Emerging Trends in Electricity Consumption for Consumer ICT

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Article Summary

Since 2009, several emerging technologies have initiated broad and disruptive impact across the ICT sector: cloud computing promises efficiency of scale both in terms of capital and operational costs; high-speed wireless networks promise near-ubiquitous network access and thin-client solutions (smart-phones and tablets) provide appropriate, low power user-interfaces to take advantage of this emerging next-generation ICT infrastructure. But despite claims that this new consumer ICT infrastructure can reduce the overall energy costs of society's new digital lifestyle, there are few studies that encompass the total energy costs of consumer ICT devices and the supporting communications networks and associated data centers that have become so essential.

This work brings together the work of many prior researchers, while also introducing a number of new methodological approaches to estimate growth in the portion of global electricity consumption that can be ascribed to digital consumer devices. Baseline estimates for the main categories of consumption - direct, manufacturing related, network-related and data-center related - are determined for 2012. A number of methodological approaches are outlined to extrapolate trends over the period 2013-2017 and projections based on *best-case*, *expected* and *worst-case* scenarios are provided.

Key trends are identified. The most significant of these, which applies in all three scenarios explored in this work, is that the proportion of direct electricity consumption by devices will drop from c. 50% to 35% or less. Thus there is a strong trend to push electricity consumption onto the network and data center infrastructure where energy costs are less transparent to consumers. Some challenges are identified for networking and data-center sectors. Of these the global roll-out of LTE will be a crucial determinant of future electricity demand.

There is a basis for significant optimism as new technologies in the TV panel and display industries, combined with the replacement of desktop computers with laptops and thin clients should lead to an overall drop in the direct energy usage of ICT devices. Our best-case analysis shows a decline in consumption from 7.4% in 2012 to 6.9% of total global electricity consumption in 2017; however the worst-case shows a rise to 12.0% driven primarily by expansion of the network and data-center infrastructure.

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1. Introduction

Sales of ICT devices - laptops, home computers, their associated peripherals (networking, storage and display) dominate market share and recent growth in the consumer electronics industry [1]. ICT markets have been driven by the consumer sector for some time now. With recent explosive growth in markets for new ICT devices - smartphones and tablets in particular - and the transition of the television from a basic receiver into a digital media center and entertainment hub these 'digital' consumer devices now dominate global sales of consumer electronics. Throughout the remainder of this paper we refer to this broad category of devices as as CE-ICT 'appliances'.

Since 2008, several emerging technologies have initiated broad and disruptive impact across the ICT sector: (i) cloud computing promises efficiency of scale both in terms of capital and operational costs [2–5]; (ii) high-speed wireless networks promise near-ubiquitous network access [6–9] and (iii) thin-client solutions such as smart-phones and tablet devices provide appropriate, low power user-interfaces to take advantage of this emerging next-generation ICT infrastructure [10]. There are strong improvements in energy efficiency promised both in terms of computational efficiencies [2], [11], [12] and data storage [13–15].

The main question we seek to answer in this paper is whether this new consumer ICT infrastructure can actually reduce the overall energy costs of society's new digital lifestyle, or is it simply catalyzing a substantial rebound effect that could skyrocket ICT-related energy costs over the next decade?

Throughout this article we employ the term *energy usage* as interchangeable with *electricity consumption* - practically all of the energy that is utilized by today's manufacturing industry, communications networks, data centers and the CE-ICT devices themselves is derived from the electricity network. It is also useful to be able to estimate the percentage total of global electricity consumption that is dedicated to support CE-ICT devices and the associated infrastructure.

Overview of this Work

To reach this answer we begin with a review of the underlying global electricity usage that can be ascribed to electronic consumer and ICT devices. Based on the work of previous researchers [16], [17] we present a methodology where electricity consumption from ICT devices is divided into 4 principle categories - (i) client devices, including PCs, laptops, TV and home entertainment systems; (ii) network infrastructure; (iii) data center computation and storage; and lastly, (iv) device manufacturing/replacement energy costs. We then proceed to evaluate the current and projected energy consumption in each of these categories using, where practical, more than one methodological approach.

Section 2 provides more background and context to this growth in energy usage by CE-ICT devices. We discuss the rapid growth in the numbers of these devices, particularly thin clients such as smartphones and tablets; the increasing reliance by such devices on network services and the emergence of cloud-computing as a consumer resource are discussed.

In section 3 the approaches of past and current researchers are considered. The different components of electricity usage driven by CE-ICT devices are considered and a unified approach to evaluating the overall energy impact of these devices is presented. We then consider the work of a range of past researchers from different fields and develop some alternative methodologies to provide different approaches to estimate the different components of CE-ICT electricity usage.

In section 4 data from the period 2008-2012 is matched with market predictions for new client devices and network infrastructures and used to determine a baseline estimate for each of the four main contributing components of electricity consumption - (i) direct consumption; (ii) manufacturing consumption; (iii) network consumption; (iv) data center consumption.

Then in section 5 these baseline values are extrapolated to estimate consumption trends over the period 2012-2017. Three different growth scenarios are employed - best-case, expected and worst-case analysis with detailed assumptions provided for each. Section 6 reviews the main trends that can be determined from this analysis.

To facilitate comparison with the work of previous researchers we include both industry and residential ICT and some non-networked consumer electronics in our methodology. This allows some understanding of how consumption patterns are changing as we transition to a home environment where most appliances – even traditional white goods such as refrigerators and washing machines - will be network connected. Our work is placed in context with a range of contributions from earlier researchers and serves to emphasize the rapidly growing significance of the CE-ICT sector as a global energy consumer.

Note that a key goal of this work is to outline a framework for evaluating future electricity growth patterns. Thus, while we present a broad range of possible future outcomes, these are supported with quite detailed sets of assumptions. It should thus be possible to review our work and assumptions retrospectively and identify where our approach has aligned usefully with future growth patterns and where it has not.

Units of Energy

An important aspect of this article is to find a common metric that is suitable for quantifying the energy usage of CE-ICT. Across different fields we find different units are employed.

In the field of communications it is common to use the metric of joules/bit, or more typically for modern communications networks the working unit is micro-joules/bit (μJ/bit). In earlier work several researchers [16], [17] adopted the instantaneous units of gigawatts (GW), while others [18], [19] have focused on the power consumption in kilowatts per subscriber or household.

As our interest is in the total energy consumption, and as this is invariably provided in the form of electrical energy we have adopted the measure of terra-watt hours per year (TWh/yr) as used by Lambert et. al [20] in their study on communications networks. All data presented in this work is converted to these common base units. Note that our interest is in the total usage/consumption and thus per-device, or per-user metrics are scaled to reflect the installed base of devices, or the estimated/measured user-base.

2. Background & Context

2.1 A Global Perspective on Electricity Consumption

Apart from a small annual decrease of 1.1% in 2009 [21], global electricity consumption continues to rise on an annual basis [22]. In the residential sector governments have responded with significant success by implementing policies designed to achieve long-term market transformation in the supply and adoption of energy efficient appliances. As a consequence the overall growth in electricity consumption in the residential sector has been kept at acceptable growth levels over the past decade. However in 2010 there was a disturbing 6.5% increase in electricity consumption over 2009 indicating that new trends may be displacing the significant success of past governmental policies to constrain growth in electricity consumption [23].

In OECD countries those appliances that previously used the majority of electricity, such as refrigerators, clothes washers and water heaters, are close to saturation levels and the net electricity consumption per appliance has seen significant improvement across the OECD [24]. However there appears to be a fundamental shift in residential electricity consumption trends, particularly in the rising ownership of personal information and communications technologies (ICT) and consumer electronics (CE) devices. In 2009 this group of appliances accounted for approximately 15% of residential electricity consumption [24].

2.2 The Growth of Consumer ICT

While the market for many traditional CE appliances is stagnant in OECD economies, the growth of consumer ICT is strong, showing a 50% growth rate over the period 2007-2012 [1]. When combined with mobile & personal entertainment CE devices (digital imaging, communications & gaming appliances) these segments represent more than 70% of sales in the consumer electronics sector in the US.

Growth in the CE sector has been further catalyzed by new network connected devices such as smart-phones, tablet computers and more recently, smart-TVs. Interestingly these new devices appear to have created new modes of usage that encourage multi-device ownership.

Throughout the remainder of this paper we will refer to these devices as 'consumer electronic-ICT' (CE-ICT).

In parallel there has been an even more rapid growth in the provision of online services designed to cater for the demand for content streaming, data storage and management driven by these 'new' devices. In turn this has led to wide-scale deployment of large data centers and the associated networking infrastructure by industry. This phenomenon is generically presented as the practical realization of 'cloud computing' [25] and provides a strong synergy for new CE-ICT devices [16].

2.2.1 CE-ICT Device Trends

A key element of the 'new' generation of ICT devices is that of network connectivity. Typically these devices are either consumers or producers of digital audio/video and their development owes much to improved coding and decoding technologies. Recent growth has been further catalyzed through new network services – making access to content of acceptable quality much easier and faster than was heretofore possible.

Smartphone sales were 800 million units in 2012 [26] and while growth must inevitably slow the current trends suggest that close to 100% adoption will be the norm in developed economies and with downwards pressures on unit costs and subsidies from service providers these devices will likely be affordable to in most developing economies.

Multi-device ownership is also likely to be the norm. Tablet computers have established their own place in the living room [27]. Within a family it is common for children to own or have access to multiple connected devices prior to being considered old enough to own a smart-phone – a handheld gaming terminal, a personal music/video player and dedicated gaming consoles. In addition most families in the OECD will have multiple desktop or laptop computers.

2.3 The Role of the Network

The role of the network as an 'enabler' for new CE-ICT devices has already been noted [1]. But the rapid growth in device numbers is in turn responsible for driving data traffic on networks [28], [29]. And as can be seen from Fig 1 the bulk of network traffic is generated by consumer activities.

But the network is also a significant source of energy consumption. In fact one recent study [20] suggests that communications networks are responsible for 3.5% of global electricity consumption and that 2.6% of that is directly attributable to consumer activity. It is also arguable that improvements in network services have catalyzed growth in the CE-ICT sector, in particular encouraging recent rapid growth in thin client devices such as smart-phones and tablets. In turn this growth will drive further demand for faster and more ubiquitous network service. Thus networking has come to represent a very significant component of electricity consumption that is directly linked to CE-ICT devices.

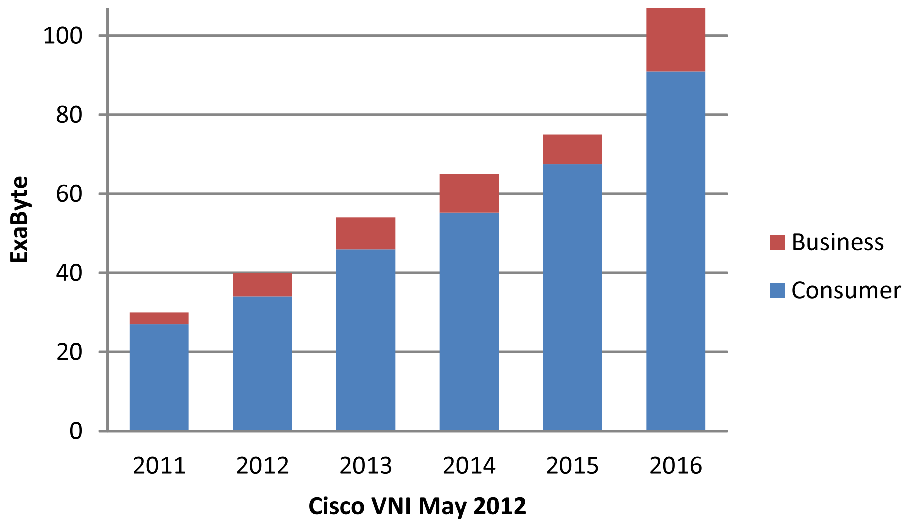


Figure 1: Consumer Vs Business Network Traffic (2011-2016); source [28].

2.4 Cloud Computing & Data Centers

Data centers have already achieved some notoriety in both academic and popular press as a growing source of energy consumption [30]. More recently there has been some evidence of significant improvements in efficiencies within data-centers [31]. Nevertheless it is clear that the volume of data being handled by such centers is growing at unprecedented rates [29] and is likely to be increasingly influenced by new growth patterns in consumer data traffic as shown in **Figure 1** above. Note in particular that consumer data growth is significantly outpacing that of business/industry users.

This particular aspect of electricity consumption represented about 1.5% of global electricity consumption in 2010 [31] [32]. However it is difficult to obtain direct information on the trends that are influencing this sector since 2010. Historic growth rates vary from 12% [17], [30], [33] to 8% [31]. We will comment further on this later and propose some approaches to obtain sensible estimates for future growth.

3. Categorization of Energy Consumption; Methodological Considerations

For this paper we have chosen a framework that is loosely based on that presented by the authors of [17]. They have provided three device categories for direct energy consumption – computers, TVs and other devices. In addition they define a distinct category for network equipment and also for the energy consumption at the data center.

While we broadly follow these 5 categories but introduce some changes to facilitate our subsequent analysis. Device consumption is merged into a single main category, and a new category is introduced to cover the embodied lifecycle energy of each device type. This effectively adds the manufacturing energy of devices into our analysis and is important because the embodied manufacturing energy is significant when compared with the lifetime operating energy for most electronics products. This is especially the case for short lifecycle products such as mobile phones and many ICT devices where the manufacturing, or embodied energy can be greater than the lifetime operating energy [34]. The communications (network) costs associated with device use are also accounted for and account is also taken of the growing phenomenon of cloud computing as this is a key enabling technology for newer thin client appliances [16]. A more detailed discussion on each of these categories is provided below.

3.1 Direct Energy Consumption by Devices

In the context of our analysis the direct electricity consumption by devices should apply to CE-ICT devices. However some earlier researchers have included other device categories in their results so we will also consider non-ICT device categories with a view to making comparisons. It is also important to understand how changing patterns of device usage within the home may be affecting electricity consumption.

3.1.1 Discussion and Related Literature

A very useful report was commissioned by the *Consumer Electronics Association* and executed by the *Fraunhofer Center for Sustainable Energy Systems* [35]. This report is particularly valuable for its methodological analysis of the usage patterns of a wide range of CE devices. This study also provides an estimated average electricity usage for each device category. We remark that these are provided in the context of the US, but they provide a useful basis from which we can extrapolate to a more global consideration of electricity consumption. Some more recent data is also available from the SMARTer 2020 report [36]. The values provided in this report align well with those in [35] and we shall discuss these further in section 4.1.2 when we present an electricity consumption model based on the installed base numbers for various devices.

3.1.2 TV and Viewing Devices

Our first category matches closely with Pickavet's TV category [17]. As a baseline we estimate the global number of TV sets in service to lie somewhere in the range of 1.8 and 2.0 billion units. Despite growth projections of 5%-8% back in 2010 [1], the annual sales of TV display panels has stabilized around the 250 million mark [37][38] for the last 2-3 years which is consistent with a unit life-cycle of approximately 8 years.

One significant change that we have seen is the switch-over to connected TVs. Again this has not been as significant as the 100 million units predicted for 2013 [16] but 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 HDMI appliances that can provide this connectivity for existing TV panels.

Another significant change that was not anticipated in 2011 [16] has been the substantial improvement in energy performance of individual TV panels. The authors of [17] used a figure of 330 Watts for a Plasma TV and 190 Watts for LCD TV. Today's state of art LCD panels are typically less than 100 Watts due to a transitioning to LED based displays – a transition that is in the process of being effected across the industry in a remarkably short 4 year period [37]. Emerging technologies such as field emission display offer potential for continued improvements for the future [39].

3.1.3 Client ICT Devices

This second primary device category follows closely on that of [17] but we have decided to extend this to include devices such as smart-phones and tablet computers. Admittedly the overall contribution of such devices to direct electricity consumption is relatively small, but their rapidly growing numbers, and the fact that many households have multiple devices suggests that they should be included in our estimates.

We also remark that the latest models of tablets are taking advantage of improvements in battery technology to allow greater charges to be carried and to support brighter and higher density display technology. While we do not expect this to be a long-term trend some high-end tablet devices have essentially doubled their charge capacities in the latest models [40]. Eventually we might expect to see such improved battery technology deployed across all smart-phone and tablet models. Thus, in contrast with other CE-ICT devices the energy consumption per device of such thin clients is likely to grow over the next few years to accommodate improved screen and CPU technology and emerging high-speed wireless connections to the network.

Markets for desktop and laptop computers can be regarded as essentially stagnant or declining in developed OECD economies, but there is some overall growth from developing economies [16], [41]. We note that this is less than previously estimated [16], most likely due in part to recent stagnation in the global economy and also because of the rapid adoption of thin clients by the consumer sector. Again we can use estimates from [35] as a basis for global calculations. This study shows a strong transition from desktop to laptop between 2005 and 2009. Now there are more laptops sold worldwide than desktops.

