THE POWER OF WIRELESS CLOUD

An analysis of the energy consumption of wireless cloud

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

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EXECUTIVE SUMMARY

Previous analysis and industry focus has missed the point: access networks, not data centres, are the biggest threat to the sustainability of cloud services. This is because more people are accessing cloud services via wireless networks. These networks are inherently energy inefficient and a disproportionate contributor to cloud energy consumption.

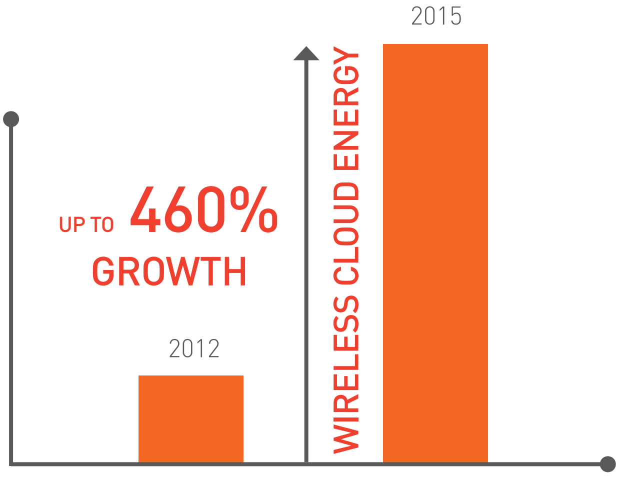
Cloud computing has rapidly emerged as the driving trend in global Internet services. It is being promoted as a green technology that can significantly reduce energy consumption by centralising the computing power of organisations that manage large IT systems and devices. The substantial energy savings available to organisations moving their ICT services into the cloud has been the subject of several recent white papers.

Another trend that continues unabated is the take-up and use of personal wireless communications devices. These include mobile phones, wireless-enabled laptops, smartphones and tablets. In fact, tablets don't accommodate a traditional cable connection; rather it is assumed a local or mobile wireless connection will be used to support all data transferred to and from the device.

There is a significant emerging convergence between cloud computing and wireless communication, providing consumers with access to a vast array of cloud applications and services with the convenience of anywhere, anytime, any network functionality from the device of their choice. These are services many of us use every day like Google Apps, Office 365, Amazon Web Services (AWS), Facebook, Zoho cloud office suite, and many more.

To date, discussion about the energy efficiency of cloud services has focussed on data centres, the facilities used to store and serve the massive amounts of data underpinning these services. The substantial energy consumption of data centres is undeniable and has been the subject of recent high-profile reports including the Greenpeace report, *How Clean is Your Cloud*.

However, focussing cloud efficiency debate on data centres alone obscures a more significant and complex problem and avoids the critical issue of inefficiency in the wireless access network.



Data centres are only part of a much larger cloud-computing ecosystem. In fact, as this white paper puts forward, the network itself, and specifically the final link between telecommunications infrastructure and user device is by far the dominant and most concerning drain on energy in the entire cloud system.

Based on current trends, wireless access technologies such as WiFi (utilising fibre and copper wireline infrastructure) and 4G LTE (cellular technology) will soon be the dominant methods for accessing cloud services. 'Wireless cloud' is a surging sector with implications that cannot be ignored.

Our energy calculations show that by 2015, wireless cloud will consume up to 43 TWh, compared to only 9.2 TWh in 2012, an increase of 460%. This is an increase in carbon footprint from 6 megatonnes of CO_2 in 2012 to up to 30 megatonnes of CO_2 in 2015, the equivalent of adding 4.9 million cars to the roads. Up to 90% of this consumption is attributable to wireless access network technologies, data centres account for only 9%.

Curbing the user convenience provided by wireless access seems unlikely and therefor the ICT sector faces a major challenge. Finding solutions to the 'dirty cloud' at the very least requires a broader acknowledgment of the cloud computing ecosystem and each components' energy requirements. There needs to be a focus on making access technologies more efficient and potentially a reworking of how the industry manages data and designs the entire global network.

