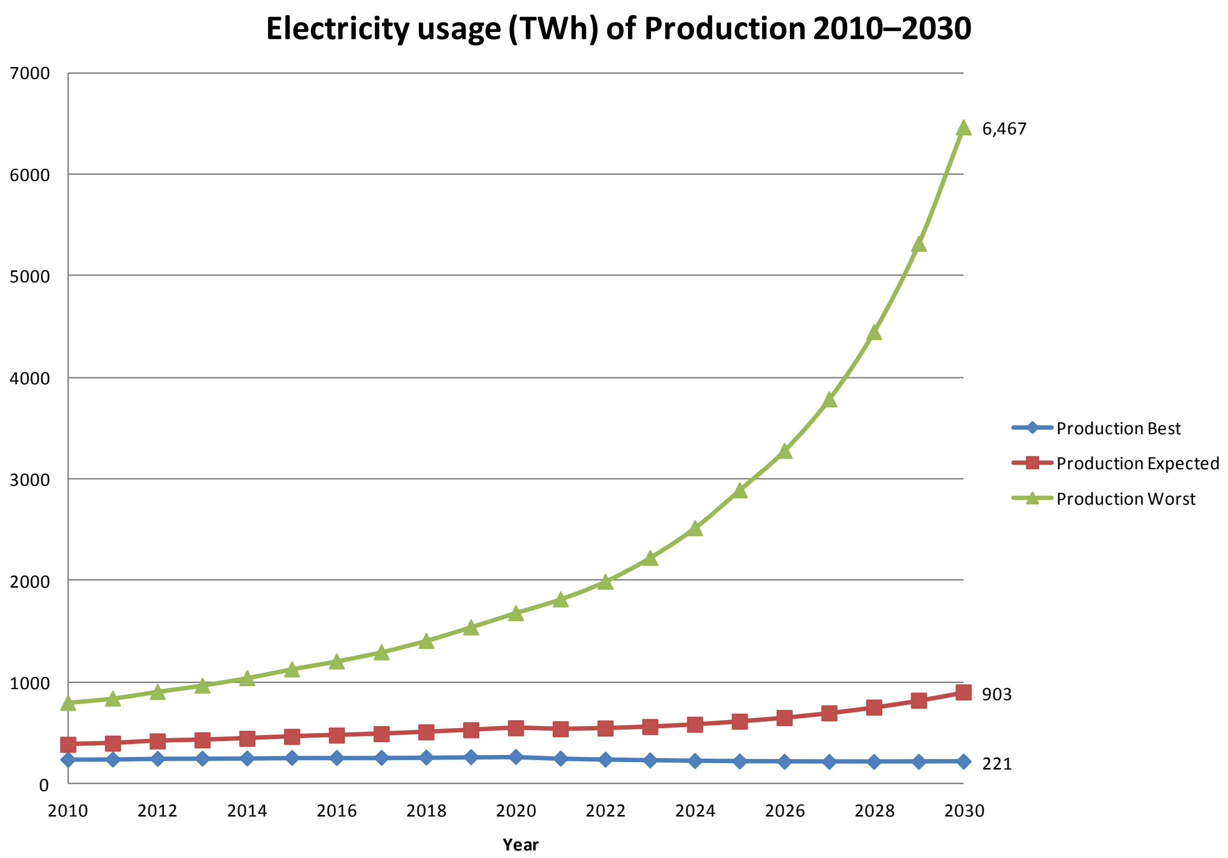


Figure 5. Global electricity demand of production of consumer devices, networks and data centers 2010–2030

7. Global Electricity Usage

It has been predicted that global electricity usage would grow by 2.8 to 3.4% per year [42,180,181]. International Energy Agency (IEA) estimated that the electricity demand in the world would rise from around 20,000 TWh to around 28,000 TWh between 2010 and 2030 [181]. However, these authors did not include the effect of the unprecedented increase of the CT infrastructure electricity usage, which is the topic of the present research. CT could presently be around 14% of global electricity usage, which is close to our worst-case scenario [182]. Apparently, there is a fundamental shift in residential electricity usage trends, particularly in the rising ownership of personal consumer electronic devices [183–185].

Based on the above references, it is assumed, for the all scenarios, that the global electricity usage that is not related to the scope of the present article, rose on an annual basis of around 3% between 2010 and 2014, and will continue with 3% annual growth until 2030, starting from around 20,000 TWh [186].