At the time of this study the installed base of desktop computers in the US was about 100 million and for laptops the figure was about 132 million. Worldwide the number of computers sold is stagnant around the 350-400 million mark [16], [41], [42] and despite growth in developing economies we expect that worldwide these will be stable, or even declining. The initial evidence from 2013 is for a significant decline during the year [43].

From [35] we have an annual estimate of energy usage per desktop of 220 kWh/yr and for laptops of 63 kWh/yr based on 2009 computer models. It is also worth noting that US households are often multi-computer and that secondary and tertiary computers have lower usage than the primary household computer. Bearing in mind that most households outside of the OECD will be single-computer some correction factor is indicated. We also expect that life-cycle will be significantly longer in the developing world where many older computers continue in use as long as they remain serviceable.

3.1.4 Other Consumer Devices

The authors of [17] introduced a third category that covers all other ICT equipment not accounted for by the first two categories. They considered this category to include gaming consoles, modems and wifi routers, audio/video (A/V) receivers, printers & multi-function devices, digital and video cameras, MP3 players and similar digital media and stand-alone video player devices.

In [17] the total power consumption of this category was estimated at 40 GW, or 350 TWh/yr which seems excessive. From our analysis, in order for this category to achieve such a large usage of electricity most of these devices would need to be operated continuously.

However the analysis of [35] shows that very few of these devices, many of which are TV or computer peripherals, are operated continuously. Indeed many devices such as DVD players and printers spend most of their time in low-power standby modes.

Rather than follow the authors of [17] it makes more sense to associate TV peripherals directly with our TV category. Thus the present category comprises set-top boxes, game consoles, DVD and Blue-ray players and A/V TV peripherals. This allows us to estimate ratios of peripheral devices per TV-set and simplifies some of the work in extending from the US-only study of [35] to a global analysis. Although not included in the present analysis, cameras and music players are more correctly grouped as client devices - e.g. most mp3 players will connect to the network in order to obtain music from online stores and digital cameras upload pictures and video onto a laptop or home network, frequently for sharing online or printing via an online service.

Another category that is beginning to emerge is that of smart-appliances – examples include network connected white goods, smart thermostats, home energy management, lighting and security systems amongst others. While this category is not currently a significant contributor to electricity consumption if we are to believe the proponents of the *Internet of Things* (IoT) we can expect that it will emerge strongly over the next few years [44]. For now, however, we do not attempt to include IoT appliances, cameras or music players in our calculations. The current contributions of such devices to direct consumption are relatively minor and their contribution to network traffic is typically via a computer. However as more content *generating* and *sharing* devices become directly active on the network their role is expected to expand significantly.

3.2 Manufacturing Energy & Life Cycle Assessment

It is not just the energy consumption of electronics that is important. In fact for most consumer electronic devices the electricity that is used in the manufacturing process is often as large as the lifetime operational electricity of the device [45], [46]. In some cases it can be multiples of the operational energy [34].

According to the International Energy Agency (IEA) there were more than 3.5 billion mobile phones subscribers, 2 billion TVs and 1 billion personal computers in use around the world in 2009 [24]. Moreover these various CE-ICT devices are distributed across developing economies - in Africa 1 in 9 of the population owned a mobile phone. And, importantly, many older low-efficiency devices are refurbished and resold within these economies even where the operational and disposal costs do not make sense [47], [48].

Recent governmental policies have significantly reduced the energy consumption of many traditional household appliances such are refrigerators and washing machines, but the rapid growth in new CE-ICT devices was not predicted. Thus the residential component of electricity consumption continues to grow worldwide, despite general improvements in white goods appliance efficiency and policy measures [24].

The reality is that the energy requirements of semiconductor and nano-material manufacturing processes can be 5-6 orders of magnitude greater than the traditional manufacturing processes used to build, say, an automobile. To manufacture a kilogram of state-of-art integrated circuits requires tens of thousands of megajoules [49], in contrast with no more than 10 megajoules for conventional manufacturing [46]. The scope of manufacturing is here Raw Material Acquisition, Production of Parts, Assembly of the Devices and Distribution to Use. These life cycle phases are defined by the ETSI LCA standard for ICT [50].

3.2.1 Discussion and Related Literature

Because the manufacturing electricity of CE-ICT devices is typically much higher than for other manufactured goods the total lifetime becomes very important in determining the overall energy consumption of an appliance. Many CE-ICT devices only reach a balance point where the operational electricity is greater than the manufacturing electricity after several years of operation. Yet many devices become rapidly obsolete - smartphones and tablets are a good example - and may be replaced by their owners after as little as 1-2 years of operation. Another cause for concern is that many of the latest CE-ICT devices are not designed with repairability in mind [51]. This reduces their total lifecycle significantly.

Overall the potential lifecycle of an electronic device has a very significant influence both on the total electricity consumption of that device, and also on the installed base. As an example, consider TV panels where we assume an average lifecycle of 8 years and an estimated installed base of 2 billion TV panels with annual manufacturing of 250 million new devices. At the end of each year an approximately equal number of TV panels are introduced into service as are withdrawn and the nett installed base remains around 2 billion units.

However if the lifecycle were to increase to 12 years then there would only be 166 million TV panels leaving service each year yet 250 million entering service and the installed base of TV panels will grow by 80 million units per annum. This is even more important for short-lifecycle devices where the differences between a 2-year or 4-year lifecycle will have an even greater influence on both growth of the installed base of devices and the total lifetime electricity consumption of the device.

Most previous studies focus entirely on the use phase of the ICT Sector. However, several authors [16], [17], [20] mention that the production of the ICT Equipment is and will become even more a significant contribution to the overall electricity usage of the ICT Sector as LCA studies have shown the beginning of life to be important for short-lived devices. In the present study this presumption will be quantified for the first time transparently for the global situation.

From published Life Cycle Assessment (LCA) studies the manufacturing electricity for each piece of consumer ICT Equipment can be derived and thus the annual global manufacturing electricity for each item of equipment. In this way, combined with annual sales data, LCA studies can be used to estimate the upstream electricity for devices, networks and data centers.

3.2.2 TV and Viewing Devices

Previous investigations [52], [34] arrive at a range between 400-559 kWh/TV.

3.2.3 Client ICT Devices

For desktops the sources are relatively rich compared to other ICT Equipment [34], [42], [53]. These studies propose values from 60-215 kWh/desktop.

For monitors [54], [34] suggest a range from 187-334 kWh/piece.

For laptops [34] suggests a range of 75-167 kWh/piece.

For smartphones the best estimations come from Apple [55]; Further France Telecom has an Eco-Rating method [56], [57] for smart phones based on metrics such as areas and masses. From FTs method two metrics were used: 0.4 kWh/cm^2 screen and 6-35 kWh/IC chip depending on flash memory storage. From these references we conclude that 30-60

For tablets again Apple [58] and France Telecoms Eco-Rating method [57], applied to open metrics for typical tablets having 7 inch and 10 inch screens were used. For these studies we conclude that 75-287 kWh/tablet is used in manufacturing. The variability is due to the importance of the screen size.

3.2.4 Other Consumer Devices

For this category only two LCAs were found in the literature, one for a set-top-box [59] indicating manufacturing costs of 50 kWh/STB and one for a DVD-player [60]. The AV

Receiver 50 kWh/unit and GC, 100 kWh/unit, were estimated with the help of a proxy from [61] and [62].

3.2.5 Networks

Network infrastructure comprises many different types of equipment including a wide range of radio base station technologies and more established wired and optical switches, routers and . The method of annual shipped units and electricity used per unit was not applied due to data gaps. Instead the annual use stage electricity consumption of Networks derived in the present study was used as basis. Then combined with previous LCA studies [34], [52], [61], [63], estimating that the manufacturing share of the total lifetime electricity of fixed and wireless networks lies in the range of 10-20%, the lifecycle ratio method proposed by Greenhouse Gas Protocol ICT Supplement [64] was applied.

Note that a sensitivity check is performed for radio base stations as these make up a large share of wireless network equipment manufacturing.

Total sales of radio base stations for mobile communications were 1.3 million in 2012. Of these 95% were macrocells. The expected sales for 2017 are around 1.6 million (70 % macro and 30% smaller cell sizes) [65]. It takes around 3 MWhr per radio base station [66] so 5 TWh per year. Radio base stations then constitute a reasonable share of the Network manufacturing, approximately 10% of 51 TWh in 2012 - see Table 3(b). On the other hand there are alternative interpretations which estimate 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 [67].

This latter scenario implies a larger global market for radio base stations. In general market reports/estimations on shipped unit fluctuate considerably and so it is challenging to predict and even back-cast a very exact number.

3.2.6 Data centers

The data centers consist of many different types of ICT Equipment and peripherals such as servers and storage systems.

Instead the annual use stage electricity consumption of Data centers derived in the present study was used as basis. Then combined with previous LCA studies (Honee 2012 [68], Andrae 2013 [61]), estimating that the manufacturing share of the total lifetime electricity of fixed and wireless networks lies in the range of 10-20%, the lifecycle ratio method proposed by Greenhouse Gas Protocol ICT Supplement [64] was applied. A sensitivity check is however done for annual shipments of servers as these contribute a significant share of data center equipment manufacturing electricity [61].

Around 10 million servers were sold in 2012 [69]. It takes around 0,4 MWhr per server [70] so 4 TWh for 2012. Servers thus constitute a reasonable share of the Data Center manufacturing, about 10%, or 4 of 40 TWh in 2012 (See Table 3(b)).

3.3 Electricity Consumption by Networks

The networking component of electricity consumption is very significant in out calculations. At this point in time we are seeing a major transformation in ICT with a shift from desktop and laptop computing to a thin client model. The very rapid adoption of smart-phones, tablets and related thin client devices coupled with the equally rapid growth in cloud-based consumer services signals a disruptive shift in ICT usage.

In turn this moves much of the computational effort from the local client and displaces it to a back-end data center. There is evidence that, with proper management, this can improve the efficiency of many computational tasks In turn this moves much of the computational effort from the local client and displaces it to a back-end data center. There is evidence that, with proper management, this can improve the efficiency of many computational tasks [4], [13],

[15], [71], [72] and thus reduce the electrical energy required per CPU cycle. However the data that is to be processed and the resulting outcome must be transmitted from client to data-center and back again over a network infrastructure which presents challenges [15], [71], [73].

A further complication with network connections is that they are 'always on' and thus [74] consuming energy even if not active.

even if not [4], [12], [14], [82], [83] and thus reduce the electrical energy required per CPU cycle. However the data that is to be processed and the resulting outcome must be transmitted from client to data-center and back again over a network infrastructure which presents challenges [14], [82], [84]. A further complication with network connections is that they are 'always on' and thus [85] consuming energy even if not used. The situation is even more complicated for mobile networks, where networking connections can be established as needed and then disabled, but there is a high cost to make and break connections, particularly for LTE [75], and while client devices can power down when not accessing the network the background network must be continually active.

In fact the optimal network connection would be under 100% constant loading in order to achieve maximum efficiency per unit of data transferred. But this is not how practical networks, either wired or wireless, work in the real world. Thus much of the peripheral infrastructure of a network will be lightly loaded and in consequence operate with very low levels of energy efficiency.

3.3.1 Discussion and Related Literature

Networks can be broadly divided into a core backbone and a local access network [18], [76]. The core networks is relatively efficient, but depending on the type of local access network employed the energy costs can be at least an order of magnitude higher [77]. This is especially the case when high-speed wireless networks are used to provide the local access.

As an example, the authors of [20] determined a model that predicts that electricity consumption by the total combined network components of ICT would exceed a baseline global figure of 350 TWh/yr in 2012. But if the applied electricity consumption figures per user from [78], drawn from access networks that primarily employs LTE technology, are incorporated into the same model then that figure would rise to 850 TWh/yr - a multiplier factor of 2.4 for electricity consumption.

Another useful study is by Baliga *et al* [76] analyzing the relative energy consumption in different wired and wireless networks. Their conclusions reinforce our comment that at data rates above 10 Mb/s wireless networks become power hungry consuming 10 times the electricity of the equivalent wired network. This leads us to another key point that is emphasized in a whitepaper [79] from the Center for Energy Efficient Communications (CEET) and relates to the significant growth in wireless access networks. The majority of today's new thin-client devices use wireless access, either via WiFi or 3G. In fact growth in mobile data has been somewhat restricted due to WiFi offloading where users restrict data connectivity on the 3G interface due to significantly higher costs [28]. But the real unknown in terms of wireless networking is the pending global rollout of 4G/LTE data services. This will be discussed later, but the CEET whitepaper gives a useful perspective, illustrating that the growing energy requirements for wireless access networks is significantly higher and growing more rapidly than the energy requirements for data networks within data centers.

While this CEET whitepaper is not the first research to study wireless access networks [76], [80], [81] it appears to be the first to explicitly highlight the significant growth in energy usage of such networks as wireless becomes the global norm for subscriber access. In an earlier publication Corcoran [16] also incorporated a substantial impact on network energy due to new rollouts of LTE networks. However many deployments were delayed and it now appears that 2013/14 will see most global network operators begin large scale rollouts of G4/LTE networks [82], [83].

A key point to make here is that it is the data rate *at the access point* that will be the primary determinant of network electricity consumption. Thus if users are expecting 2-3 Mb/s data rates a single 10 Mb/s could support a maximum of 4-5 concurrent users. As LTE/4G networks will mainly be deployed in crowded urban environments we expect that operators will seek to optimize the number of users per base-station thus running base-stations at higher data rates, in theory up to 100 Mb/s. This, in turn, could drive the electricity consumption of these access networks up by two, even three *orders of magnitude* higher than the equivalent wired backbone. In fairness many researchers are aware of this issue and a variety of proposals to reduce the power requirements for mobile networks have been proposed and will be discussed in due course.

Typically to operate at a data rate of 10 Mb/s or higher over LTE/G4 mobile networks requires at least on order of magnitude higher electricity consumption compared with wired access network technologies. To date the roll-out of such high-speed wireless networks has been delayed by the global recession, but various OECD economies are in the process of rolling out these networks over the next few years and China has indicated that it intends to complete the world's largest high-speed LTE/G4 network by the end of 2013 [83]. This will feature 200,000 base-stations across 100 cities and will cater for 500 million people. It will be very interesting to see the impact of this infrastructural development on local electricity supply.

Note that while some improvements in the efficiency of such high-speed networks might be expected, practical physical limitations arise from Maxwell and the $1/R^2$ loss of power with distance from source, R. This has led Telco operators to investigate more granular networking architectures using femto-cells, effectively opting for more access points with lower data rates [84–90]. In practice we do not know what level of service users will expect and this will strongly influence how LTE/G4 deployments evolve. If users want faster data rates and more ubiquitous access then we could see soaring electricity consumption by mobile operators.

If we next consider the roll-out of data services in the developing economies it becomes clear that LTE/G4 offers a very attractive infrastructure that can be rapidly deployed in large urban environments without modern telecommunications backbone or wired switching infrastructure. These wireless networks do not require substantial civil works such as the laying of additional optic fiber backbone, or installing MAN networks or the equipping of local digital exchanges. More importantly they can be deployed rapidly – note our earlier comments about China's ambitions in this regard. Given the rapid growth in such urban centers, particularly in Africa and Asia, LTE/G4 offers a very attractive approach to bring broadband infrastructure to developing economies.

3.3.2 Rationale and Methodologies

The energy consumption of networks is very well studied in the literature [91], [78], [80], [92]. There is also a lot of focus on certain categories of network. In particular optical networks [93–98] are important as these form the backbone or 'core' network that handles all bulk data traffic. Another field where substantial research is taking place is that of energy usage and efficiency in wireless or mobile networks [77], [91], [99–101].

For our purposes we will take a fairly top-level view of communications networks. Nevertheless there are different components to any network infrastructure and it is important to make some key differentiations. One of the reasons for doing this is that we will later use some of the available growth projections for network traffic to help understand the likely future growth in network electricity consumption. In this regard we do need to make some distinction between different categories of network technology as will be discussed in the next section.

Mobile and Fixed Data

In a very broad sweep we could assert that practically all networking is converging towards the Internet. Or perhaps a better way to express this is that the Internet, as it continues to evolve, is defining a global scalable networking infrastructure. Yes, there are many 'secure' or 'partitioned' networks, but how many of these do not support at least some Internet protocols? And rely on commoditized 'Internet' routing and interface hardware?