This white paper sets out to establish a starting point for addressing these issues, presenting a detailed model that estimates the energy consumption of wireless cloud services in 2015 taking into account all of the components required to deliver those services.

BY 2015 WIRELESS CLOUD WILL GENERATE UP TO 30 MEGATONNES OF CO_2 COMPARED TO 6 MEGATONNES IN 2012

= 4.9 MILLION NEW CARS

01 INTRODUCTION

01.1 BACKGROUND

Over the past decade, advances in information and communication technologies (ICT) have transformed how society interacts with and uses technology. Developments in computing technologies have driven continued miniaturisation and reduced costs supporting the development of more affordable and powerful devices such as notebooks, smartphones and tablets. As a result, most people in the developed world now carry computing and communication devices with them wherever they go [1].

The Internet, underpinned by global telecommunications infrastructure, has fostered innovation and provided access to services that have changed the way humans communicate and gather information. Examples include web browsing, information retrieval, online retail services, social networking and video on-demand. These services, accompanied by many other emerging and existing applications, are driving continued demand for broadband connectivity and capacity. This, in turn, is fuelling a continuous expansion of telecommunications networks [2].

Advances in personal computing and the widespread availability of high-speed fixed-line and wireless broadband access have helped create an environment where anywhere, anytime access to data and services is a way of life. These services are increasing supported by data storage and processing infrastructure located in large centralised facilities spread around the globe. This infrastructure is commonly referred to as *the cloud*, and the practice of remotely storing, accessing and processing data across this infrastructure is known as *cloud computing* [3].

Cloud computing relies upon concentrated computational resources, typically housed in data centres, that are accessed via the public Internet or a private network.

One key advantage of cloud computing is that it enables resources and infrastructure to be shared between many users, and returned to a resource pool when not needed. This offers economies of scale in data provision, computation and storage, while allowing users to gain easy access to computing resources far more powerful than that provided by a single desktop computer. Data centres are undeniably significant consumers of energy, but can be optimised for efficiency and as a result, cloud services

WIRELESS NETWORKS ARE THE BIGGEST THREAT TO THE SUSTAINABILITY OF CLOUD SERVICES, NOT DATA CENTRES

ENERGY CONSUMPTION
90% = WIRELESS NETWORKS
DATA CENTRES = 9%

are often promoted as sustainable alternatives to desktop processing [4].

Cloud computing has faced criticism for the substantial scale of carbon footprint. Greenpeace raised the issue of 'dirty' electricity generation to power cloud service data centres [5]. However, scrutiny of 'dirty cloud' to date has generally missed an opportunity, being largely focused on the energy efficiency of data centres in isolation. Data centres are generally highly optimised for energy efficiency [6] and, importantly are only a single component in the cloud-computing ecosystem. This ecosystem includes the metro and core network, and access network components incorporating both fixed-line and wireless technologies. All of these elements require power and, as this white paper demonstrates, as a whole consume more energy than data centre facilities.

This white paper builds on previous research undertaken by CEET examining the power consumption of cloud computing. The 2011 CEET publication *Green Cloud Computing: Balancing Energy in Processing, Storage and Transport* [7] showed that when high volume of traffic is exchanged between a service provider and user, the majority of energy consumed is related to the transport of information. This was an important demonstration that analysis of cloud energy consumption must consider multiple elements.

Given growth in the consumption of cloud services via portable devices, this white paper focuses on the energy consumption of the components required to support wireless access to cloud services, or 'wireless cloud' for the purpose of this report. In this report we define wireless into two categories: local and mobile. Local is defined as home or shared/public WiFi and mobile is defined as 4G LTE.

Wireless, local and mobile, is fast becoming the standard access mode for cloud services. Global mobile data traffic overall is currently increasing at 78% per annum and mobile cloud traffic specifically is increasing at 95% per annum [1]. Take-up of smartphones and tablets is increasing the move toward wireless access to cloud services [1], while major cloud industry players strongly advocate the use of cloud services via wireless technologies. Should the projected industry trends become reality, wireless devices

will become the dominant technology for accessing Internet services around 2016 [1].