The amount of electricity used by CT (E_{CT}) is given by Eq. 13:

$$E_{CT,2010+n} = E_{CDU,2010+n} + E_{F,2010+n} + E_{w,2010+n} + E_{CDP,2010+n} + E_{P,networks,2010+n} + E_{P,DC,2010+n} \quad (13)$$

For respective scenario, E_{CT} is added to the non-CT related electricity. In this way the growth of E_{CT} is separated from the growth of non-CT electricity. The anticipated additional electricity demand driven by the electric mobility revolution is not included in our projections.

For the worst-case scenario, in 2030, the global electricity production is expected to be around 61,000 TWh, whereas the renewable power supply is expected to be ≈18% of global electricity usage, ≈11,000 TWh, as shown in Figure 7. Then, in 2030, the average global electricity GHG intensity will be between 0.54 and 0.65 Megatons/TWh. In 2010, world average electricity released 0.623 Megatons CO_2 equivalents per TWh [187].

8. Renewable Electricity

According to IEA, in 2009, renewable power was ≈20% of global electricity usage or ≈4000 TWh [186]. Moreover, IEA predicted in 2010 for China that between 2010 and 2035 the share of low carbon power sources could go from 19% to 78% [186]. We then assume globally that renewable electricity is set to grow annually 5% between 2010 and 2030 [188].

In Figure 6 below are shown the approximate amount of total electricity usage and the amount produced from renewable sources between 2010 and 2030. The details for Figure 6 are shown in the Supplementary Materials file, section "Future 2030".

9. Overall Results

When the above category results shown in Figures 1–5 are synthesized according to Equation 13, the following graphs, Figures 7 and 8, appear. The details for Figures 7 and 8 are shown in the Supplementary Materials file, section "Future 2030".