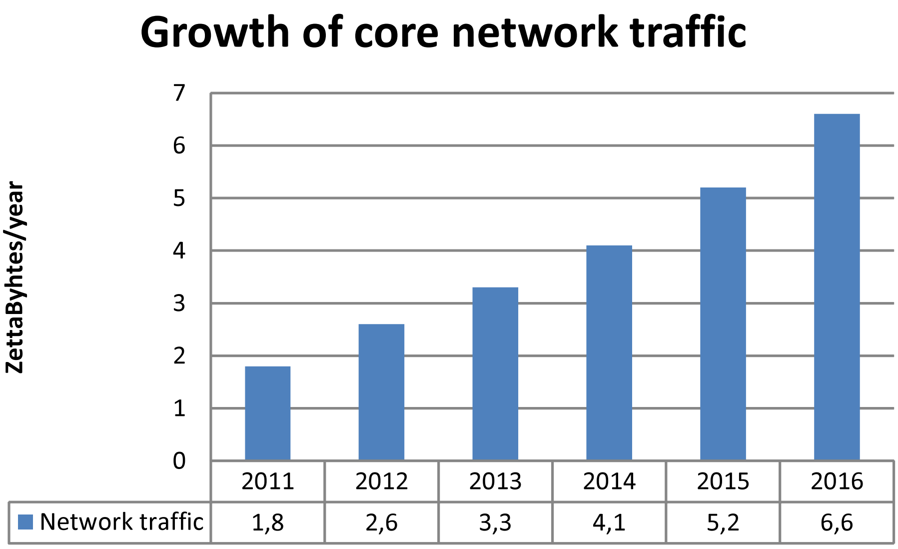
Now the biggest change to the Internet model in the last decade has been the introduction of mobile data. To date this is still a small proportion of the overall network traffic, but since the introduction of smartphones and, more recently, tablet devices and the rapid market adoption of both technologies the growth of mobile data has accelerated at a very fast pace. Indeed it has been dampened significantly by high tariffs applied by most service providers, and the growing availability of Wi-Fi hotspots, but has still grown at 60%+ year on year for the last 3-4 years. Now that high-speed mobiles networks have started to be more widely deployed by ISPs mobile data looks set for a significant stimulus in 2013.

This, in turn, leads to our consideration of telecoms networks in two primary components. We see the 'core' network and its wired extensions, including the wired access network, as one primary entity. This network infrastructure will continue to expand as it has in the past and its energy efficiency will be essentially static. As we shall discuss shortly, this means that we can estimate the growth in energy consumption over the next few years from the growth in network data traffic.

The second component is that of the wireless access network - essentially today's mobile phone networks. As explained above this is the most interesting component of the network as we are on the cusp of a widespread deployment of LTE networks. These wireless networks are capable of much higher data rates than today's mobile networks, but in parallel they have potential to increase energy consumption substantially.

Thus our methodology seeks to separate the more conventional optical and wired network components, which may be modeled based on the growth of core networks traffic, from the wireless, or mobile component which can be modeled based on the predicted growth in mobile traffic. The details of this approach are given in section 4.2.3.

Network Traffic Growth Projections



Growth of core network traffic.

Figure 2(a): This illustrates the growth in core network traffic, including traffic within data centers; about 70% of total traffic is within or between data centers.

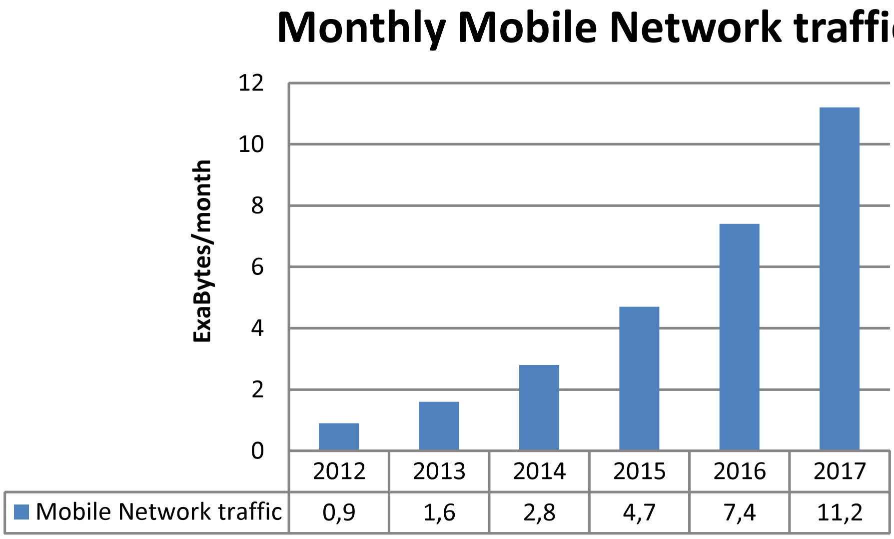


Figure 2(b): Monthly mobile traffic; this excludes traffic from mobile devices that is offloaded to Wifi connections; in 2012 most mobile traffic is carried by 2G/3G networks but by 2017 as much as 45% of mobile data will be carried by new LTE/G4 mobile networks.

3.4 Electricity Consumption by Data Centers

Data centers have existed as recognized entities for at least the past two decades. The concept of a centralized computing resource can be traced back to the 1960s when the original concept of 'cloud computing' was presented by Douglas Parkhill [25]. In recent years we have seen data centers growing from enterprise computing facilities to provide the backbone for Internet growth and, more recently, to emerge as an essential back-end infrastructure [102] for a new generation of thin-client consumer electronics devices [16].

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 [72], [103].

3.4.1 Discussion and Related Literature

Koomey [30], [31], [33] is a key contributor to studies on electricity usage by data centers. Other authors have focused on the sheer size of today's data center [102], or on the energy efficiency of the underlying architecture [104], [105] or specific operational aspects [106], [107], [108] or have considered energy related issues of cloud computing [109], [3], [5], [73] but it is Koomey who has quantified the total energy costs.

In [31] Koomey has reviewed and arrived at a revised and lower estimate of power consumption by worldwide datacenters for 2010 lying in a range between 203 and 272 TWh/year. This compares with a best guess/worst case of 301/397 TWh/year from his earlier work. Much of this improvement derives from the migration of data from in-house data centers where most servers operate at low loading, to cloud computing centers where server loads are balanced using virtual machines (VM) techniques [2]. A second contributory factor is improvements in server power consumption through use of lower power chipsets and architectures [108]. We will use Koomey's estimates as a basis for our calculations in section 4 below.

3.4.1 Rationale and Methodology

Data centers and networks are highly interlinked and many authors are happy to consider a combined metric for both infrastructures. As commented above we prefer to try and separate the data center component of electricity consumption from the network component. In practice this is not as difficult as it may seem. The internal network infrastructure of data centers will be wired, and mainly optical thus having relative low power consumption. This is confirmed by Table 2 of Koomey's [31] most recent analysis to be approximately 6% of data center electricity consumption. Note that this also explains the low figures for Data Centers used in [79] - these authors are comparing the communications network infrastructures rather than the total energy use of data centers.

Thus it is relatively straightforward to separate the network dependent portion of energy within data centers. This, in turn, facilitates the use of network focused studies such as that of Lambert et al. [20] in combination with the work of Koomey to provide separate evaluations for the electricity usage by data centers and by the global network infrastructure.

4. Recent Data Sources and Trends (2008 – 2012)

In one sense much of this data is historic and so it should be possible to obtain fairly accurate estimates. However, it is not practical to know the exact energy consumption of even a single device once it is installed, as we do not have direct access to measure its on-site usage. Thus any determination of the overall usage of electricity by the CE-ICT ecosystem can only be an estimate. Nevertheless we believe a reasonable convergence can be shown across the work of a number of different researchers.

In this section we review a range of such work across a number of different areas that are relevant to CE-ICT and in parallel develop our own methodologies based on alternative data sources. The main goal is to establish some reasonable convergence in estimates for today's rate of electricity usage by the CE-ICT device ecosystem.

4.1 Direct Energy Consumption by Devices

A first challenge is to consider the direct usage of electric power by CE-ICT devices. As was explained in section 3.1 it makes sense to separate devices into two main categories - (i) TV & TV-centric devices, and (ii) ICT devices.

The latter category are also referred to throughout this report as 'client' devices because their primary usage tends to be accessing networked content and services. Another way to describe this categorization is as 'broadcast' and 'network' devices. From a practical perspective almost every modern CE-ICT device falls into one of these categories.

4.1.1 Previous Researchers

We begin by comparing estimates from the literature for the client device category. The two principle research papers that identify and attempt to quantify this particular group of devices are [17] and . These are compared with the total *business as usual* estimate from [24] for all CE-ICT devices.

Table 1(a): Electricity consumption for client ICT devices 2008-2012

Citation	Devices	2008	2009	2010	2011	2012
Pickavet, et al. [17]	PC, Ltop, Display	262.8	282.5	303.7	326.5	351.0
Corcoran [16]	PC, Ltop, Display, smart-phone & tablet	262.8	286.5	312.2	340.3	371.0
IEA [24]	ICT & CE	670	720	**776**	830	885

Table 1(b): Electricity consumption for TV devices and peripherals 2008-2012.

Citation	Devices	2008	2009	2010	2011	2012
Pickavet, et al. [17]	TV, Plasma, LCD	385	420	458	499	544
Corcoran [16]	TV, Plasma, LCD, Smart-TV	350	350	350	438	548
IEA [24]	ICT & CE	670	720	**776**	830	885

There are various inconsistencies between the approaches used by these, and other researchers, but the main point of tables 1(a) & 1(b) is that there appears to be a good consensus as to the combined electricity usage of devices in 2011/2012. Note that the IEA figures are a combined total for all CE-ICT devices.

In 2011, all three research reports agree that combined CE-ICT electricity consumption lies between 778 and 830 TWh/year; in 2012 this quantity lies between 885 and 919 TWh/year.

4.1.2 Analysis of the Installed Device Base

As indicated in the introduction to this section it is possible to find detailed information on the installed base of devices in a range of different categories from various government & industry sources. It is also possible to apply a detailed usage analysis model such as those developed by [35] to each category of devices. In table 2(a) a summary of our results is presented, extrapolating the usage models of this report to apply more broadly to the installed base of global CE-ICT devices.

There are several adjustments/refinements that are worth noting. Firstly the annual kWhr rating for a typical US TV panel was estimated at 180 kWhr in 2010. Here a 10% higher figure of 200 kWhr has been adopted to reflect two factors: (i) in emerging economies we expect a higher proportion of older high-power TV sets in the installed base, and (ii) there will be a larger proportion of single-TV households in developing economies and these primary TV sets have higher annual usage than 2nd and 3rd TVs in multi-TV households.

Table 2(a): Electricity consumption (TWh/yr) for CE-ICT devices and peripherals 2011-2013.

Installed Devices (x10^6)	**2011**	**2012**	**2013**	**kWh/yr (2010)**
Desktops	579	588	598	*220*
Monitors	608	617	628	*97*
Laptops	729	832	946	*80*
Smartphones	700	1000	1350	*5*
Tablets	50	150	250	*15*
TV	1900	2000	2100	*200*
TV STB	722	760	798	*100*
TV GC	380	400	420	*135*
A/V Receiver	570	600	630	*65*
DVD/Blueray	665	700	735	*28*
TWh/yr				
Desktops	127	129	132	
Monitors	59	60	61	
Laptops	58	67	76	
Smartphone	4	5	7	
Tablets	1	2	4	
TV	380	400	420	
TV STB	72	76	80	
TV GC	51	54	57	
A/V Receiver	37	39	41	
DVD/Blueray	19	20	21	
Total (TWh/yr)	**808**	**852**	**897**	

For laptops the [35] study used an estimate of 63 kWhr/yr per laptop, based on a usage model where 43% of portable computers are second computers for their user and where energy star power savings strategies are mandatory. In developing economies we expect a higher proportion of older or second-hand laptops without advanced energy saving features and almost all portable computers will be primary devices for their users thus incurring a higher level of usage. For these reasons a higher base usage figure of 80 kWhr was adopted to reflect such differences. (Note that the SMARTer 2020 report [36], which is more recent, does not have an explicit figure for laptops which we assume are included as part of the energy consumption by desktop computers.)

Based on these estimates we see that annual consumption for all devices is estimated at 808 TWh/yr in 2011, which fits nicely between the estimates of 778 to 830, TWh/yr determined from the work of prior researchers. For 2012 these suggest a figure of 852 TWh/yr with is somewhat lower than prior estimates but this can be explained in part by changes in the both PC and TV markets. PC sales have stagnated in recent years and have been strongly displaced by laptop sales and more recently tablet computers. Thus there is a shift to lower power client devices in the ICT category although there is still a significant installed base of older PCs and laptops in 2012.

On the TV side we note that the market has stagnated at c. 250M units per annum [37], [38] in contrast to a 7.5% or higher growth rate predicted by past researchers. Again there is evidence of changing use patterns that lead to more viewing of content by consumers on low-power ICT client devices. Thus the figures presented in table 2(a), although slightly lower than previous estimates, appear to offer a sensible baseline for direct electricity consumption by CE-ICT device.

Note on information sources for the main device categories

For clarity we provide an outline of our methodology for the main devices.

Desktop and Laptop Computer: Market estimates for these are taken from IDC market analysis [41] with an assumed lifecycle of 4 years. For later projections the lifecycle is varied from 3-5 years depending on the growth scenario.

TV Panels and Peripherals: Market estimates are taken from [37] with a lifecycle assumption of 8 years. Most TV peripherals are assumed to have a lifecycle that tracks the TV itself.

4.1.3 New Efficiencies and Best Practice

In the analysis presented above we applied the power consumption in annual KWhr per device from the [35] study. These values were based on a study of CE and ICT devices in the US in the period 2009-2010, but some categories of device will have improved on their gross power consumption even in the last few years.

Notably the TV industry has been very successful in migrating from older TV panel technologies such as plasma and LCD to more power efficient LED panels. Thus in 2011 25% of TV panels were LED based, rising to 55% in 2012 and >75% projected for 2013 [38], [110].

Thus while past researchers predicted that larger display sizes would increase electricity power consumption, in fact new TV panels will actually tend to reduce overall power consumption over the next few years. Based on our estimation of 150M 'high inefficiency' TV panels replaced annually from the 250M sales of new TVs we expect the power consumption of those 150M replaced devices to be halved. This assumes the replacement of a high-power panel (200-300 Watts) by a state-of-art LED panel (<100 Watts).

Taking as an example our estimates above for 2011-2013 and our replacement rate of 150M per annum. Thus over this three year period we have added 300M additional 150 Watt TV sets, but we have also displaced 225M @ 200+ Watt TV sets with 100 Watt TV sets -

thus about 50% of the increase in electricity consumption is offset by replacement of high-power TV panels or older CRT based TVs. As the industry approaches 100% LED technology, expected in 2014/15 then we could expect to see a net reversal in total electricity consumption by TVs for a number of years.

However the actual replacement rate of TV panels is quite significant and if it is sufficiently high then even with positive market growth we could see substantial reduction in the direct electricity consumption of TV panels as older models are scrapped. On the other hand if consumers hold onto their TV panels beyond their 10-year lifecycle - as 2nd or 3rd household TVs - we can expect that electricity consumption could continue to grow even in a declining market for new devices. In the current state of the global economy it is challenging to understand exactly how consumer behavior will evolve over the next few years.

4.1.4 Growth in Consumption (2008-2012)

It is helpful to compare our three main sources of recent data to see how each predicts the increased consumption of CE-ICT devices. The IEA estimates [24] begin from 2010 and are closely in line with Pickavets estimates [17]. Corcoran is lower which is most likely because that work restricted itself to the major categories of ICT Clients (PC, laptop and other consumer ICT devices) and to TV displays and associated peripherals [16] (*i.e.* Pickavets includes an additional 'other' category that is only partly covered by Corcoran's estimates).

Nevertheless we see a close convergence in 2011 and 2012 from all three of these researchers and this supports our model described in section 4.1.2 above.

Table 2(b): Electricity consumption (TWh/yr) for all primary CE-ICT devices and peripherals (2008-2012) from previous researchers, compared with the individual device model of this work.

	2008	2009	2010	2011	2012
IEA [24]			**776**	824	873
Pickavet, et al. [17]	648	703	762	826	895
Corcoran [16]	613	625	645	824	870[1]
This Work				**808**	**852**

The main goal of this section is to obtain a consensus estimate for the electricity consumption of devices in 2012. Given the improvements in energy efficiencies for TV sets and, to a lesser extent, for PC and laptop clients it seems reasonable to use the 852 TWh/year estimate from our model as a basis for predicting the future trends in electricity by CE-ICT devices in section 5.

1 The original estimate provided in [16] had assumed strong growth in TV sales driven by a broad adoption of 3D technologies and the introduction of Smart-TV; the figure provided here has been modified to reflect the actual market condition of 2012.

4.2 Manufacturing Energy and Life-Cycle Considerations

4.2.1 Previous Researchers

To the authors knowledge there are no overall global ICT electricity footprint estimations that transparently include the manufacturing electricity. In this sense this research will shed light on the importance of the relative importance of the manufacturing of ICT as compared to the use stage. Individual more or less transparent LCA studies do exist for individual parts of the present scope. Here facts from these LCA studies are put together.

4.2.2 Analysis of the Installed Device Base

Several sources present annual numbers of shipped devices that can be used for 2008-2012 [26], [37], [38], [69], [111] [34], [41], [112]. The present set top box and game console shipments can be regarded as low estimates [113], [114]. Monitor sales follow the desktops shipments [114]. In Table 3(a) the basis for 354 and 281 TWh for Use stage Networks and Data Centers are presented below in Sections 4.3 and 4.4, respectively.