By focusing debate and analysis on data centres, industry risks obscuring the true energy cost of cloud services and impairing any effort to make them more sustainable. Any attempt to make cloud computing more sustainable must target the most inefficient parts of the system.

The results in this white paper show that the current focus on data centres is misplaced and that wireless access networks are clearly the biggest and most inefficient consumer of energy in the cloud environment.

This white paper presents a detailed model that estimates the energy consumption of cloud services delivered via wireless access networks in 2015 taking into account the broad range of components required to support those services, including data centres and the telecommunications networks. The model is based on the expected up-take of wireless cloud services and forecasts of the telecommunications technologies that will underpin wireless cloud services in 2015. This estimate uses an *incremental energy calculation* that is based on a scenario where wireless cloud traffic is part of many other traffic flows through the network and data centres. Wireless cloud traffic is carried through a network that is already carrying a large amount of traffic, with wireless cloud traffic being about 20% of mobile traffic and approximately 35% of data centre traffic [2,4].

01.2 KEY FINDINGS

1. There is an emerging convergence and trend towards cloud services being accessed via wireless communication networks such as WiFi and 4G LTE.
2. The total energy consumption of cloud services accessed via wireless networks could reach between 32 TWh and 43 TWh by 2015. In 2012, the figure was closer to 9.2 TWh.
3. Wireless access network technologies account for 90% of total wireless cloud energy consumption. Data centres account for only about 9%. The energy consumption of wireless user devices is negligible.
4. Previous analysis and current debate on making cloud services more energy efficient is misplaced on data centres and ignores the massive impact of wireless cloud growth.
5. Industry must focus efforts on making cloud services more energy-efficient, including developing more energy-efficient wireless access network technologies.

02 WHAT IS THE CLOUD?

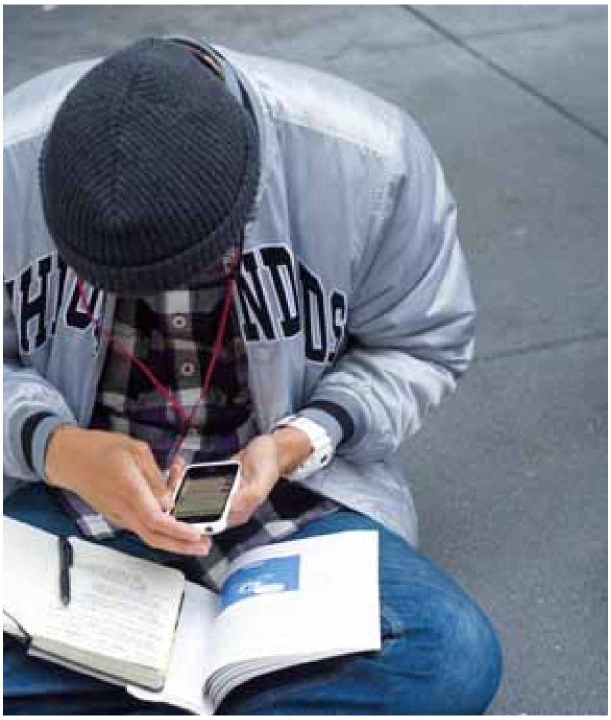
There have been many descriptions or definitions of what constitutes cloud computing, but the most commonly quoted one is from the US Department of Commerce National Institute of Standards and Technology, which has defined cloud computing as follows:

Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction [8].

Cloud computing is underpinned by a number of technologies, including:

1. The data centre(s) where the user's data is stored and/or processed.
2. The core and metro telecommunications networks that connect the user's access network to the data centre(s), which may be located locally or globally.
3. The broadband access technology including fixed broadband, mobile and local wireless solutions, detailed in Section 3.
4. The end user's device, for example a PC, laptop, smartphone or tablet.

Cloud services may be used by: consumers for personal computing, gaming, and social networking activities, by businesses in lieu of a traditional desktop computing environment, or to provide additional scalable computation or web-server resources to a wide range of organisations.