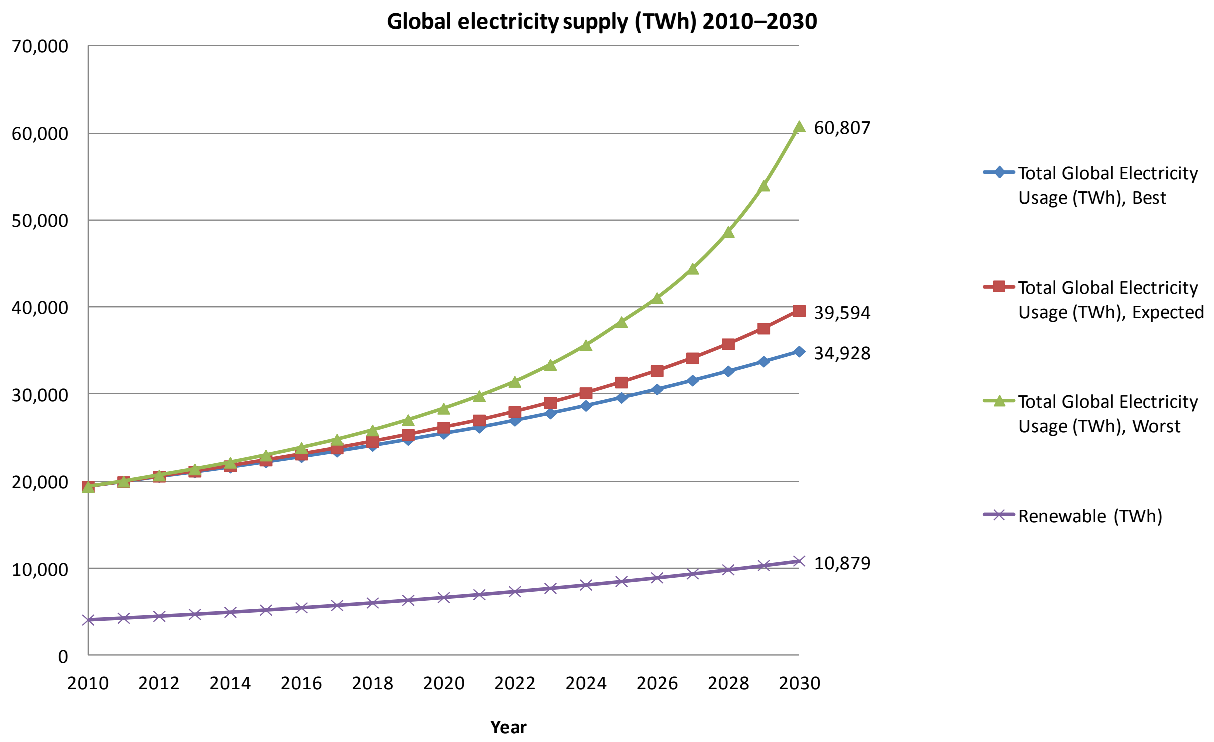


Figure 6. Global electricity supply 2010–2030

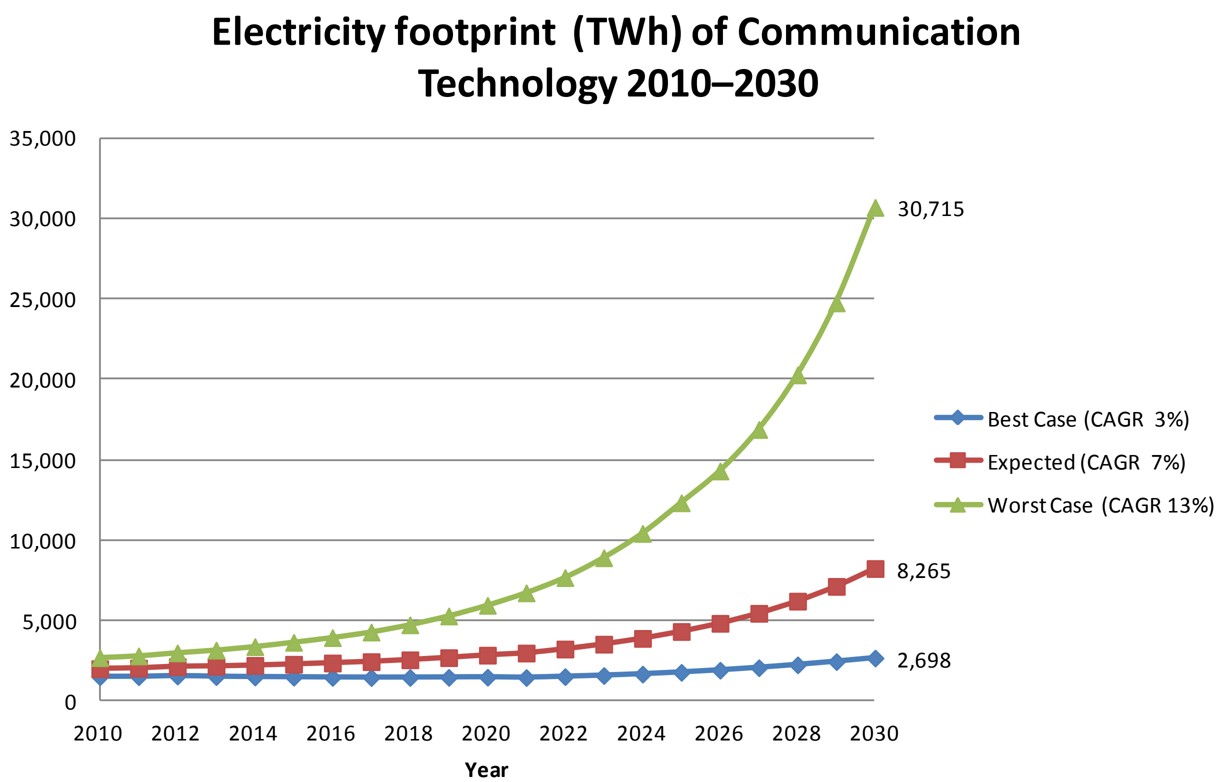


Figure 7. Global electricity demand of communication technology 2010–2030.

As shown in Figure 8 below, the share of CT Sectors, depending on scenario, in 2010 is 8%–14%, in 2020 6%–21% and in 2030 8%–51%, respectively.