Table 3(a): Numbers of Shipped Devices and per-unit Manufacturing Electricity

	2008	2009	2010	2011	2012	KWhr/unit (2010)
Desktops	141	143	146	148	151	188
Monitors	157	159	162	165	169	268
Laptops	143	170	201	215	246	134
Smartphones	120	160	350	460	700	40
Tablets	1	1	50	100	150	75
TV	241	244	252	255	258	400
TV STB	92	93	96	97	98	45
TV GC	48	49	50	51	52	150
A/V Receiver	72	73	76	77	77	100
DVD/Blueray	84	85	88	89	90	200
Networks eq (TWh)					354	Manuf: 15% Use 85%
Data center eq (TWh)					281	Manuf: 15% Use 85%

To get the TWh for Desktops in 2008 141 million units was multiplied with 188 kWh/unit. Then an annual improvement in electricity efficiency is assumed so the TWh for Desktops in 2009 in 143 million×188kWh×(1-0,05)=26 TWh, in 2010 146×188×$(1\text{-}0{,}05)^2$, and so on.

For Networks and Data Centers the manufacturing electricity was estimated with a formula from the Greenhouse Gas Protocol which uses a so called LCA stage ratio factor from which Network equipment manufacturing electricity (E_{man}) can be estimated. The expected share of the use stage electricity (E_{use}) for a Network is around 85%, i.e. C_{use} = 85%.

$E_{man} = \{E_{use} / (C_{use}/100)\} \times (1 - C_{use}/100)$

E_{man} = {354 kWhr / 85%/100)} x (1 – 85%/100) = 62 TWh. We assume a 5% annual improvement of the manufacturing electricity since 2008, 62×$(1\text{-}0{,}05)^4$=51 TWh

Table 3(b): Manufacturing Electricity (TWh/yr) by Device Category

	2008	2009	2010	2011	2012
Desktops	27	26	25	24	23
Monitors	42	40	39	38	37
Laptops	19	22	24	25	27
Smartphones	5	6	13	16	23
Tablets	0,04	0,07	4	8	11
TV	96	93	91	87	84
TV STB	4	4	4	4	4
TV GC	7	7	7	7	6
A/V Receiver	7	7	7	7	6
DVD/Blueray	17	16	16	15	15
Networks equipment					51
Data center equipment					40
Total	277	309	322	327	327

4.3 Electricity Consumption by Networks

4.3.1 Previous Researchers

It is not a surprise to find that the electricity usage of networks has been a topic considered by many earlier researchers. Both Pickavets [17] and Corcoran [16] identified networks as a key component of the overall electricity usage by CE-ICT devices. A number of other researchers have studied, in varying degrees of details, the growth in electricity requirements of telecommunications networks and the networking phenomenon known as the 'Internet'. Now it is not our goal to perform a very granular study of networks, but rather to try and obtain a sensible 'top-level' understanding of how they are evolving and obtain a consensus estimate of the current level of electricity consumption in 2012. Thus we focus on a number of the most relevant research studies supporting this objective.

Lambert [20] provides a detailed study of the use phase electricity consumption in communications networks, specifically telecom operator networks and including customer premises equipment and an estimate for office and building networks. They also provide a very helpful comparison of their results with a number of other recent research studies. The overall estimate for 2012 is included below in section 4.3.3 and will be used as a baseline for later projections of growth in electricity consumption due to network growth.

One interesting observation made by these researchers is that when they take per-user electricity consumption figures from another study by Kilper [78] and applied these in their model they found that the total electricity figures were more than doubled to 812 TWh/year. This study by Kilper was based on an early LTE network and this importance of the access network technology in determining the overall electricity consumption of the network infrastructure is underlined by this thought experiment. We already discussed the operational power consumption of LTE and other high-speed networking technologies in some detail in section 3.3.1 and there will be further discussion on the potential impact of LTE when we discuss our future projections.

One key point that is emphasized in a whitepaper [79] from the Center for Energy Efficient Communications (CEET) relates to the significant growth in wireless access networks. The majority of today's new thin-client devices use wireless access, either via WiFi or 3G. In fact growth in mobile data has been somewhat restricted due to WiFi offloading where users restrict data connectivity on the 3G interface due to significantly higher costs [28]. But the real unknown in terms of wireless networking is the pending global rollout of 4G/LTE data services. This will be discussed later, but the CEET whitepaper gives a useful perspective, illustrating that the growing electricity requirements for wireless access networks is significantly higher and growing more rapidly than the electricity requirements for data networks within data centers.

While this CEET whitepaper is not the first research to study wireless access networks [76], [80], [81] it appears to be the first to explicitly highlight the significant growth in electricity usage of such networks as wireless becomes the global norm for subscriber access. In an earlier publication Corcoran [16] also incorporated a substantial impact on network electricity due to new rollouts of LTE networks. However many deployments were delayed and it now appears that 2013/14 will see most global network operators begin large scale rollouts of G4/LTE networks [82], [83].

4.3.2 Methodological Considerations

Partitioning the Network

Based on our considerations of the literature, and the shifting perspectives of various researchers in the last 2-3 years it is clear that networks can be broadly divided into 'core' and 'access' components. The 'core' component is the main wired backbone, based on optic-fiber technology with some conventional copper wire in the outer branches. The 'access' component comprises of a number of different technologies and connects consumers to the actual 'core' network. In practice we can subdivide the access network into two main components - wired and wireless. The wired access network uses digital subscriber lines and in some regions even older analog phone lines to provide connectivity to consumers. The wireless access network is mainly mobile technology such as GPRS and G3, or where fixed wireless access makes economic sense WiMax or HPSA may be used. And in some geographical areas more advanced G4/LTE mobile networks have begun deployment.

From an energy perspective the access network is the greedy part of any service provider's network. For a typical ISP it will consume 2/3 of the network electricity although as some components (e.g. ADSL modems) are on the customer's premises these do not impact on electricity costs for the service provider. It is also worth remarking that wireless technologies are significantly more costly in terms of electricity consumption. There is a significant body of recent research, in particular on LTE (long-term evolution) networks that will provide the infrastructure for next-generation mobile networking and we will discuss this in more detail in section 5.4 when we consider forward projections.

Networks and Datacenters

In much of the literature the networking and datacenter components are intertwined and from an electricity consumption perspective it is not always easy to disentangle them. Now while it is tempting to combine these into a single category we feel it is important to distinguish between the electricity growth of data-centers and that of the networking infrastructure.

The deployment of a new generation of data-centers is targeted specifically at consumer applications and services and indications are that this rebirth of the 'cloud computing' concept of the 1960s will catalyze a new growth phase for the ICT industry. But it is important to realize that this will be very different from the 'passive' data network we call the Internet where content was stored and managed on a relatively small number of 'servers' and delivered to a much larger number of clients.

New data services aim to encourage consumers to generate much of their own data and content that will then form the 'raw material' of this new growth phase. Much of this data will be stored and processed in data centers and shared over a variety of 'social networking' channels. Naturally growth in the volume of raw data will also drive network capacity, but we feel it is important to understand this relationship, how increasing data volumes affect both growth of the underlying infrastructure and the fundamentals of energy consumption. For this reason we look to research that separates the data-center component of energy from the networking component.

4.3.3 Growth in Consumption (2008-2012)

Table 4(a) shows a comparison of the total electricity consumption of global networks from a number of previous researchers. Note that the network growth figures for Corcoran [16] have been adjusted to take account of the delayed deployment of LTE networks. After this adjustment we can see that all researchers have broadly convergent estimates leading to a consensus figure of the order of 350 TWh/yr for 2012.

Table 4(a): Electricity consumption (TWh/yr) for all data communications networks (2008-2012) from previous researchers; note that Kilper, et al. [78] is included to illustrate the potential impact of LTE wireless access technology on overall power consumption.

Citation	Devices	2008	2009	2010	2011	2012
Pickavet, et al. [17]	Datacom & Teleco Networks; excludes Data Center networks	219	245.3	274.7	307.7	**344.6**
Corcoran [16]	Datacom & Teleco Networks; excludes Data Center networks	219	251.9	276	318[2]	**365**[2]
Lambert, et al. [20]	All networks - based on subscriber numbers		240	265	320	**354**
Kilper, et al. [78]	Mobile Network					**812**

Note that the figure provided for Kilper, et al. [78] is derived from table 5 of Lambert, et al. [20] and illustrates the potential effects of LTE access networks if these were introduced across the entire communications infrastructure.

One way to view this figure of 812 TWh/yr is to consider it as an upper bound on electricity consumption for the network infrastructure deployed in 2012. It also tells us that a communications network that uses LTE, or equivalent wireless technology exclusively for its access infrastructure can consumer up to 2.2 times as much energy compared with a network where the primary access is via wired connections.

4.4 Energy Consumption by Data Centers

Obtaining reliable information on Data Centers is difficult. Some corporations are very open about their energy policies and usage, but others are not [115].

It is clear that with the recent growth in cloud computing and the outsourcing of a wide range of IT services that there are many providers of data-centers. Some are large corporations, but there are also a significant number of smaller and more specialized cloud service providers. Similarly, there is a wide range of data-center infrastructure ranging from massively scalable and geographically distributed infrastructures, employed by major corporations like Google and Amazon, to smaller more specialized local installations that are customized for a particular service, or application.

We can expect to see ongoing rationalization in the sector over the next decade, and eventually standards and industry best practice should lead to consolidation and improved efficiencies across the sector. But today it is one of the fastest growing technology sectors and as a consequence it is difficult to arrive at a clear picture of where cloud computing and the underlying data-center infrastructure is heading. Nevertheless we should be able to find a

2 The original estimate provided in this research paper [14] assumed that significant LTE deployments would begin in 2011; in fact major roll-outs of LTE networks have been rescheduled by most global ISPs to a 2013/14 timeframe; the estimates provided here in Table 4(a) are modified to take account of this change.

sensible baseline value for 2012 energy consumption and this is the main focus of this section.

4.4.1 Previous Researchers

Much of the definitive work in this area has been undertaken by Koomey [30], [108], [33]. His work was used by other researchers [16], [17] to arrive at estimates for electricity consumption in data centers over the period 2008-2012. These estimates are provided in Table 4b below.

More recently Koomey has undertaken a detailed audit of his earlier work and employing a number of different methodologies arrived at a refined, and lower estimate for electricity consumption of data centers with a specific focus on the accuracy of his 2010 estimates [31]. This employs a number of alternative methodologies to develop a range of estimates and ultimately the output is a significantly reduced estimate of the global energy consumption figures for 2010.

4.4.2 Impact of Emerging Technologies & Synergies

There are a number of technological reasons that can help explain the significant differences between the earlier work of Koomey and his most recent results [31].

Firstly we note the trend of data centers to allocate resources using virtual machines, rather than physical servers. This enables operational hardware to operate at close to 100% utilization and unneeded physical servers to be turned off, keeping a buffer of operational servers to handle fluctuations in load demand. By operating physical servers at high load and switching off unneeded computing capacity the overall efficiency of the data center is optimized. Several researcher have written extensively on this approach [3], [11], [14], [116] [90], [91] [119], [120] and it has been widely adopted as 'best practice' across the industry. It is not clear what the overall impact of this change in operational procedures has been across the industry but it has certainly contributed to the revised estimates provided in [31].

A second trend on the hardware side has been a transition to low-power, multi-core CPU platforms [121], [122] and even GPU clusters [123], [124] for computationally intensive works such as video processing and transcoding. As new CPU designs are currently driven by the rapid growth of the smartphone and tablet markets we expect further enhancements in multi-core and GPU on-chip CPU designs. Many of these architectural enhancements will likely find their way into next-generation data centers and such trends have undoubtedly contributed to the improvements presented in [31].

4.4.3 Growth in Consumption (2008-2012)

It should be clear from the above discussions that the work of Pickavet et al [17] and that of Corcoran [16] were based on the original estimates of Koomey [30], [33] and as a consequence they significantly overestimate the actual power consumption of data centers. This is illustrated in **Table 4b** where Koomey's original work [30], [33] and his later revisions [31] are both included.

As Koomey has only provided an estimate for 2010 it was also decided to include an estimate of consumption for 2011 and 2012 as our goal is to provide a reference baseline value for 2012 in each of the four main categories of electricity consumption. To this end we have adopted an annual growth rate of 12% for 2011 and 2012. This is in line with the growth rates identified by Pickavet, et al. [17]. Now Koomey [31] has indicated a lower rate of growth from 2005-2010 of about 8%. However he has speculated that the slowdown in the growth of data centers was at least in part due to external economic conditions. Moreover we note that a significant number of new consumer cloud services have been introduced since 2009 (Dropbox, Sugarsync, Amazon cloud drive, Skydrive, Google drive, etc). In addition online storage, sharing and processing of personal content such as pictures (Flickr, Snapfish, Photobucket) and video (youtube) went through a strong growth phase during this period.

Given these developments it seems reasonable to revert to a 12% growth rate for data centers for 2011 and 2012.

Table 4b: Electricity consumption (TWh/yr) for data centers from previous researchers.

Citation	Devices	2005	2008	2009	2010	2011	2012
Pickavet, et al. [17]	Severs & Data Center		254.0 (1)	284.5	318.7	356.9	399.7
Corcoran [16]	Severs & Data Center		254.0 (1)	285.6	343.0	411.5	514.4
Koomey [30], [33]	Severs & Data Center	152.5	**268.7**				
Koomey [31]	Severs & Data Center				**237.4**	**265.9** (2)	**297.8** (2)

Notes: (1) Pickavet and Corcoran have lower estimates for 2008 than Koomey because network energy (c. 6%) within the data center is not included; (2) These are extrapolated from Koomey's revised 2010 estimate at an annual growth rate of 12%; these values include c. 6% network energy.

4.5 Baseline Estimates for 2012

This brings us to our final estimates for 2012 summarized in Table 5 below.

It is worthwhile to recap our rationale for establishing these values. They are based on a combination of previous research work and estimates and our own best estimates deduced from a combination of known market, economic and, where available, hard data for each metric.

For direct consumption by devices we have compared the estimates of previous researchers and matched this with our own model of device categories and estimated per device consumption and usage patterns. The selected value is lower than some of the estimates of previous researchers, but seems sensible given global economic conditions over the last few years.

The contribution of networks offers perhaps the best consensus. This does require some adjustment of the projections of Corcoran [16] to correct for delays in the roll-out of LTE/G4 networks. After this we find the estimates of network energy usage are within 20 TWh/yr of each other and the recent work of Lambert et al [20] offers a median estimate. We remark that the core network component of datacenters is included in this estimate and thus estimates for energy consumption in datacenters shoudl be reduced accordingly - by approximately 6%.

Table 4(c): Best Estimate Values for 2012 in each category.

2012 Baseline	
Device Consumption	852 TWhr/yr
Manufacturing (LCA)	330 TWhr/yr
Networks	352 TWhr/yr
Data Centers	281 TWhr/yr
Total	**1,815 TWhr/yr**

Given the relatively close agreement between these estimates for network we do not provide an alternative model at this point, but in section 5 the energy consumption of the core network is separated from that of the wireless access network. This separation is based on the observed trend that mobile data will employ wireless access networks and given the projected growth in such data [28] there will be a equivalent growth in the energy consumption by these wireless access networks [79]. This will be discussed in more detail in section 5.4 where our projections will be made separately for core network and wireless access networks.

For Data Centers we note that much of the previous research was influenced by Koomey [30] who has since provided more accurate, revised estimates for the year 2010 [31]. Given the detailed nature of the latter work we adopt this estimate for 2010 but assume a year-on-year growth rate of 12% from 2010 to 2012 rather than the 8% annual growth rate identified from 2005 to 2010 in the same work by Koomey. The rationale for this higher growth rate is the ramp-up in 'cloud computing' since 2010, in particular the introduction of a wide range of new consumer services. Further details were given in section 5.4 above. Our 2012 estimate of almost 300 TWh/yr for Data Centers is then reduced by 6% to account for the energy usage of core data networks inside data centers.

5. Projections for CE-ICT Energy Consumption (2013 – 2017)

Having made some estimates using different approaches for electricity consumption in 2012 we now seek to extrapolate to determine likely growth scenarios over the period 2013-2017. This can be achieved by extending the same approaches used to determine our 2012 figures for each principle category of energy consumption.

For direct consumption by devices we develop projections that cover likely market growth patterns over the period 2013-2017. We can compare these with projections from the 2009 IEA study [24] and these can be matched with overall growth rates in energy consumption by the installed base of CE-ICT devices. Here it is reasonable for a number of reasons to assume that overall consumption by devices will remain in a state of overall balance as increased efficiency of new devices balances any overall growth in the installed base.