02.1 CLOUD INFRASTRUCTURE

Cloud infrastructure can be broadly categorised into:

Public cloud infrastructure

Public cloud infrastrutre is available for open use by the public. The data centre infrastructure that hosts the cloud services may be owned, managed and operated by businesses, academic institutions, or government organisations. This infrastructure is typically located in a data centre under the control of the cloud provider [8]. Public cloud services are accessed via the public Internet via the customers Internet Service Provider (Figure 1).

Private cloud infrastructure

Private cloud infrastructure is generally intended for exclusive use by a single organisation. It may be owned, managed, and operated by the organisation, a third party, or a combination, and it may be located on the user's premises or hosted by a third party [8]. Private cloud services use privately owned enterprise networks that connect users to the data centre via a corporate network (Figure 2). This can provide a higher quality of service, but generally at a greater cost than that of the public Internet/public cloud.

Cloud infrastructure is able to offer a diverse range of services to customers. These are often categorised into one or a combination of three generic service types [8]:

1. Software as a Services (SaaS): Users are able to use the cloud provider's applications, such as a word processor, email, calendar, database manager, etc., running on cloud infrastructure. The applications can be accessed from simple user devices such as a laptop, PC, tablet or mobile phone. Google Apps, Dropbox and Salesforce.com are examples of SaaS.
2. Infrastructure as a Service (IaaS): The user has the ability to provision processing, storage, networks, and other computing resources where the user is able to deploy and run software. Examples of an IaaS include Rackspace, Amazon Elastic Compute Cloud (EC2) and Simple Storage Service (S3).
3. Platform as a Service (PaaS): The capability provided to users to create and deploy applications using programming languages, libraries, services, and tools provided in the cloud. Google's App Engine and Microsoft Azure Compute are examples of PaaS, which provide software developers facilities to draft, test and deploy their products without having to own computing infrastructure.

In the three service types customers do not manage or control the underlying cloud infrastructure. However, PaaS enables the customer to have control over the deployed applications and possibly configuration settings for the application-hosting environment.

Figure 1 Public cloud infrastructure

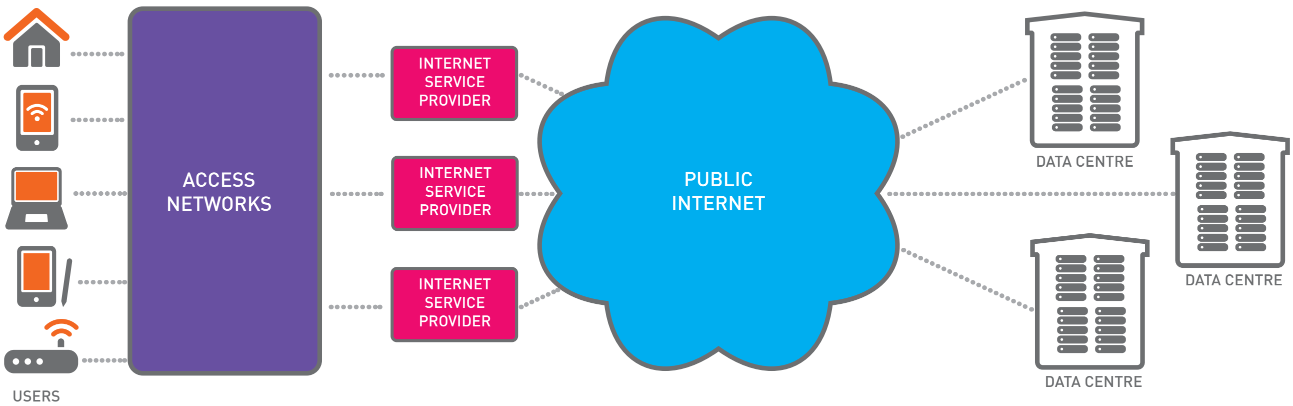


Figure 1 Schematic representation of public cloud infrastructure. The users are connected to the data centres that provide the cloud services via the pubic Internet.