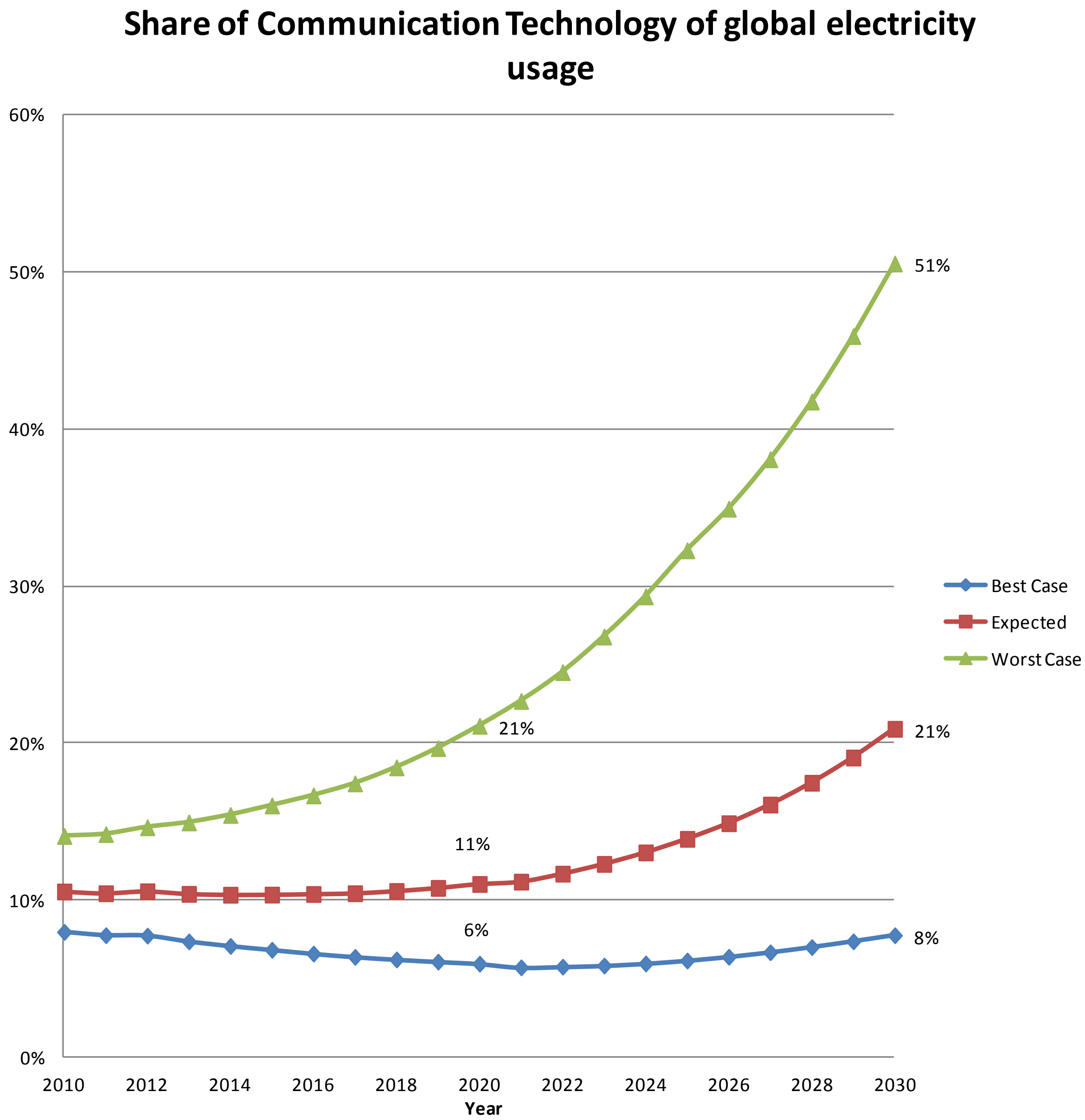
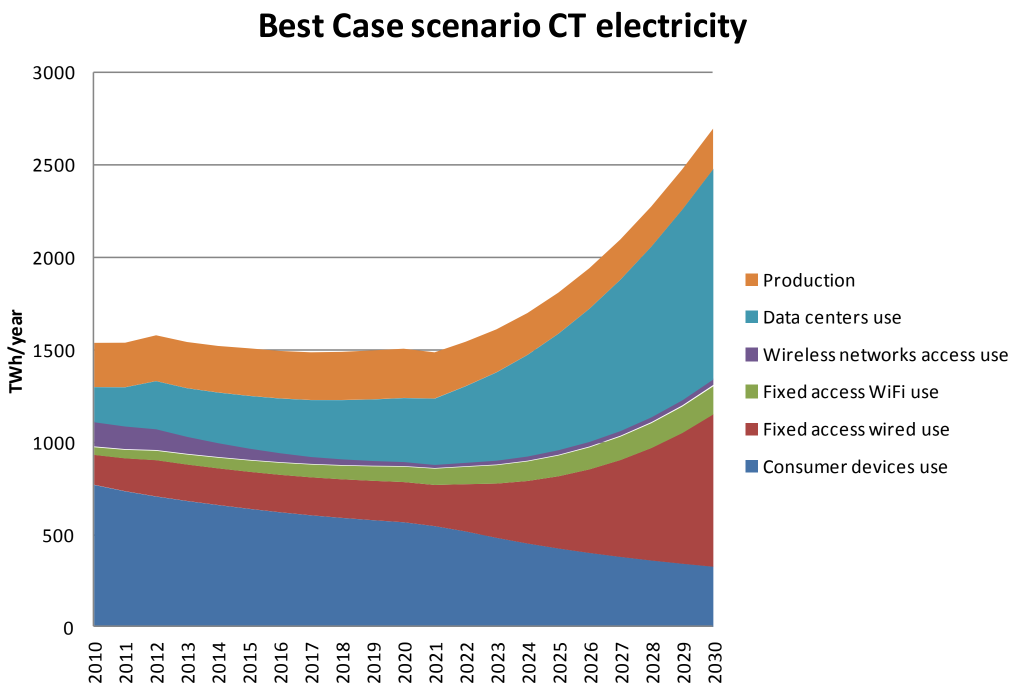