For network consumption we take the approach to separate energy consumption by the core network from that of the peripheral wireless access network. As was discussed earlier, the core network is already very efficient and thus we can use the global metric of TWh/EB which is available for many network operators to provide an estimate of core network electricity consumption. Naturally we expect this to be continually improving and thus our various scenarios assume a fixed rate of annual improvement. Against this is the steady growth of data traffic which is predicted to rise from 2600 Exabyte in 2012 to 8500 Exabyte in 2017 [29].

Electricity consumption by data centers will also rise inevitably, driven in particular by increased consumer adoption of thin client devices. We can use our estimates of global growth in communications networks to determine overall growth rates in the scale of underlying infrastructure. In turn these growth rates suggest how the data-center infrastructure will grow to accommodate the increase in network data. It seems reasonable to assume a linear relationship between increased data traffic and the processing and storage infrastructure associated with this.

5.1 Different Growth Scenarios

Based on the above approaches to extrapolating energy consumption we can now provide a set of criteria that define our three main growth scenarios. We first consider a low-growth case that assumes best conditions in all three categories of electricity consumption. Then an expected-growth assumption where sensible growth estimates are balanced against improved energy efficiencies. The final case looks at continued growth in all categories with only small improvements in efficiency acting to restrain energy consumption.

Interestingly we can match these three scenarios with the three cases outlined in Annex I of the IEA study [24]. Detailed tables of each scenario will be provided later. In the remainder of this section we provide the main input assumptions and a summary of the outcomes in terms of electricity consumption.

5.1.1 Low Growth Assumptions

For devices we assume that the installed base will remain essentially fixed from 2013-2017 with market size also remaining stable. Thus every new CE-ICT device displaces an older model. This leads to an overall year-on-year improvement in energy efficiency of 5% for most device categories. In this scenario we see energy usage by the installed base of CE-ICT devices falling from 852 TWh/yr to 682 TWh/yr.

For network technology it is clear that the growth in data traffic will not allow any overall reduction in energy consumption. We choose a fairly ambitious target of 15% per annum improvement in the efficiency of the core network from a starting point of 0.135 TWh/EB. Even with this level of across-the-board improvement energy consumption in the core network is expected to rise from 351 TWh/yr to 509 TWh/yr. This scenario also assumes relatively slow growth in wireless traffic via the access network with only 5% of overall electricity consumption being due to wireless access networks and an total for core + wireless of 535 TWh/yr.

Finally our determined rate of growth in infrastructure for this low-growth case is about 7.5%. Applying this to our 2010 base for data center electricity usage we determine 258 TWh/yr in 2013 rising to 370 TWh/yr in 2017.

5.1.2 Expected Growth Assumptions

For devices we assume a stagnating market for desktop computers, TVs and device screens. There is a modest growth of 8% in laptops and the markets for smartphones and tablets will plateau around 1.2 billion and 400 million units per annum by 2017 (These numbers are actually conservative compared with current market estimates [112]). Energy efficiency improvements for most devices are limited to 2% per annum - this implies more older devices are retained in use, being resold or reused within the same household. This scenario keeps electricity consumption from devices stagnant at 854 TWh/yr over the period from 2013-2017.

For networking technology we assume a starting point of 0.14 TWh/EB and an annual improvement in energy efficiency of 10% across the core network. Wireless access network is limited to 9% of total electricity usage and total consumption rises to 733 TWh/yr by 2017. In turn this determines a growth rate for infrastructure for this mid-level scenario of 14% leading to a data-center figure for electricity usage of 558 TWh/yr.

5.1.3 High Growth Assumptions

In the case of devices we assume that current trends in terms of market sizes and replacement rates continue. The market for TV panels continues at 250 million units with similar replacement rates (8 year lifecycle). This leads to an increase in the installed base of TV sets from 2 billion to 2.5 billion over the period 2013-2017. Desktop PCs and monitors continue a steady but small growth of 2% while the installed base of laptops continues a strong growth rate c.14% and smartphones and tablet markets grow to 1.6 billion and 450 million respectively. Annual efficiency improvements vary from 1% to 5% depending on the particular device category. The net result is a growth in device related electricity consumption from 852 TWh/yr in 2012 to 1087 TWh/yr in 2017.

Our high-growth scenario for networks assumes only a 5% year-on-year improvement in efficiency that leads to a growth in core network electricity consumption to 870 TWh/yr. The wireless access network grows to contribute 15% of total electricity consumption leading to a combined figure of 1027 TWh/yr. In turn this indicates a growth rate in excess of 20% for the underlying infrastructure. Applying this to our starting point for data centers we arrive at a figure of 800 TWh/yr by 2017.

5.2 Electricity Consumption by CE-ICT Devices

Here we take a look in more detail at these individual numbers.

5.2.1 Electricity Consumption based on Installed Device Numbers

Here we take the device-centric model developed in section 4.1.2 and apply it to estimate growth in the installed base for the various devices categories provided. As before there are two main groupings - TV and TV-peripherals form one of these, the other being that of ICT client devices ranging from desktop PC's to smartphones.

Our estimates for energy use per devices are drawn from [35] applying a fixed year-on-year improvement in device efficiency to each device category. Most ICT devices are assumed to have a short life cycle of 1.5-3 years, but TV peripherals are typically much longer with an 8-year lifecycle.

A First Set of Assumptions - Business as Usual for Client, TV Markets

Our initial assumptions correspond to a high-growth scenario and are based on continued growth in the installed base numbers for each device category. It is further assumed that many older devices are resold or reused thus there is significant growth in the installed bases of laptops and TV panels. There is only very slight growth in the installed base of desktop computers and monitors as laptops, tablets and even smartphones are gradually superseding these.

For the various categories of TV peripheral we assume that: (i) 38% of TV panels have some form of set-top-box; (ii) 20% have a game console; (iii) 30% have an external A/V surround amplifier/speaker system and (iv) 35% have a DVD or Blue-ray disk player. Many TV sets will have more than one of these peripherals and the power ratings applied reflect the somewhat intermittent usage of some peripherals. For example, DVD players have an average electric power consumption of 28 KWhr/yr because they are used less frequently than a set-top box (100 KWhr/yr) which is often operated on a 24/7 schedule or an A/V receiver (65 KWhr/yr) that is typically switched on while the TV panel is operational. A detailed discussion of methodology can be found in [35].

Year-on-year device efficiency for older ICT devices is assumed to improve by 5% whereas newer smartphone and tablet devices are actually considered to lose efficiency at a similar annual rate due to the use of improved battery technology allowing increases in the total electricity use of these devices. In other words these devices will be able to carry more battery charge but that will drive a trend towards more power hungry devices. Thus we anticipate a negative efficiency for such devices, at least for the next few years.

In due course we shall compare this high-growth scenario to the 'business as usual' scenario of IEA [24] and it will be clear that there is a close correspondence between the two. It should be remarked that there was already a sharp drop (c 10%) in the sales of desktop and laptop computers in the last quarter of 2012 and the first quarter of 2013 [43]. It is not yet clear if this marks an underlying trend, or is simply a market aberration caused by the introduction of Windows 8™, followed by a slow initial adoption by consumers. However it does seem likely that our high-growth scenario delineates the likely worst-case electricity consumption over the next 5 years.

Table 5(a): Worst case consumption (2013-2017): direct energy consumption by category of device.

Device Numbers $\times 10^6$ (Clients)	2012	2013	2014	2015	2016	2017
Desktops	588	598	608	619	629	640
Monitors	617	628	639	649	660	672
Laptops	832	946	1076	1223	1391	1581

Smartphones	1000	1200	1296	1400	1512	1633
Tablets	150	190	236	293	363	451
Device Numbers x10^6 (TV)						
TV	2000	2100	2205	2315	2431	2553
TV STB	760	798	838	880	924	970
TV GC	400	420	441	463	486	511
A/V Receiver	600	630	662	695	729	766
DVD/Blueray	700	735	772	810	851	893
Power Consumption (TWhr/year)						
Desktops	129	132	127	129	131	134
Monitors	60	61	61	62	63	64
Laptops	67	76	82	93	106	120
Smartphones	5	6	7	7	8	9
Tablets	2	3	4	5	6	7
TV	400	399	419	440	462	485
TV STB	76	78	82	86	91	95
TV GC	54	57	60	63	66	69
A/V Receiver	39	41	43	45	47	49
DVD/Blueray	20	21	22	23	24	25
Total (TWhr/year)	**852**	**872**	**905**	**952**	**1,003**	**1,057**

Alternative Assumptions #1 - Client, TV Markets Decline then Grow Sporadically

An alternative scenario is our 'expected growth' estimate. This broadly corresponds to the least life-cycle cost scenario of IEA [24]. In this case we have introduced a sudden 10% drop, year-on-year, in 2013 for the desktop and laptop markets. This is followed by a slow 2% year-on-year growth in the installed base for desktops but a much higher 14% growth year-on-year for laptops. Despite the rapid adoption of smartphones and tablets we still consider that laptop computers are more versatile for most users and the installed base will continue to grow driven by developing markets in Asia and South America.

We are also conservative with regard to the installed base of TV panels. We see this peaking in 2014 and entering a slight decline, stabilizing at 2.1 billion units. Given the increased number of tablet devices and smartphones and the growth of online video content there is less need for a TV set in the bedroom and we believe that many 2nd and 3rd TV sets will find themselves gathering dust. Consumers are also likely to engage with proactive recycling programs to dispose of older energy-hungry panels. TV panels represent 50% of the overall electricity consumption budget for CE-ICT devices so any significant savings start with this device category.

Table 5(b): Expected Consumption (2013-2017): direct energy consumption by category of device.

Device Numbers x10[6] (Clients)	2012	2013	2014	2015	2016	2017
Desktops	588	529	537	546	554	563
Monitors	617	556	565	573	582	591
Laptops	832	749	812	880	955	1035
Smartphones	1000	1143	1176	1209	1244	1279
Tablets	150	190	229	275	331	398
Device Numbers x10[6] (TV)						
TV	2000	2100	2205	2100	2000	2100
TV STB	760	798	838	798	760	798
TV GC	400	420	441	420	400	420
A/V Receiver	600	630	662	630	600	630
DVD/Blueray	700	735	772	735	700	735
Power Consumption (TWhr/year)						
Desktops	129	116	116	118	119	121
Monitors	60	54	54	55	55	56
Laptops	67	60	64	69	75	81
Smartphones	5	6	6	6	7	7
Tablets	2	3	4	4	5	6
Power Consumption (TWhr/year)						
TV	400	412	432	403	376	380
TV STB	76	78	82	77	72	72
TV GC	54	57	60	57	54	57
A/V Receiver	39	41	43	40	38	39
DVD/Blueray	20	21	22	21	20	21
Total (TWhr/year)	**852**	**846**	**881**	**849**	**821**	**840**

In this 'expected consumption' scenario we anticipate some year-on-year improvements in device efficiencies but these will be gradual. With TV sales of 250 million units per annum it would take 8 years to replace all existing TV panels assuming 1-to-1 replacements. Over the 5-year period covered by our estimates lets assume that a panel with 20% less power consumption replaces 50% of TV panels. This would provide overall net savings of 10%, or annual savings across all TV panels of 2% year-on-year.

Note that we did not chose a higher efficiency for this 'expected consumption' scenario because many upgrades are to a larger TV panel or a smart-TV and this will offset some of the gains from higher efficiency panels.

Alternative Assumption #2 - Stagnant Markets with Growth in Efficiency

Our last scenario uses similar growth assumptions for the ICT sector and caps the installed base of TV panels at around 2 billion in 2017. As discussed in the 'expected consumption' scenario devices like tablets and smartphones are seen as displacing secondary TV sets during this period in the same way they have recently begun to displace desktop and laptop computers. However most households will retain a main TV set.

Table 5(c): Best Case Consumption (2013-2017):, energy usage by category of device.

Device Numbers $x10^6$ (Clients)	2012	2013	2014	2015	2016	2017
Desktops	588	529	521	579	588	529
Monitors	617	556	547	608	617	556
Laptops	832	749	656	729	832	749
Smartphones	1000	1143	1149	1156	1163	1169
Tablets	150	190	217	247	281	321
Device Numbers $x10^6$ (TV)						
TV	2000	2000	2050	2101	2050	2000
TV STB	760	760	779	798	779	760
TV GC	400	400	410	420	410	400
A/V Receiver	600	600	615	630	615	600
DVD/Blueray	700	700	718	735	718	700
Power Consumption (TWhr/year)						
Desktops	129	116	109	103	111	90
Monitors	60	54	50	53	51	42
Laptops	67	60	50	53	57	46
Smartphones	5	6	6	6	6	6
Tablets	2	3	3	4	5	6
Power Consumption (TWhr/year)						
TV	400	390	399	370	343	324
TV STB	76	70	72	63	55	49
TV GC	54	54	56	53	51	49
A/V Receiver	39	38	39	38	37	37
DVD/Blueray	20	19	20	18	17	16
Total (TWhr/year)	**852**	**810**	**804**	**761**	**733**	**665**

In this scenario, which is analogous to the 'best available technology' case of IEA [24] we assume year-on-year improvements in efficiency of 5% - implying double the savings in electricity consumption for TV panels, desktop and laptop computers. When combined with stagnating markets this leads to a net decline in energy consumption, dropping to 665 TWh/yr by 2017. It is not clear that such savings are realizable, but recent trends such as the substantial improvements in power consumption realized by TV panel manufacturers over the last 3 years and significant declines in PC sales during 2013 do suggest that this scenario may not be such an outlier. If further technology breakthroughs are combined with smart and proactive government policies there is no reason.

5.2.2 Comparative datasets

It is interesting to match our model projections with those of other research studies, but unfortunately there are not too many detailed studies available in the literature.

Another approach is to match our three model scenarios with equivalent fixed growth rates. This latter approach provides us with an overall trend for device consumption that can be easily matched with economic and market trends.

Consumption Calculated from IEA [24]

This detailed study by IEA [24] is the most detailed research study available on the electricity usage of CE-ICT devices. Even though it dates from 2009 many of the finding remain very relevant.

We note that IEA identified three different growth scenarios, similar to our own, shown in **table 6(a)**. These are taken from *Annex I, p372* of [24] with intermediate values obtained by simple linear interpolation. These projections are quite compelling, aligning closely with our own estimates from section 5.2.1 and

The equivalent to our high-growth estimate corresponds to the IEA *business as usual* scenario. Similarly our *expected growth* equates to IEA's *least life cycle* (LLC) and our *low growth* matches their *best available technology* (BAT). Numerically all the IEA estimates are in similar ballparks. Their LLC is a bit low in its 2012 estimate, but matches our 852 TWh/yr closely by 2017; the BAT scenario shows negative growth, achieving 678 TWh/yr by 2017 compared to our 665 TWh/yr; finally the high growth estimate from IEA lies close to our 852 TWh/yr in 2012 and grows at a similar rate achieving a higher 1,112 TWh/yr to our 1,057 TWh/yr, but from a higher starting point of 873 TWh/yr.

Table 6(a): TWh/yr for IEA scenarios - BaU (high), LLC and BAT (low) for period 2013-2017.

IEA Predicted (TWhr/year)	2012	2013	2014	2015	2016	2017
Low Growth (Best Available Technology	740	722	704	**686**	682	678
Expected Growth (Least Life Cycle)	793	802	810	**819**	838	857
High Growth (Business as Usual)	**873**	921	970	**1,018**	1,065	1,112

Consumption based on Fixed Growth Rates

While there are not many detailed research studies on electricity consumption of CE-ICT devices is interesting, as discussed above, to match our model predictions with overall growth trends. If we take our 2012 baseline of 852 TWh/yr we find the results of **table 6(b)** for growth rates of -5%, 0% and +5%. These align very closely with our three different growth scenarios.

Table 6(b): TWh/yr for fixed growth rates of -5%, 0% and +5% (2013-2017).

Growth Rate	2012	2013	2014	2015	2016	2017
Low (-5%)	**852**	809	769	730	694	659
Expected (0%)	**852**	852	852	852	852	852
High (+5%)	**852**	895	939	986	1,036	1,087

Our conclusion here is that the three scenarios that we explored in section 5.2.1 can be reasonably matched with these three simpler scenarios. There is no doubt that the per-unit electricity usage by CE-ICT devices is improving. New TV panel display technology and the transition from desktop computer clients to laptops, tablets and smartphones will all bring down the average consumption per device - in some cases quite significantly. At the same time we are seeing stagnation in traditional market segments, but rapid growth in some new device segments. A final consideration is that many older devices are making their way to developing economies, often as e-waste [48]. Yet much of this e-waste is repaired and re-enters the local market extending its lifecycle. It is to be expected that such practices will continue and become more widespread as long as a global economic downturn persists, even where the economic benefits are marginal.