Figure 2 Private cloud infrastructure

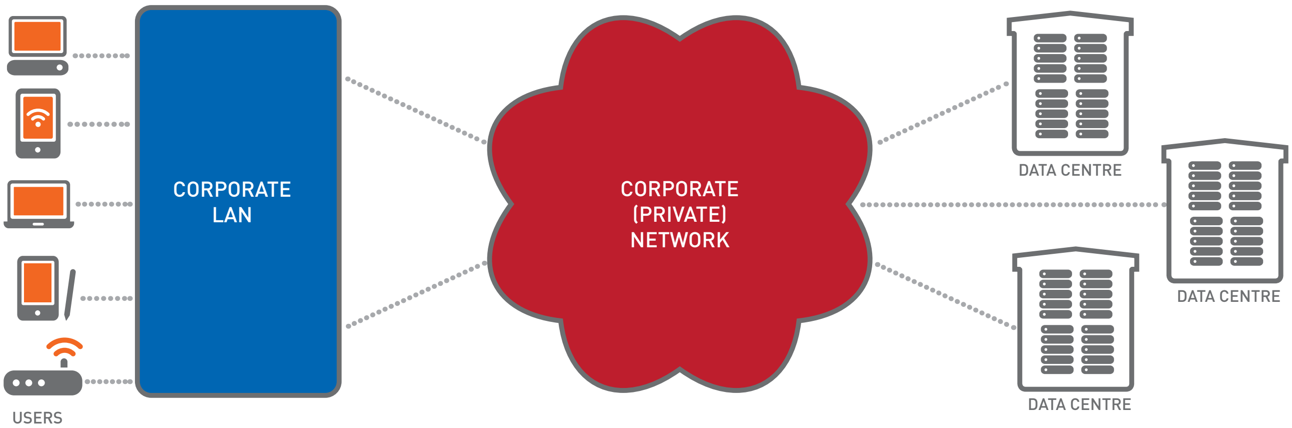


Figure 2 Schematic representation of private cloud infrastructure. The users are connected to the data centres that provide the cloud services via a private network.

02.2 THE DATA CENTRE

The data centre is essential to cloud computing providing the processing and storage capacity to deliver services to customers. The typical data centre is a large facility housing many tens or hundreds of thousands of services. These facilities often consume tens of megawatts of electrical power to operate and cool the equipment. Despite the large power consumption, the ability of a data centre to centralise and pool-computing resources enables improved energy efficiency compared with traditional computing services. The centralised computers are shared among a number of customers who see their share as a computer in its own right. In turn, this reduces the amount of equipment required to deliver computer services.

Modern data centres are highly optimised for energy efficiency [6]. Many reports promote cloud services as technologies to make enterprise ICT more energy efficient by reducing equipment purchases and the operational energy consumed in-house [9,10,11]. By using centralised computing services from a cloud service provider, enterprises can provide employees with a simpler low power device that connects to the cloud.

According to the Carbon Disclosure Project in 2011, the adoption of cloud computing will allow "US businesses with annual revenues of more than $1 billion can cut CO2 emissions by 85.7 million metric tons annually by 2020." [9]

Consultants Accenture and WSP Environment and Energy stated:

"for large deployments, Microsoft's cloud solutions can reduce energy use and carbon emissions by more than 30 percent when compared to their corresponding Microsoft business applications installed on-premises. The benefits are even more impressive for small deployments: Energy use and emissions can be reduced by more than 90 percent with a shared cloud service." [10]

While a report by WSP Environment and Energy consultants for SalesForce.com concluded that:

"Salesforce.com's estimated total customer carbon emissions footprint for 2010 is at least 19 times smaller than an equivalent on-premises deployment, and is 3 times smaller than an equivalent private cloud deployment." [11]

The improved energy efficiency of cloud computing has been described or evaluated in many reports [12,13,14,15]. A similar approach is found in these reports and is reasonably intuitive: by maximising their utilisation and minimising the power consumption of cloud data centres, the energy per user can be reduced to levels much lower than that for a dedicated desktop PC. Therefore, cloud services appear to be intrinsically more energy efficient than traditional desktop computing.