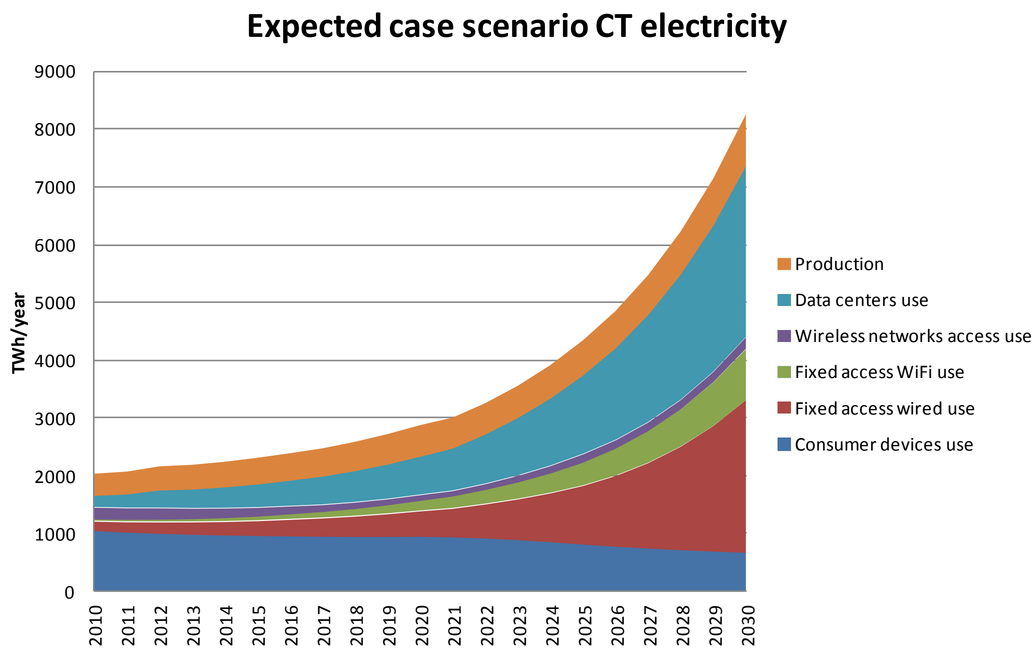