When we balance all these factors we see that while the stagnation of traditional markets for PC and TV panels suggests that the installed base of such devices will not grow significantly there is likely to be an extension of device lifecycle as consumers 'hold on' to devices beyond their normal lifecycle or where devices that are scrapped and exported as e-

Waste are brought back into active service in the gray economy. In parallel there is a gradual improvement in per-device efficiency as newer devices gradually replace older ones. For the newer devices, their contribution to direct electricity consumption is very small compared with the PC and TV segments. A reasonable conclusion is that growth will stagnate, or even decline on an annual basis. Only if the global economy can achieve a significant turnaround in the next couple of years are we likely to see any return to growth in traditional CE-ICT markets over the next 4-5 years.

5.2.3 The Significance of Device Lifetime

The total electricity consumption by CE-ICT devices is dependent on the installed base. In turn the installed base depends on the number of new devices that are entered into service and the corresponding number of devices removed from service. These, in turn, are correlated with the device lifetime.

Of course device lifetime varies considerably even across a single type of device. Nevertheless we can say that a TV typically has a longer lifetime than a desktop computer or laptop. Here, however, we are simply interested in the average lifetime of each device category. More specifically the dependency between shipped units and lifetime has not been considered in sections 5.2.1 and 5.3. The number of new devices entering service can be estimated and this establishes the installed base numbers based on a fixed device lifetime. However variations in device lifetime can have very pronounced effects on both the installed base of devices and the total energy consumption.

The results for Best, Expected and Worst Device electricity consumption are provided below and cans be used as a sensitivity analysis with regard to previous sections 5.2.

Table 7(a): Short (Best) lifetimes

Device Numbers x10^6 (Clients)	2012	2013	2014	2015	2016	2017
Desktops (3y)	445	452	459	467	475	482
Monitors (3y)	495	499	504	510	525	540
Laptops (3y)	662	745	862	1000	1159	1343
Smartphones (2y)	1160	1600	2075	2565	3020	3556
Tablets (2y)	250	400	600	850	1070	1347
Device Numbers x10^6 (TV)						
TV (8y)	1973	1993	2016	2042	2071	2100
TV STB (8y)	691	697	706	715	725	735
TV GC (8y)	296	299	302	306	311	315
A/V Receiver (8y)	592	598	605	613	621	630
DVD/Blueray (8y)	691	698	706	715	724	734
Power Consumption (TWhr/year)						
Desktops	98	94	96	93	90	82
Monitors	48	46	46	45	44	41
Laptops	53	57	66	72	79	83
Smartphones	6	8	11	13	16	19
Tablets	4	6	9	13	18	23
Power Consumption (TWhr/year)						
TV	395	379	383	369	355	340
TV STB	69	63	63	58	53	48
TV GC	40	40	40	40	39	38
A/V Receiver	38	37	37	36	35	33
DVD/Blueray	19	19	19	18	17	17
Total (TWhr/year)	**770**	**747**	**771**	**756**	**746**	**725**

Table 7(b): **Medium (Expected) lifetimes**

Device Numbers x10^6 (Clients)	2012	2013	2014	2015	2016	2017
Desktops (5y)	729	741	753	766	778	791
Monitors (5y)	811	820	830	843	859	875
Laptops (5y)	975	1116	1278	1460	1689	1953
Smartphones (2y)	1160	1600	2075	2565	3020	3556
Tablets (2y)	250	400	600	850	1070	1347
Device Numbers x10^6 (TV)						
TV (10y)	2455	2475	2498	2524	2553	2582
TV STB (10y)	859	866	874	883	893	904
TV GC (10y)	368	371	375	379	383	387
A/V Receiver (10y)	737	743	749	757	766	775
DVD/Blueray (10y)	859	866	874	883	893	903
Power Consumption (TWhr/year)						
Desktops	160	163	162	165	164	164
Monitors	79	79	79	80	80	80
Laptops	78	89	100	114	130	147
Smartphones	6	8	11	14	17	23
Tablets	4	6	10	14	20	28
Power Consumption (TWhr/year)						
TV	491	485	490	485	481	467
TV STB	86	85	86	85	84	82
TV GC	50	50	51	51	52	52
A/V Receiver	48	48	48	48	48	48
DVD/Blueray	24	24	24	25	25	25
Total (TWhr/year)	**1,025**	**1,039**	**1,061**	**1,082**	**1,101**	**1,115**

Table 7(c): **Long (Worst) lifetimes**

Device Numbers x10^6 (Clients)	2012	2013	2014	2015	2016	2017
Desktops (7y)	1011	1023	1038	1055	1072	1090
Monitors (7y)	1281	1133	1146	1164	1185	1206
Laptops (7y)	975	1116	1278	1460	1689	1953
Smartphones (3y)	1510	2060	2775	3465	4195	5079
Tablets (3y)	300	500	750	1100	1420	1833
Device Numbers x10^6 (TV)						
TV (10y)	2455	2475	2498	2524	2553	2582
TV STB (10y)	859	866	874	883	893	904
TV GC (10y)	368	371	375	379	383	387
A/V Receiver (10y)	737	743	749	757	766	775
DVD/Blueray (10y)	859	866	874	883	893	903
Power Consumption (TWhr/year)						
Desktops	223	225	224	227	227	226
Monitors	124	110	109	111	110	110
Laptops	78	89	100	114	130	147
Smartphones	8	11	15	19	24	32
Tablets	5	8	12	19	26	38
Power Consumption (TWhr/year)						
TV	491	485	490	485	481	467
TV STB	86	85	86	85	84	82
TV GC	50	50	51	51	52	52
A/V Receiver	48	48	48	48	48	48
DVD/Blueray	24	24	24	25	25	25
Total (TWhr/year)	**1,135**	**1,135**	**1,158**	**1,184**	**1,207**	**1,227**

One immediate observation is that variations in the device lifetime can have very significant effects on the installed base and consequently the total electricity consumption. Longer device lifetimes are better in terms of reduced manufacturing energy, but imply that older, less energy efficient appliances remain in use longer. We did not find any extensive studies in the literature but there is a clear need to better understand patterns of appliance re-use and, in the global context, how emerging secondary markets (e.g. Africa) are evolving.

5.3 Projections for Manufacturing Electricity

For the future projection of manufacturing electricity the variable is the kWh/unit and the share of the Use stage of total lifetime electricity for Networks and Data Centers. The number of shipped units is also variable but has not been explored.

Data sources for device shipments are given in Section 4.2.2. The tables presented below are deduced using the same methods described in Section 4.2 (table 3). We provide three examples from the "expected case" scenario to clarify the TWh obtained in these tables, namely 1) tablets in 2015 2) data centers in 2017 and 3) monitors in 2014. *(Note that the starting year for these estimates is 2008 manufacturing data, thus 5% efficiency improvement is applied over 7 years for 2015 estimates, 9 years for 2017 estimates, etc)*

1) **Tablets:** 500 million × 75kWh×$(1\text{-}0{,}05)^7$= 26 TWh,

2) **Data Centers:** 541 kWhr / 0.85)} x (1 – 0.85) ×$(1\text{-}0{,}05)^9$ = 60 TWh,

3) **Monitors:** 170 million × 268kWh × $(1\text{-}0{,}05)^6$ = 33 TWh.

Table 8(a): Unit numbers entering service and estimated manufacturing electricity per unit.

Best Case	2013	2014	2015	2016	2017	KWhr/unit (2010)
Desktops	153	156	158	161	164	60
Monitors	165	170	175	180	185	187
Laptops	284	332	384	443	511	75
Smartphones	900	1175	1390	1630	1911	30
Tablets	250	350	500	570	650	78
TV	261	264	267	270	273	400
TV STB	99	100	101	102	103	41
TV GC	52	53	53	54	55	150
A/V Receiver	78	79	80	81	82	100
DVD/Blueray	91	92	93	94	95	200
Networks eq (TWhrs)	383	416	453	495	544	Use stage 90%
Data center eq (TWhrs)	302	325	349	375	403	Use stage 90%

Table 8(b): Manufacturing Electricity Consumption (TWh/yr) - best case scenario.

	2013	2014	2015	2016	2017
Desktops	23	23	23	22	22
Monitors	35	34	34	33	33
Laptops	28	30	32	34	36
Smartphones	27	32	35	38	42
Tablets	14	19	26	28	31
TV	81	81	81	81	81
TV STB	3	3	3	3	3
TV GC	6	6	6	6	6
A/V Receiver	6	6	6	6	6
DVD/Blueray	14	14	14	14	14
Networks eq	52	53	54	56	57
Data center eq	41	42	42	43	43
Total (TWhr/yr)	**330**	**343**	**356**	**365**	**375**

Table 9(a): Unit numbers entering service and estimated manufacturing electricity per unit.

Expected	2013	2014	2015	2016	2017	KWhr/unit (2010)
Desktops	153	156	158	161	164	188
Monitors	165	170	175	180	185	268
Laptops	284	332	384	443	511	134
Smartphones	900	1175	1390	1630	1911	40
Tablets	250	350	500	570	650	75
TV	261	264	267	270	273	400
TV STB	99	100	101	102	103	45
TV GC	52	53	53	54	55	150
A/V Receiver	78	79	80	*81*	82	100
DVD/Blueray	91	92	93	*94*	95	200
Networks eq (TWhrs)	407	469	542	629	731	Use stage 85%
Data center eq (TWhrs)	320	365	416	475	541	Use stage 85%

Table 9(b): Manufacturing Electricity Consumption (TWh/yr) - expected case.

	2013	2014	2015	2016	2017
Desktops	22	22	21	20	19
Monitors	34	33	33	32	31
Laptops	29	33	36	39	43
Smartphones	28	35	39	43	48
Tablets	15	19	26	28	31
TV	81	78	75	72	69
TV STB	*3*	*3*	*3*	*3*	*3*
TV GC	6	6	6	5	5
A/V Receiver	6	6	6	5	5
DVD/Blueray	14	14	13	12	12
Networks eq	56	61	67	74	81
Data center eq	44	47	51	56	60
Total (TWhr/yr)	**338**	**356**	**375**	**390**	**408**

Table 10(a): Unit numbers entering service; estimated manufacturing electricity per unit.

Worst Case	2013	2014	2015	2016	2017	KWhr/unit (2010)
Desktops	153	156	158	161	164	215
Monitors	165	170	175	180	185	334
Laptops	284	332	384	443	511	167
Smartphones	900	1175	1390	1630	1911	60
Tablets	250	350	500	570	650	287
TV	261	264	267	270	273	500
TV STB	99	100	101	102	103	50
TV GC	52	53	53	54	55	150
A/V Receiver	78	79	80	81	82	100
DVD/Blueray	91	92	93	94	95	200
Networks eq (TWhrs)	431	528	649	797	981	Use stage 80%
Data center eq (TWhrs)	337	405	485	583	699	Use stage 80%

Table 10(b): Manufacturing Electricity Consumption (TWh/yr) - worst case scenario.

	2013	2014	2015	2016	2017
Desktops	22	22	21	20	19
Monitors	34	33	32	31	30
Laptops	30	34	38	42	47
Smartphones	31	41	47	54	61
Tablets	30	48	74	83	92
TV	80	76	72	69	65
TV STB	3	8	7	7	7
TV GC	6	12	11	11	11
A/V Receiver	6	12	11	11	11
DVD/Blueray	14	28	27	26	24
Networks eq	62	76	92	111	134
Data center eq	48	57	68	80	93
Total (TWhr/yr)	**366**	**445**	**501**	**543**	**593**

5.4 Network Electricity Consumption

There is general consensus in the literature that networks are growing as is the amount of electricity that they consumer [20], [36], [76], [79]. A more difficult question is to try and quantify this growth in some sensible way. However the communications networking infrastructure is so intertwined and no one body or organization has an overview of how it is evolving. And a lot of data on network infrastructure is commercially sensitive, thus no available publicly.

However there is a way to get a broad sense of network growth and that is to look at projections for data traffic over the next few years. This information is quite readily available and in fact a number of annual reports are available [28], [29]. These suggest growth rates of 30% for core network data and 70%+ for mobile data and were discussed previously in some detail in section 3.3.2. Naturally we don't expect the energy usage to rise a the same rates, because improvements in terms of both technology and data management practices will lead to an annual increase in operating efficiency.

Another important point to make is that it is not simply the growth in device numbers that drives the need for increased network capabilities. In parallel there are more network services available and thus network usage per device is growing. This is shown in Table 11 which compares the averaged monthly data usage for different categories of device as determined by the CISCO Visual Networking Index (VNI) studies [28] from 2009, 2010, 2011 and 2012. The projected growth rate for the period 2012-2017 is taken from the 2012 VNI.

What is particularly interesting from this comparison is that tablet devices and 4G smart-phones are predicted to consume as much network data as laptops by 2017 and this is more than twice the amount of data that is consumed by one of today's laptops. Thus, in the context of the network, thin clients such as smart-phones and tablets will be every bit as important in terms of bulk network data and consequently network electricity consumption as desktops and laptops are today.

Table 11: Data from the annual CISCO VNI reports - 2009, 2010, 2011 and 2012 - showing evolving trends in terms of network data consumption (MB/month) by various categories of handheld devices.

Device Category	2009	2010	2011	2012	CAGR (2012-2017)	Projected (2017)
Laptop	1,145	1,460	2131	2,503	31%	5,731
Smartphone	35	55	150	342	81%	2,660
Smartphone (4G)	--	--	--	1,302	--	5,114
Tablet	28	405	517	820	113%	5,387
Gaming Console	--	244	317	--	--	NA
Mobile Phone	1.5	1.9	4.3	6.8	--	31

From table 11 we can thus begin to understand the radical shift that is occurring and the potential impact of thin clients on electricity consumption. While these devices use very little electricity themselves they catalyze growth in communications networks, and in particular in wireless access networks. From table 11 it can be seen that these devices will match laptops in terms of their requirement for network bandwidth by 2017. And that, in turn, is twice the bandwidth usage of today's laptops.

5.4.1 Based on Raw Data Traffic Growth

The growth of network electricity consumption and its research by previous authors is considered in sections 3.3 and 4.3. Our goal here is to determine an approach to extrapolate our estimated base figure for 2012 over the period until 2017. The most useful and reliable source of data we have for this period is that of network data traffic. As previously discussed thus suggests a 30% year-on-year growth rate for core data [29] and in excess of 70% for mobile data [28].

The next metric we need is the energy cost per unit of data. This was considered recently as the core topic of Coroama *et al* [125] where they estimated the energy flow at 0.2 kWhr/GB, or to convert it to units that make more sense for our scale of estimation we multiply above & below the line by 10^9 to get 0.2 TWh/EB. As indicated by Coroama *et al* this is likely a conservative estimate for the wired Internet so we should search for more exact estimates.

The 'Corporate Responsibility Report 2010/11' for Verizon [126] indicates 0.15 TWh/EB in 2009 and 0.13 TWh/EB in 2010. Verizon has set targets to increase its network efficiency to achieve below 0.08 TWh/EB by 2020. This is a relatively modern company and these metrics appear to be relatively high-performing compared to others in the telecoms sector.

For example Telecom Italia reported values of their Eco-Efficiency indicator [127] that give energy costs for data of 0.32 TWh/EB in 2007 and 0.24 TWh/EB in 2008 [128] but suggest that further improvements on the 2008 figures will not be realistic. However in a more recent 2012 sustainability report [129] this metric is again provided indicating its 2010 value at 0.17 TWh/EB, 2011 value at 0.13 TWh/EB, and most recently the 2012 value is 0.115 TWh/EB.

Thus after some consideration we have decided to use an industry-wide value of 0.135 TWh/EB representing our best-case 2012 scenario; a slightly higher starting point of 0.14 TWh/EB represents our expected case and our worst case scenario begins at 0.145 TWh/EB. As with all our estimates these are speculative, but the intention is to show how only a small change in the overall efficiencies and the targets set by industry can result in wide variations in the eventual outcomes. For our best case we assume 15% increase in efficiency on a year-by-year basis – this is even more challenging than the goals set by Verizon for 2020. The expected case uses a target of 10% annual improvement while our worst case only aims for 5% year-on-year improvement in efficiency. These are summarized in **Table 12** below.

Table 12: Network Electricity Consumption (TWh/yr) estimated from network data traffic.

	YoY Efficiency Increase	2012	2013	2014	2015	2016	2017
Data Traffic (EB)		2600	3300	4100	5200	6600	8500
0.135 TWhr/EB	**15%**	351	379	400	431	465	509
0.14 TWhr/EB	**10%**	351	401	449	512	585	678
0.145 TWhr/EB	**5%**	351	423	500	602	726	888

Here we can see the importance of continual improvement, as even assuming an optimal industry-wide starting point of 0.135 TWh/EB and 15% annual improvements in efficiencies we find that network consumption of electricity will rise from the 2012 baseline of 351 TWh/yr to more than 500 TWh/yr. The substantial growth in data traffic is ultimately responsible for this. For our expected projections the growth is even more substantial leading to an increase to 678 TWh/yr or a 91% increase on the 2012 consumption of electricity. For our worst case the 5% annual efficiency improvement is shown to be inadequate with more than 150% increase in electricity consumption.