PUBLIC DEBATE
NEEDS TO MOVE FROM THE ENERGY CONSUMPTION OF DATA CENTRES TO THE EFFICIENCY OF WIRELESS ACCESS NETWORK TECHNOLOGIES

Despite the fact that data centre servers are more energy efficient than desktop PCs, the reality is that data centres consume a considerable amount of energy. Between 2005 and 2010 the energy consumption of data centres grew by 56% [16]. In 2010 data centres contributed to approximately 1.5% of global electricity use [16] .

Greenpeace recently published a series of reports questioning the environmental impact of data centres. A 2010 report, *How dirty is your data*, focused on the carbon footprint of data centres owned by several major cloud service providers, including: Apple, Microsoft, Google, Facebook, and Amazon among others [17]. A second report *Make IT Green* examined the carbon footprint estimates for data centres presented in the SMART 2020 report published by GeSI and The Climate Group [18,19]. Additionally, Greenpeace have noted that the location of a data centre and the use of coal-generated electricity can have a significant impact on a data centre's carbon footprint.

A follow up report, *How Clean is Your Cloud* was published by Greenpeace in April 2012 [5]. This report analysed the power consumption of data centres operated by all major cloud service providers, while also looking at the percentage of that power sourced from renewable electricity. Greenpeace rated the providers on their approach to minimising the carbon footprint of data centres. Several of the cloud service providers took exception to the Greenpeace report [20]. As data centres are becoming a major consumer of electrical power, researchers and the industry worldwide are working towards improving data centre energy efficiency and seeking low carbon power supplies [21,22].The reduction of the power consumption of data centers is not only an environmental priority, but also driven by a reduction of the operational costs associated with power consumption. This includes the direct electricity bill, as well as secondary cost as power back-up and cooling. Another approach is locating the data centres in cooler climates to reduce the cost of removing heat from the facility [23].

Public debate continues to focus on the energy consumption of data centres and the savings available to industry. However, there is a broader issue of energy consumption in the cloud computing environment not restricted to data centres. Accessing cloud services via wireless networks is also an issue.

02.3 THE GROWTH OF CLOUD COMPUTING

The efficiency of data centres and the ability for organisations to reduce their ICT infrastructure costs and resulting emissions has lead to an uptake of cloud computing by many organisations. Cloud computing offers many advantages over conventional computing. The key to cloud computing is that resources and infrastructure are pooled and allocated to customers as they are required and returned at the end of the session. This leads to the efficient utilisation and delivered economies of scale in the provision of computation and storage. However, the most advantageous aspect of cloud computing is the convenience of access anywhere, anytime enabled from devices via wireless broadband networks. The result has seen massive growth in the wireless cloud.

Major industry participants, such as Apple, Microsoft and Google, vigorously promote wireless cloud services. The common theme in accessing their cloud services is via a wireless connection. A number of devices including tablets, smartphone and laptops no longer need to connect to telecommunication networks via a cable, using instead a WiFi or cellular connections [24].

A summary of the offerings is provided below.