Figure 8. Share of communication technology of global electricity usage 2010–2030

Figure 9a–c show the growth trends of worldwide electricity usage of CT categories for the best-, expected- and worst-case scenarios. The details for Figure 9a–c are shown in the Supplementary Materials file, section "Future 2030".

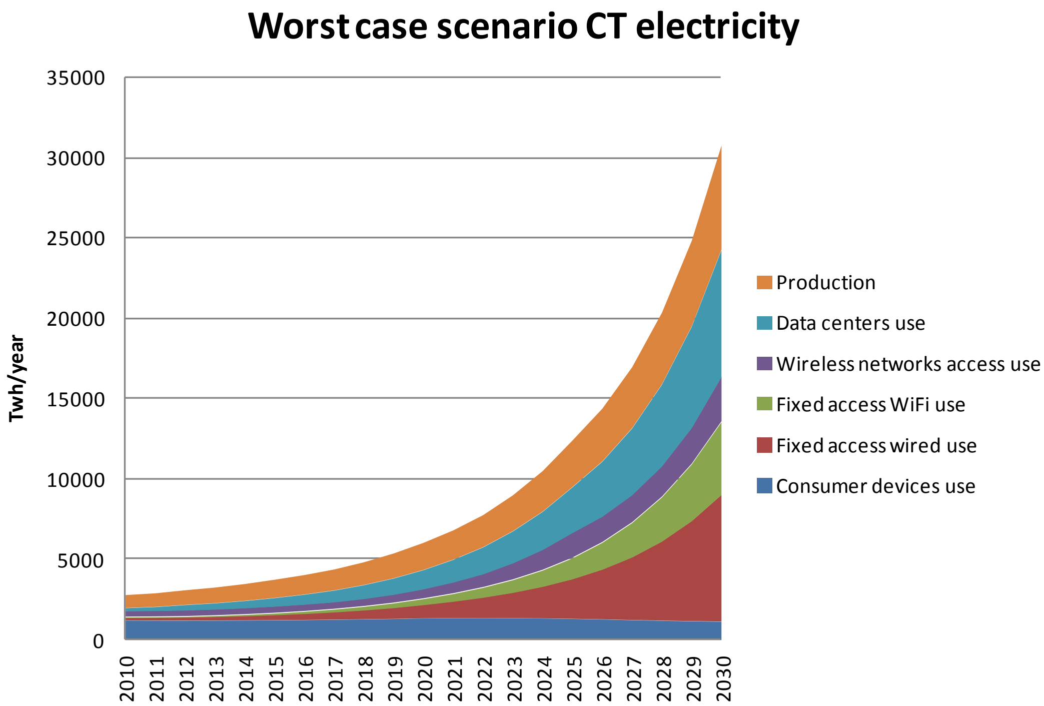


(a)



(b)

Figure 9. *Cont.*



(**c**)

Figure 9. (**a**) Trends per CT category for best-case global electricity usage 2010–2030. (**b**) Trends per CT category for expected-case global electricity usage 2010–2030. (**c**) Trends per CT category for worst-case global electricity usage 2010–2030.

10. Discussion

We believe that by including three scenarios, with wide, albeit realistic, assumptions in a top-down approach, a fair view of the coming electricity usage of communication is captured. The top-down modeling was chosen for FAN, WAN and data centers as the present scope is judged to be too large [96] to measure, and/or collect measurements for each type of CT equipment. We do not know in detail how each device and its usage transform over time, and therefore top-down is more suitable than bottom-up. The worst-case scenario is dramatic, and might not happen due to financial costs. However, with a high likelihood, the electricity usage for CT will develop somewhere along an average of the best and expected-case scenarios.

Our projections, shown in Figure 9a–c, especially for the best and expected scenarios, are well in line with other recent studies predicting the development between 2010 and 2020 [46]. For example, it was recently projected that ICT will take a global share of 14% of electricity usage by 2020, compared to its 4.7% share in 2012 [49]. As shown in Figure 8, our prediction is 6, 11 or 21% in 2020. Hoang *et al*. mentioned 14% in 2014 [182].

Apparently there will be a shift of the electricity usage from consumer device use onto the networks and data centers. Anyway, surprisingly, WAN are just 3% of the networks use in best-case 2030 and 6% in the expected-case, however, 18% in the worst-case scenario. The results shown in Figure 9c imply that the data centers and FAN could drive a staggering 66% of the global CT electricity use in 2030, with fixed access Wi-Fi 15% and data centers 26%. For a study on the primary energy demand of video streaming in the United States, Shehabi *et al*. concluded that the data centers were negligible, and the use of networks and consumer devices were the main contributors [189]. This example shows that different findings might emerge from top-down analyses, like the present investigation, and bottom-up analyses of individual CT services. This is not surprising, as the dominating power consumption depends on the circumstances surrounding each specific investigation [20].

The result for fixed access wired could be over-estimated due to too high starting values for TWh/EB in 2010–2012. However, our starting values are based on [41] and Cisco traffic [88]. Moreover, the production electricity worst-case is too much dependent on the imprecise way of estimating the FAN, WAN and data centers.

It can, moreover, be argued that the present capacity-based modeling is not suitable for all parts of CT, such as customer premise equipment, which might benefit from "power per user" modeling [96].

Moreover, the parameters of the three scenarios could be combined to derive more outcomes, e.g. worst assumed traffic growths combined with best-assumed efficiency gains.

TVs, desktops and monitors electricity usage have shown a remarkable decline in the United States between 2010 and 2013 [68,69]. It remains to be seen if the United States overall annual decline rate of 5% [68,69] for consumer devices can be kept globally in the coming decade, as assumed for our best-case.