5.4.2 Wireless Access Networks

There is a growing realization in the literature that the primary cost of modern telecommunications networks does not in fact arise from the core wired or fibre-optic network, but in fact from the access network – that portion of the network that enables individual subscribers to connect and gain access to the main core infrastructure. To date this has not been of great concern to the telecommunications industry as the amount of data that originates through their wireless access networks is very small when compared with overall network traffic.

For example, in 2012 mobile networks are expected to carry no more than 0.9 EB of data per month, or just over 10 EB in the entire year; but the global IP traffic, including data-centers will be 1800 EB over the same year. Thus mobile data is only 0.6% of the network traffic. By 2017 global IP traffic will be close to 9000 EB whereas mobile IP traffic will be a mere 134 EB, or 1.5%.

Wireless Home Access – A Hidden Cost?

Of course the figures we give here relate to what ISPs call 'mobile data' implying that it is data gathered by the ISPs own network. This does not include the significant volumes of data that are introduced to the network via home Wifi routers. In fact quite a significant proportion of home network access is via a Wifi router but as the electricity costs are paid by the subscriber this does not impact on the service provider and thus is not included in their metrics. Most modern thin clients provide features to restrict mobile data so that only a home Wifi link is used to upload and download large data files. This practice is known as 'data offloading' and it tends to hide the true costs of the wireless component of the access network.

Some studies have suggested that up to 50% of current network energy costs are due to the wireless portion of the network [36]. This may indeed be true if we factor in home WiFi routers and take into consideration the huge growth in new thin client devices. We also note that some studies do not seek to make a distinction between the two network infrastructures [17], [20], [126] although it is broadly recognized that the wireless access portion of the network requires significantly more power [36], [45], [76], [77], [79].

The recent study from CEET [79] on wireless networks has addressed this issue and provides estimates of the portion of wireless network energy consumption arising form home WiFi. This is about 50% of the mobile access network in 2012 and should remain at about that ratio to 2015.

Energy Efficiency and LTE/G4 Networks

From figure 11, page 16 of the VNI 2013 report [28] we note that by 2017 almost half of mobile data will be carried by LTE/G4 networks. Thus LTE is envisaged to become the access network of choice for many subscribers although many networks are still being rolled out in a 2013/14 timeframe.

We next need to consider the energy per data unit for the wireless access infrastructure. It is actually not easy to find a sensible value for this part of the network infrastructure. There are studies that provide some insight but few that give practical data or measurements. The most useful of these is the EARTH project funded by the European Union [130] which contains the outcome of detailed modeling and practical studies on LTE networks and in table 11 of deliverable 2.4 [131] provides practical estimates of two different LTE network scenarios – one with 20% of heavy users and an efficiency of 1.37 TWh/EB and a second scenario with 50% of heavy users and an efficiency of 0.73 TWh/EB. These figures are derived using the 2010 power model for LTE networks.

Other studies exist but not at the level of detail of the EARTH project. In fact there is a very significant body of literature surrounding LTE and various aspects of power consumption and efficiency relating to LTE. What is clear is that LTE can be efficient but it needs to operate at very high throughput to achieve efficiency, whereas in more practical cases where it is employed it is significantly under-utilized. In the EARTH study it is mentioned that even with many heavy users on the system it operated on average with no more than 10% of transport frames carrying data. Another study [132] presents the work of the EARTH project in a more concise format.

A study by Huang *et al* [75] on working LTE networks in the US found significantly better downlink and uplink data rates of 13 Mpbs and 6 Mbps respectively when compared with 3G and Wifi networks. But, despite several new power saving improvements, LTE networks were found to be as much as 23 times less power efficient compared with WiFi, and also less power efficient than 3G. In particular the long high-power tail of LTE was found to be a key contributor. In another study by CEET [79] the significance of the wireless access network is again highlighted. These authors also find that LTE/G4 is about to become the main source of electricity consumption in the access network and when combined with Wifi and other mobile wireless networking technologies will grow much faster than the network component of data centers.

5.4.3 Separating the Wireless Access Component

Our next challenge is to figure a sensible approach to achieve this separation. There are multiple issues here as some of the wireless access consumption is, in our opinion, hidden by home wireless installations. However it is better to analyze and quantify where we have useful data so we adopted this approach.

To separate the wireless access component we used the data projections from CISCO [28] for growth in mobile data. These show monthly estimates of mobile data growing from 0.9 EB in 2012 to 11.2 EB in 2017. Thus annual totals increase from 10.8 EB to 134 EB in 2017

– an annual growth rate in excess of 70%[20]. If we remove this element from the core data we can treat it based on what appear to be sensible efficiency estimates based on the literature specializing on wireless and LTE/G4 networks.

To match our three scenarios – best/expected/worst cases – we used the higher value estimate from the EARTH project of 1.37 TWh/EB as a starting point; for expected case the lower EARTH value of 0.73 TWh/EB was employed and for best-case analysis we used a lower starting point of 0.5 TWh/EB – these are shown in Table 13 below. An annual improvement rate of 5% was applied starting with 2012 values. We used a ration of 1.46 for the relative efficiency of 3G networks, deduced from [75]. Thus the energy usage of 3G is estimated at c. 66% that of our LTE and mobile data is split between 3G and LTE as estimated by [28]. We did not assume a higher improvement rate that 5% on the basis that LTE/G4 networks are a new technology and it is to be expected that many large-scale deployments will perform less efficiently than the 'ideal' cases studied by EARTH.

Table 13: Network Electricity Consumption per Exabyte (TWh/EB) estimates for best, expected and worst case network growth scenarios.

	Low Growth	Expected Growth	High Growth
LTE	0.5 TWh/EB	0.73 TWh/EB	1.37 TWh/EB

One difference that will be noted by the observant reader is that our estimates for the core network projections differ slightly from those in section 5.4.1 – this is because we decided to align our three growth scenarios for the core network with a fixed growth percentage. This provides an alternative metric to compare our estimates with other studies. We found in the best case analysis that overall core network growth is likely to proceed at 7.5% - this may seem higher than some studies but we have used the 30% year-on-year growth projections for network data, combined with an optimistic 15% year-on-year improvement in efficiency. For our expected growth case the match is to a 14% annual growth rate with our worst-case analysis achieving a 20.5% growth rate with only a 5% annual efficiency improvement.

Projections for all three growth scenarios are presented in tables 14(a), (b) and (c) below. The total annual mobile data projected for each year is shown in table 14(a) followed by the projected electricity consumption of the core and wireless access networks. We note that CEET [79] project a low value of 17.8 TWh/yr for 2015 which matches our best-case and expected estimates; their worst-case is 25.5 TWh/yr which aligns nicely with our expected growth scenario. It is worth commenting that in the early part of the 21st century many large telcos had been quite successful in achieving annual improvements in energy efficiency of up to 20% in core networks but this has slowed to a 10% improvement in recent years [78].

Perhaps the most notable aspect of all three scenarios is that wireless network contributions will be more than doubled from their 2015 values by 2017. The overall contribution of wireless access is still relatively small (<10%) compared to the core network expansion, but based on our assumptions it is projected to grow at rates of 2-3 times that of the core.

Table 14(a): Network Electricity Consumption per Exabyte (TWh/yr) estimates for wireless and core from 2012-2017. Data in Exabytes is also shown. Best case.

	2012	2013	2014	2015	2016	2017
Non-LTE (EB)	9.3	15.7	25.9	40.0	56.8	73.9
LTE (EB)	1.5	3.5	7.7	16.4	32.0	60.5
Wireless	3.7	6.4	10.9	17.8	27.4	40.8
Core	350.3	376.5	404.8	435.1	467.8	502.8
Total	354.0	383.0	415.7	453.0	495.2	543.7

Table 14(b): Network Electricity Consumption per Exabyte (TWh/yr) estimates broken into wireless and core from 2012-2017 – for expected case analysis.

	2012	2013	2014	2015	2016	2017
Wireless	5.5	9.4	15.9	26.0	40.0	59.6
Core	348.5	397.3	453.0	516.4	588.7	671.1
Total	354.0	406.7	468.9	542.4	628.7	730.7

Table 14(c): Network Electricity Consumption per Exabyte (TWh/yr) estimates broken into wireless and core from 2012-2017 – for worst-case analysis.

	2012	2013	2014	2015	2016	2017
Wireless	10.2	17.6	29.8	48.7	74.9	111.6
Core	343.8	413.9	498.4	600.0	722.4	869.8
Total	354.0	431.5	528.2	648.7	797.4	981.4

5.5 Data Center Electricity Consumption

Data Centers have been discussed in some detail in sections 3.4 and 4.4. As was previously commented this is the most difficult component to find useful data. Koomey's approach [31] leverages data on the shipment of servers, but even this is likely to be incomplete. Some operators use custom builds of hardware and these may not appear under conventional server shipments.

Nevertheless we have started from Koomey's 2010 baseline. Our original approach was to select separate growth rates from the 2010 baseline, but this led to different 2012 estimates. Again, a key goal of our work is to have a common starting point from 2012 for each category of electricity consumption. Thus, if some of our baseline estimates are shown to be inaccurate it is very straightforward to adjust the model upwards, or downwards from 2012 as appropriate. Bearing this in mind we decide to extrapolate from 2010 using our expected scenario and use this to establish a common 2012 baseline. This is illustrated in Table 15 where we obtained a 2012 baseline of 281 TWh/yr.

From 2012 we then decided to use the fixed rates determined from our analysis of the core network data to model data center growth. This is a relatively crude approach, but at this point it is the best we have and it seems quite reasonable that data center growth would follow that of the core network. Again we restate the assumption that network infrastructure within and between data centers is part of core network - thus we are only considering the data processing, storage and HVAC infrastructures of data centers.

Applying this approach to our baseline yields the projections provided in table 15 below.

Table 15: Network Electricity Consumption projections for Data Centers in (TWh/yr); based on fixed growth rates determined from growth in core network capacity in section 5.4.3 above.

	2010	2011	2012	2013	2014	2015	2016	2017
Low Growth (7.5%)	223.2		280.9	302.0	324.7	349.0	375.2	403.3
Expected Growth (14%)	223.2	254.4	280.9	320.3	365.1	416.2	474.5	540.9
High Growth (20%)	223.2		280.9	337.1	404.5	485.5	582.5	699.1

A first observation is that growth is not as aggressive as for networks. There is no equivalent element of data center function that can be equated to the LTE/G4 access network. Thus data centers are likely to evolve in a more straightforward way compared to the networks that supply them. In fact data centers may benefit from a range of emerging strategies such as strategic choice of geographic location to minimize HVAC costs; use of GPU technology to mitigate the computational costs of video processing; economies of scale as smaller data-centers coalesce into larger regional clusters. Note, however, that many economies within the data center require greater data mobility and will thus tend to drive network traffic. The reality is that data center and network are becoming increasingly entwined in a 'back-end' that is no longer transparent to the consumer. We will return to this concept of the hidden back-end in our concluding discussion.

6. Projections for Total CE-ICT Electricity Consumption

Now we must first thank the reader for their patience as we worked through the various parts of this complex puzzle. It has been quite a journey, but we can now put the pieces back together and get a better understanding of the combined electricity consumption due to today's digital lifestyle.

6.1 Combined Projections for Low, Expected and High Growth Scenarios

Here we present in table 16(a) the combined totals for the different growth scenarios of our model. These are annual electricity consumption totals given in terrawatt-hours per annum (TWh/yr). We note that if all 'best case' criteria are met there could in fact be an overall reduction in electricity consumption generated by CE-ICT devices. Indeed some of the trends that might be essential to this transition are already in evidence. We already commented on the recent drop in sales of personal computers [41] [43] and it was also mentioned that TV panel sales have been stagnant for the last few years [37], [38]. Both device categories are the most energy-hungry of CE-ICT devices thus a shift in device sales to tablets and a reduction in TV panel sales could help meet the reduced direct consumption targets of our best-case scenario. Our best case scenario suggests that consumption can be constrained to less than a very reasonable annual 2% growth rate - this is below the overall growth rate of world electricity consumption and would be achieved through a combination of improved operational efficiencies and new technologies.

Table 16(a): Projections of total electricity consumption in (TWh/yr); based on the best/expected/worst case scenarios for devices (direct consumption and manufacturing energy), networks and data centers, as outlined throughout section 5.

TWh/yr	2012	2013	2014	2015	2016	2017
Best Case	1,817	1,832	1,858	1,895	1,929	1,982
Expected	1,817	1,923	2,051	2,200	2,358	2,547
Worst Case	1,817	2,045	2,317	2,643	2,998	3,422

On the other hand our worst case scenario suggests that a near doubling of electricity consumption over the next 5 years could also be plausible! This suggests an overall growth rate in the region of 13% per annum, driven primarily by unconstrained expansion in the networking and data center industries and a return to growth in consumer markets for CE-ICT devices. Now while this latter scenario seems less probable given the current state of the World economy it is interesting to note that global electricity consumption rebounded by 5% in 2010 compared with a 1.9% decline in 2009, driven mainly by the developing economies, particularly China [23].

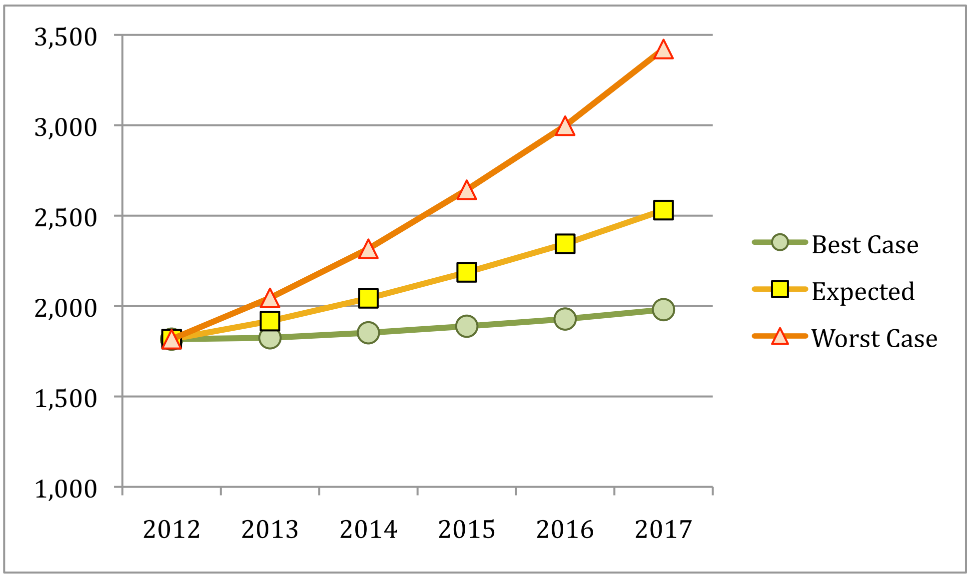


Figure 3(a): Graph of electricity consumption in TWh/yr for best/expected/worst case scenarios.

Perhaps a more useful presentation is provided by table 16(b) which shows the percentage of total global electricity that is attributable to CE-ICT 'gadgets' – here we have assumed a 3% annual growth in total electricity consumption, a figure that has been adopted by other authors [20]. This is from a baseline of 23,192 TWh/yr in 2010, the most recent figures available to us [23]. In this case our best case scenario shows the consumption of electricity by CE-ICT decline as a proportion of global electricity consumption from 7.4% in 2012 to 6.9% in 2017. For our expected growth scenario the increase is to 8.9%, a significant rise but not unexpected given the many disruptive technologies at work in the CE-ICT sector.

Table 16(b): Projections of the combined %age of total global electricity consumption in (TWh/yr); based on the best/expected/worst case scenarios as outlined throughout section 5.

Total Electricity	21,039	21,670	22,320	22,990	23,680	24,390
Best Case	7.4%	7.2%	7.1%	7.0%	7.0%	6.9%
Expected	7.4%	7.6%	7.9%	8.2%	8.5%	8.9%
Worst Case	7.4%	8.1%	8.9%	9.8%	10.8%	12.0%

If however, things do not go to plan we have our outlier, but plausible, worst-case scenario. Here we see demand for PCs & TV panels is revitalized by the demands of emerging economies and the new middle classes of Brazil, India, Russia and China. In turn LTE/G4 networks create new demands for network services and introduces broadband Internet to large urban population centers in Africa and Asia, but the communications industry fails to mitigate the large electricity requirements of these networks in their quest for short-term profits. In turn new data centers and core network backbones are hurriedly installed to handle the accelerated global demand for network and cloud services. In turn electricity consumption will jump by 40% in a five-year timeframe and the proportion that can be associated with CE-ICT becomes 12% of global electricity.