APPLE ON iCLOUD

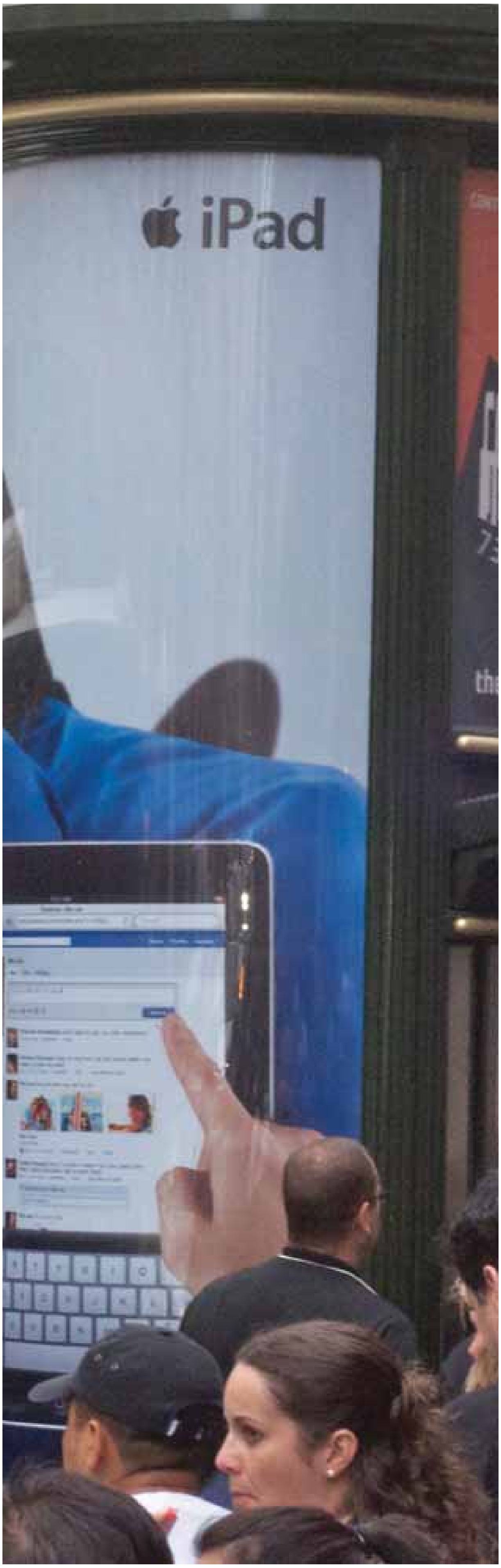
"..FREE NEW CLOUD SERVICES THAT WORK SEAMLESSLY WITH APPLICATIONS ON YOUR iPHONE®, iPAD®, iPOD TOUCH®, MAC® OR PC TO AUTOMATICALLY AND WIRELESSLY STORE YOUR CONTENT IN ICLOUD AND AUTOMATICALLY AND WIRELESSLY PUSH IT TO ALL YOUR DEVICES. WHEN ANYTHING CHANGES ON ONE OF YOUR DEVICES, ALL OF YOUR DEVICES ARE WIRELESSLY UPDATED ALMOST INSTANTLY." [25]

MICROSOFT ON SKYDRIVE

"STORE ANYTHING ON YOUR SKYDRIVE AND IT'S AUTOMATICALLY AVAILABLE FROM YOUR TRUSTED DEVICES—NO SYNCING OR CABLES NEEDED." [26]

GOOGLE ON GOOGLE DRIVE

"GOOGLE DRIVE IS EVERYWHERE YOU ARE – ON THE WEB, IN YOUR HOME, AT THE OFFICE AND ON THE GO. SO WHEREVER YOU ARE, YOUR STUFF IS JUST... THERE. READY TO GO, READY TO SHARE." [27]



02.4 INDUSTRY FORECASTS

ICT industry commentators predict substantial growth in cloud services and wireless cloud services over the coming years [28,29]. Moreover it is expected that wireless devices will gradually replace PCs as the preferred device for accessing web and cloud services [30,31,32]. Examples of industry forecasts for the growth in wireless cloud services include:

- ABI Research: the number of wireless cloud users worldwide will grow rapidly to just over 998 million in 2014, up from 42.8 million in 2008, an annual growth rate of 69% [33].
- Forrester: the global market for cloud computing will grow from $40.7 billion in 2011 to more than $241 billion in 2020 and the total size of the public cloud market will grow from $25.5 billion in 2011 to $159.3 billion in 2020 [34].
- Cisco: global cloud IP traffic (fixed and mobile) is increasing 66% per annum and will reach 133 exabytes per month in 2015 [3].
- Cisco: global mobile data traffic (including both cloud and non-cloud traffic) grew by 113% in 2011 and is forecasted to grow at 78% per annum. In 2016 data traffic will reach 10.8 exabytes per month, with wireless cloud services (cellular and WiFi) accounting for 71% (7.6 exabytes per month) of this traffic [1].
- Juniper: the cloud-based mobile applications market is expected to grow by 88% per annum between 2009 and 2014 [35].