10.1. Battery Electric Vehicles Additional Electricity Usage to the Global Total

Will the anticipated high growth of sales and usage of battery electric vehicles (BEV), which is unaccounted for in our electricity projections, add a significant amount of electricity usage to the global total? In 2010, globally, around one billion cars were in operation [190]. The annual growth rate has been estimated at 1.7–2.7% [191–193], suggesting that around 1.4 billion cars will be in operation in 2030. However, in 2014 the share of BEVs was still negligible at 400,000 [194]. The electricity usage of BEVs is around 10–20 kWh per 100 kilometer [195] and the current average kilometers driven per car per year is around 18,000 [196–199]. Hence, if 25% [200] of all cars in 2030 are BEV, their electricity usage would be some 1,260 TWh, *i.e.* around 3% of total global electricity usage. This suggests that the electricity demand of BEV is not a large source of error in the present research.

10.2. Bottom-Up Estimation of Generated Mobile Data Traffic in 2030

The amount of generated mobile data traffic is hugely important for the electricity use of WAN. Therefore a sanity check calculation (summarized in Table 1, with more details in Supplementary Materials file, section "Traffic generated by devices") is done to understand if the mobile data traffic assumptions, 16,000 to 58,000 EB until 2030, are in the right order of magnitude. This is done via assumptions on global population and the generated traffic by mobile wireless consumer devices from watching so-called 8K three-dimensional (3D) video, 4K 3D ultra-high definition video, and 2K format.

The values 8K, 4K, and 2K refer to display devices, or content, which have a horizontal resolution on the order of 8,000, 4,000 or 2,000 pixels, respectively. Watching video content in 8K format is expected to be the service that will demand the most bandwidth, and thereby generate the most mobile data traffic.

In 2030, the number of mobile devices in use per citizen is assumed to be 1.4 (penetration 140%), and the number of citizens, is assumed to be 7.61 billion, expected to rise by 0.52% per year between 2010 and 2030 [201].

Equation 14 describes the relation between annually generated mobile data traffic by a category of mobile consumer devices (MCD), shares of the category of MCD, which use a certain service, total number of used MCD, bandwidth required for the service, and hours using the service:

$$MDT_{2030} = SCDS_{2030} \times TCD_{2030} \times \frac{BWS}{8} \times \frac{10^9}{2^{40}} \times HCD_{day} \times 3600 \times 365 \quad (14)$$

where

MDT_{2030} = global mobile data traffic generated from a consumer device, EB

$SCDS_{2030}$ = share of consumer device at hand (e.g. tablet) total mobile consumer devices in use in 2030, %

TCD_{2030} = total number of mobile consumer devices in use in 2030, 10.66 billions

BWS = Bandwidth required for service, Megabits per second

HCD_{day} = daily hours using service, 1.5 hours.

Table 1. Mobile data traffic generated by consumer devices in 2030.

Use mode service	$SCDS_{2030}$	HCD_{day}	BWS	MDT_{2030}
Tablets for 8K 3D video	10%	1.5	120	28,700
Phablets for 4K 3D video	30%	1.5	15	10,700
Smartphones for 2K video	10%	1.5	2	480
Mobile broadband modems + laptop for 8K 3D video	2%	1.5	120	5,700
Triple play wireless router for 8K 3D video	2%	1.5	120	5,700
SUM				51,400 EB

The sum of 51,400 EB is around 89% of the worst-case generated mobile data traffic in 2030. This check demonstrates that the mobile data traffic could rise enormously in the coming 15 years.

Normalization—Electricity Intensities of Fixed, Wireless and Data Centers

The total usage numbers are here normalized per data. As shown in Table 2 for wireless subscribers, the values are currently some kWh per GB.

Table 2: Electricity intensity roadmap for networks and data centers 2010, 2020 and 2030.

	2010 (kWh/GB)	2020 (KWh/GB)	2030 (KWh/GB)	Reduction of electricity intensity 2030 compared to 2010
FAN wired	0.50	0.11–0.28	0.061–0.17	66%–87%
FAN Wi-Fi	0.36	0.07–0.17	0.014–0.10	72%–96%
WAN	6–15	0.047–1.04	0.002–0.048	>99%
Data centers	0.13–0.14	0.027–0.085	0.014–0.051	64-89%

The numbers in Table 2 are in line with other international estimations [27,99,101,202].

10.3. Improvement of Electricity Efficiency for Electricity Usage and GHG Reduction

Which levels of improvements of the electricity intensities, for the best-case scenario, would be necessary to keep the electricity usage flat until 2030? As shown in Figures 1–5 above, the suggested annual improvements of the electricity intensities are absolutely necessary, however likely not enough, for halting the total CT electricity usage.