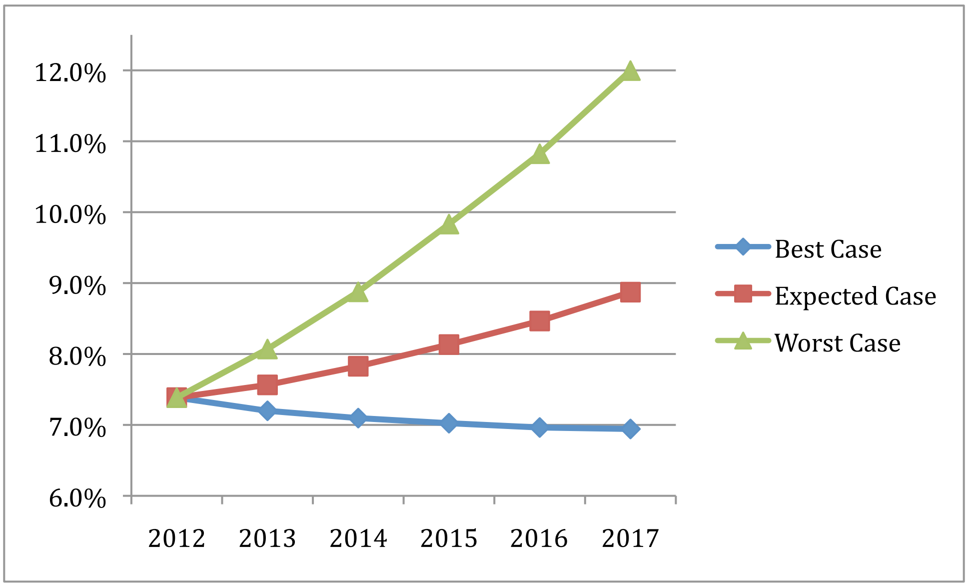


Figure 3(b): Percentage of global electricity consumption due to CE-ICT for best/expected/worst case scenarios.

6.2 Comparative Analysis

At the beginning we outlined the scope of this work was to try and quantify the total proportion of global electricity consumption that can be ascribed to the use of CE-ICT devices. To this end we categorized 4 principle forms of energy that contribute to total energy usage: (i) direct usage; (ii) manufacturing energy (LCA); (iii) network infrastructure; (iv) data centers. It is instructive to consider the relative contribution of these components and, more interestingly to observe how they are likely to change over the next five years.

To this end *figure 4* shows the relative contributions for our 2012 baseline data in each category. It is pretty clear from this figure that direct consumption by devices is just a shade less than half of the total contribution at 47%. Each of the three remaining components are nearly equal with data centers at 15%, manufacturing at 18% and networks at 20%.

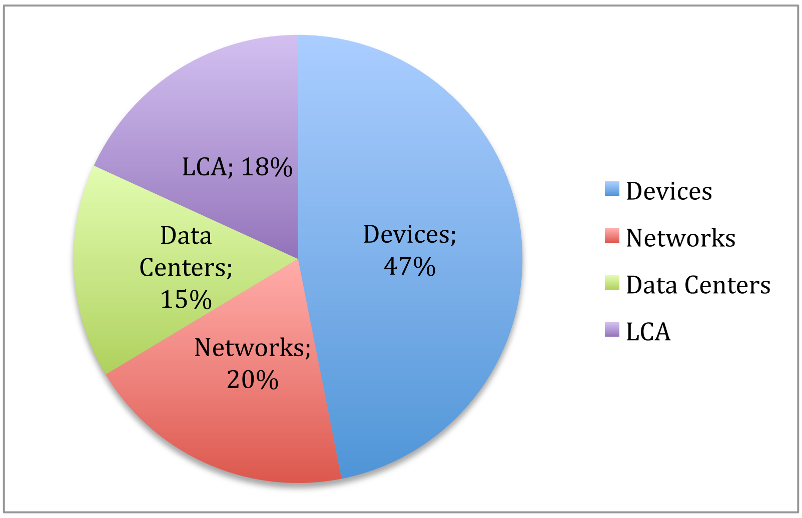


Figure 4: Graph of the 4 main components of electricity consumption (2012 baseline).

Next in *figure 5(a), (b)* and *(c)* we take a look at the same data for 2017. What is remarkable here is that there is very little difference between the ratios of these components regardless of the growth scenario. The direct energy usage by devices ranges from 31-34%; networks range form 26%-29% and data centers from 21%-25% with LCA lying in the range of 16%-19%.

We can make a number of observations on this projected 2017 data:

• direct consumption by devices is less than 1/3 of electricity; compare with 1/2 in 2012.

• data centers + networks combined now represent 1/2 of electricity usage

• LCA remains approximately at the same level of contribution

So over the next 5 years we will see the combined contributions of networks & data centers switch place with direct electricity usage. In other words our CE-ICT devices will consume more electric power *indirectly*, outside the home than in the home itself. And this trend looks set to continue for the foreseeable future. It is also interesting that this transition is independent of the growth scenario.

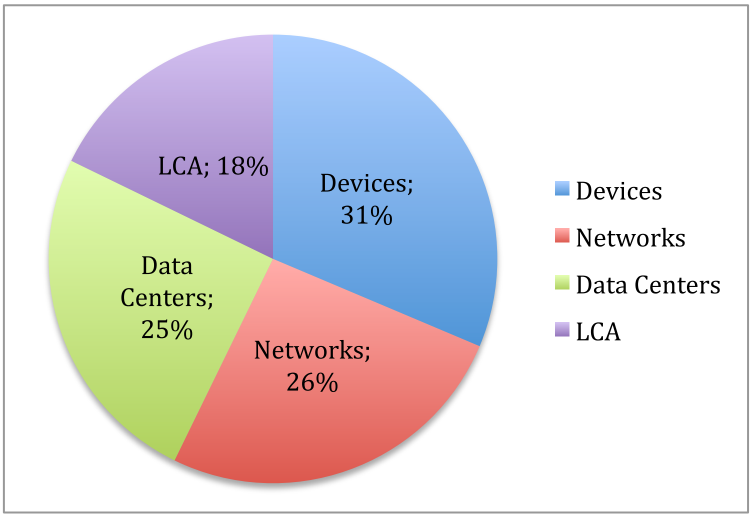


Figure 5(a): Graph of the 4 main components of electricity consumption (2017 best-case scenario).

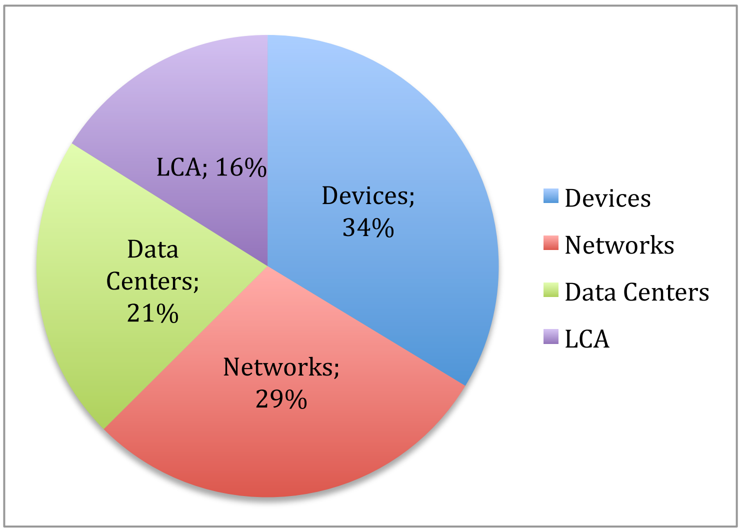


Figure 5(b): Graph of the 4 main components of consumption (2017 expected-case scenario).

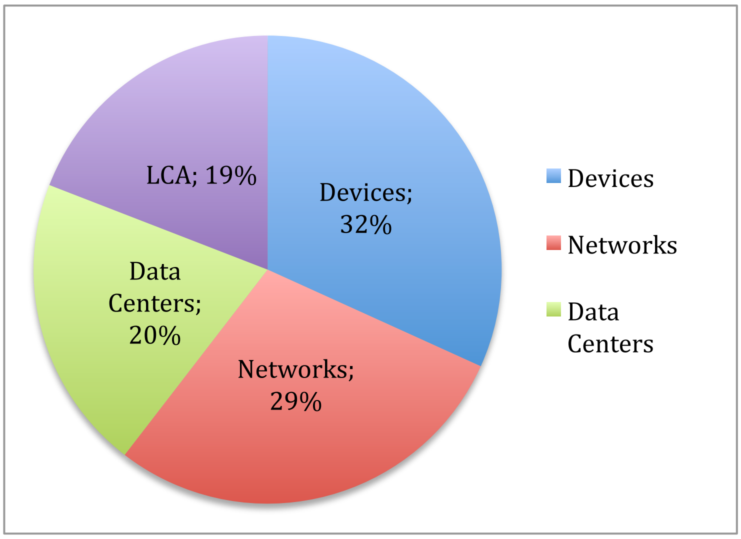


Figure 5(c): Graph of the 4 main components of consumption (2017 worst-case scenario).

6.3 Discussion

Our study highlights some trends that have been commented on by earlier researchers.

The clearest trend in 2013 is the decline in the desktop computing market as growth in sales of thin-client devices, tablets & smartphones, continues unabated. But this is not the only trend that can be observed from our analysis.

To help with organizing our final discussion we have grouped it into three sections: firstly we discuss some of the encouraging trends that suggest our best-case scenario may be viable; secondly, we discuss emerging challenges - these are the factors that will push consumption in the direction of our worst-case analysis; finally, we give some consideration to external factors - the global economy, the potential impact of developing economies and global shifts in demographics, social structures and individual behaviors all of which could strongly influence how CE-ICT evolves over the next decade.

6.3.1 Positive Impacts of Emerging Technologies & Synergies

The Energy Efficient TV Panel

We have already commented on this in section 4.1.3 noting that very significant improvement has been made and that by 2014 practically all TV panels will consumer less that 100W. This is important because TV panels are the single most significant source of direct electricity consumption among CE-ICT appliances and industry efforts to improve the underlying technology are to be commended.

The key variable here are the replacement rate of older TV panels, a variable that has not been researched in the literature. This variable is, in turn, tied in with the lifecycle of TV panels. In section 5.2.3 we took a look at the potential impact of different device lifecycles and it is clear that this can be substantial. Many TV panels will continue to function beyond their planned lifecycle and may be re-sold, or re-used within the household of the original owners. Government policies and industry recycling initiatives can encourage a higher replacement of older devices and there is a need for more studies in this area to determine how best to optimize the transition to lower power appliances.

What we can say with some certainty is that the contribution of TV panels to electricity consumption will enter a downward trend over the next decade and there is some scope to accelerate the rate of this decline. At some point towards the end of the decade we should see at least a 50% decline even if the installed base of TV panels continues to grow.

The Demise of the Desktop?

The market for desktop PCs has been stagnant for some time, primarily because of the reduced costs and greater convenience of laptop computers but from early 2013 there has been a pronounced decline in this market [43]. However we are not convinced that consumers are substituting desktop computers with tablets because the use-modes are different; desktop or laptop computers are still needed for 'work' in the home office, whereas tablets are primarily entertainment devices for use on the couch [27].

A continuation of the transitioning to laptops is, however, likely to continue and the desktop computer will need to reinvent itself if it is to survive the next decade. As in the case of TV panels the transitioning from today's desktop to laptops is very likely to eventually lead to at least a 50% decline in direct electricity consumption by home computing appliances over the next decade, even if there is growth in the installed base of these devices. But within the timeframe of the current study a growth in demand from developing economies will counterbalance any declines in the developed world. Our best-case estimate sees PC sales remaining stagnant, but with 5% annual improvement in efficiency reducing electricity consumption by c. 25%.

New Network Architectures

One challenge we will discuss shortly is that of mobile access networks. Modern devices almost invariably use a wireless connection to connect to the network. Next generation mobile wireless access networks have much potential inefficiency built-in and could become a very expensive 'power-hog'. On the other hand consumer are coming to expect ubiquitous connectivity.

In response various researchers have suggested new hybrid wireless/optical approaches to provide broadband access networks. A recent summary is given by Shi *et al* [133].

6.3.2 'Emerging' Challenges and their Potential Impacts

The Growth of Mobile Access Networks

There remain, however, significant challenges in the networking and data center portions of the energy consumption equation. Network operators across the world, from China to Europe and the Americas are in the process of rolling out the next generation of mobile access networks. Our reviews of the literature on LTE/G4, as this technology is commonly known, suggest that the energy efficiency of these networks will be highly dependent on well thought out deployments and the use of sophisticated load balancing/shifting policies. This is a largely unknown quantity for the communications industry and if things do not go smoothly the networking component of electricity consumption could become an industry-wide power hog. However the industry is aware of this and has strong motivations to achieve successful deployments of LTE/G4 as future profitability will depend on these.

This was discussed at some length in section 5.4.2 and despite many studies the practicalities of these networks remain largely unknown. Two things are clear - firstly most LTE/G4 networks will operate at much less than capacity and thus at poor overall efficiency; secondly, the local network topology, traffic balancing between different cell sizes and operational policies will determine the practical efficiencies of these networks rather than the digital simulations that are used for most of today's estimations.

There is already a large body of literature concerned with the problems of optimizing these networks. In this paper we simply identify their energy-efficient deployment and management as a significant challenge for service providers over the nest 5 years. If successful these access networks will bridge almost half of all global mobile data traffic onto the core network by 2017 [28].

For data centers we envisage less challenges as the industry is already working on innovative modular solutions and low-power CPU technology is being driven strongly by the needs of the mobile device market. However it is important that improved sources of data are made available. There is an admirable policy in the communications industry to make available key metrics on energy efficiency of networks The data center industry needs to introduce similar strategies in order to capture public confidence. Google is one of the more forthcoming operators of data centers, but they represent a relatively small proportion of this industry. In fairness it is still a young industry and will have significant challenges to face, particularly in terms of public image [115], over the next few years.

Cloud Computing

Originally a concept of the 1960s [25] cloud computing transitioned from a business-to-business solution into a consumer service industry during 2009-2011 with the emergence of a range of new services for consumers. These included data backup and storage from Dropbox, Sugarsync, Amazon cloud drive, Skydrive and Google drive and services offering added value sharing and management of personal content such as pictures (Flickr, Snapfish, Photobucket) and video (youtube).

Now cloud-computing services drive demand for both network infrastructure and data centers. There are arguments that some efficiencies are better implemented on a large scale and cloud-computing will facilitate these - for example it makes sense to share one copy of a song, or movie between 100,000 users rather than have each user store and access a personal copy. On the other hand a cloud computing storage service encourages a user to upload and share their personal content that might have stayed on a home computer. Consider a video of an Xmas school play that is uploaded to *youtube* and then shared with 20 sets of parents, generating many gigabytes of data traffic. And frankly, many of these new services are quite compelling for consumers.

The challenge for the cloud-computing industry is not how to put the genie back in the bottle - it is already too late for that! - but rather how to stop the genie growing too quickly.

The Internet of Things and the 'connected' Microwave oven

Network-connected appliances are becoming more commonplace. Our CE-ICT devices are mostly connected to the Internet, but even legacy TV sets can now be linked to a low-cost "smart-TV" box that bridges your TV onto your home network. However the real breakthrough into what is known as the "Internet of Things" (IoT) will come when our kitchen appliances start to become 'connected' [134]. Expert projections indicate that the number of networked appliances could reach 50-100 billion over the next 5 to 10 years [135], [136].

However the concept of network-connected appliances is not exactly new [137–140] and there are anecdotal discussions about the networked refrigerator every time a new 'smart-home' concept is unveiled to the public, but this deluge of devices has yet to manifest itself. It is true that given the low cost of modern wireless connectivity there has never been a better time for the IoT to gain momentum but the authors remain a little skeptical of the benefits, except in some limited examples. Thus we record IoT as a potential emerging challenge, but a 'potential' one that has not made significant progress in the last 20 years.

6.4 Concluding Remarks

As noted in our introduction the CE-ICT industry is experiencing a radical and global shift brought on by a confluence of disruptive technologies. Cloud computing, high-speed wireless access networks and rapidly evolving thin client technology are emerging to meet changing consumer demands and new usage patterns for CE-ICT. In turn we are seeing the emergence of a wealth of new ICT products and services together with new patterns of consumption and socio-economic behaviors and an evolving network infrastructure to support these changes.

A key goal of this work has been to outline a framework for evaluating future electricity growth patterns and determine various factors and emerging trends that can influence the future evolution of CE-ICT.

Thus, while we have presented a broad range of possible future outcomes, these are supported with quite detailed sets of data and assumptions and compared with equivalent work from other researchers to provide, where practical, a consensus. It should thus be possible to review our work and assumptions retrospectively and identify where our approach has aligned usefully with future growth patterns and where it has not.

The three growth scenarios used to project 2013-2017 data represent a very wide range of possibilities, but the goal of this work is not so much to provide an accurate future prediction - in reality there are too many unknowns. Instead we have tried to consider some alternative scenarios and illustrate how the future may unfold. And while our hopes lie with an overall decline in electricity consumption on the lines of our best-case scenario, the alternative worst-case scenario shows annual compound growth rates in electricity usage of more than 12% for the next 5 years. This can serve as a motivation for all of us in different industry sectors to continue to focus research efforts to improve efficiency and reduce the impact of new technologies across the sector.

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