- The necessary electricity efficiency for FAN wired in 2030, to keep its electricity usage at the 2015 level, is 0.18 Mbits/J (intensity 0.015 TWh/EB).
- The necessary electricity efficiency for FAN Wi-Fi in 2030, to keep its electricity usage at the 2015 level, is 0.47 Mbits/J (intensity 0.0056 TWh/EB).
- The necessary electricity efficiency for data centers in 2030, to keep the total data center electricity usage at the 2015 level, is 0.66 Mbits/J (intensity 0.004 TWh/EB).

For FAN Wi-Fi, 28 times improvement of the TWh/EB between 2015 and 2030 is necessary to keep electricity usage at 2015 level, while 11 times improvement is predicted.

For FAN wired and data centers, 17 times improvement of the TWh/EB between 2015 and 2030 is necessary to keep electricity usage at 2015 level, while four times improvement is foreseen.

- The necessary electricity efficiency for 5G WAN in 2030, to keep the total wireless electricity usage at the 2020 level, is 2.9 Mbits/J (intensity 8.9×10^{-4} TWh/EB).

For 4G WAN, 50 times improvement of the TWh/EB between 2015 and 2030 is necessary to keep electricity usage at 2015 level, while four times improvement is foreseen.

From the present analysis, it can also be concluded that electricity intensity improvements will likely not be enough for reducing GHG emissions related to the CT sector.

10.4. Renewable Electricity Capacity for Greenhouse Gas Emission Reduction

Using renewable electricity is theoretically an effective way to reduce GHG emissions. In 2030, theoretically, the generated renewable electricity (≈11,000 TWh), will, with some likelihood, exceed the electricity demand of all networks and data centers (2200 to 23,100 TWh).

However, presently, the lack of flexibility and availability in the electricity system prevent the full potential of renewable power supply [23]. Nevertheless, more CT usage is part of the solution to these problems, too [203]. To mitigate the worst-case scenario for climate change related to CT, the challenges related to introducing renewable electricity need to be overcome.

11. Conclusions

This work presents an estimation of the global electricity usage that can be ascribed to Communication Technology (CT) between 2010 and 2030. The scope is three scenarios for use and production of consumer devices, communication networks and data centers. Three different scenarios, best, expected, and worst, are set up, which include annual numbers of sold devices, data traffic and electricity efficiencies/intensities. The most significant trend, regardless of scenario, is that the proportion of use-stage electricity by consumer devices will decrease and be transferred to the networks and data centers. Still, it seems like wireless access networks will not be the main driver for electricity use. The analysis shows, for the worst-case scenario, that CT could use as much as 51% of global electricity in 2030. This might happen if not enough improvement of the electricity efficiency of wireless access networks and fixed access networks/data centers is possible. However, until 2030, the globally generated renewable electricity is likely to exceed the electricity demand of all networks and data centers. Nevertheless, the present investigation suggests, for the worst-case, that CT electricity usage could contribute up to 23% of the globally released greenhouse gas emissions in 2030.

12. Next Steps

Forecasting a trajectory for 2030 is challenging, no matter the target of the prediction. Still, there are enough data to make a forecast of CT electricity possible. Nevertheless, below are suggestions for complementing the understanding on where CT is heading.

- Individual nations' progress [44,51,53] are summed to get a better precision of the global footprint, combined with more scenarios.
- Effect of circular economy business cases, which affect the lifetime of devices.
- Improvement of the production electricity estimation for networks and data centers by using numbers on produced hardware, such as base stations and servers.
- Apart from electricity and climate change, include other indicators for CT, such as primary energy, and eco-environmental impact categories, such as resource depletion and land use.
- Include transportation and end-of-life treatment activities.
- Correlate the findings of this paper with estimations of the amount of electronic waste [204] to be generated until 2030
- Include the enabling effect of CT [25–28] in the calculation.

Acknowledgements

Peter M. Corcoran of National University of Ireland, Galway, Ireland, is acknowledged for inspiration. Anonymous reviewers are greatly appreciated for comments, which improved this paper.

Author Contributions

Andrae wrote the paper and Edler contributed with Equations 1,10–12, as well as ideas and input data for the wireless traffic discussions in clause 4.2, the electricity growth in clause 7 and the overall discussion in clause 10.

Conflict of Interest

The authors declare no conflict of interest.

Supporting Materials

In the freely available Excel file in the Supplement Materials, all detailed numbers and calculations can be found.

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