It is important to note that of the 133 exabytes per month of IP cloud traffic forecast by Cisco, only 17% is between customers and cloud data centres. The rest of this traffic is within or between data centres [3]. This means that, in 2015, there will be approximately 23 exabytes per month cloud IP traffic between users and data centres.

Using the Cisco data [1], at an annual growth rate of 95%, 7.6 exabytes of wireless cloud traffic between customers and data centres in 2016 correspond to 4 exabytes per month in 2015. Therefore mobile cloud traffic will constitute approximately 17% of all customer IP cloud traffic between customers and data centres in 2015.

THE NUMBER OF WIRELESS CLOUD USERS WORLDWIDE WILL GROW TO JUST OVER 998 MILLION IN 2014, UP FROM 42.8 MILLION IN 2008, AN ANNUAL GROWTH RATE OF 69% [33]

03 WIRELESS ACCESS TO THE CLOUD

As outlined in section 2, consumers are increasingly accessing cloud services wirelessly. The wireless cloud is made accessible via the many devices, such as tablets, smartphones and laptops that use WiFi or cellular connectivity. In order to develop a holistic view of the energy consumption of cloud services, the energy consumption of the access technology needs to be accounted.

While some users will access cloud services via a cable, such as Ethernet, wireless access, in homes, offices and public spaces is fast becoming the predominant choice. These access technologies can be categorised into three groups: fixed, local wireless and mobile wireless. The various broadband access technologies consume different amounts of power.

In order to calculate the energy consumption of the wireless cloud, the power consumption of wireless access technologies need to be determined. This paper will explore two types of wireless access, local wireless access and mobile wireless access. These two technologies are outlined below.

03.1 LOCAL WIRELESS ACCESS TECHNOLOGIES

Local wireless broadband access technologies enable the transfer of information over short distances (typically a few tens of metres) between devices, to wireless routers that generally connect to fixed broadband access technologies. The most common local wireless broadband access technology is WiFi. WiFi is commonly used in homes, hotels/motels, as well as public wireless hotspots. In public wireless hotspots the infrastructure is shared by tens or even hundreds of multiple users, e.g. in a library, cafe or airport. These local wireless solutions have the advantage of providing itinerant and fast broadband speeds, comparable to fixed broadband access speeds.

03.2 MOBILE WIRELESS ACCESS TECHNOLOGIES

Mobile wireless broadband access technologies provide services to customer devices via 3G and 4G LTE mobile networks. The quality of mobile wireless solutions depends on multiple, often uncontrollable, factors including the location of users accessing the facility. Mobile wireless broadband access technologies have the advantage of providing mobility, but they are not able to provide broadband speeds comparable to fixed or local wireless access technologies [7].

04 DETERMINING THE ENERGY CONSUMPTION OF WIRELESS CLOUD SERVICES

The energy consumption of a cloud computing service is contained within four key technology components:

1. The end-user's device
2. The broadband access technology
3. The metro and core telecommunications network
4. The data centre(s)

Each of the above components needs to be considered to properly assess the energy consumption of cloud service. CEET has built upon previous research to construct a detailed model of the energy consumption for cloud services. The CEET model is outlined below.

04.1 THE CEET WIRELESS CLOUD ENERGY CONSUMPTION MODEL

The CEET model provides an estimate of the total annual energy consumption of the wireless cloud in 2015. The calculations presented in the model are indicative, providing upper and lower estimates for the annual energy consumption that would occur based on wireless cloud uptake projections. These projections are from publically available reports and white papers [1,3,4,33,36,37,38,39]. Technical details of the model are found in the Appendix.

There are different units contained in the CEET model, some of the values below are measured in power (*Watts* W), while others are in energy per bit of data (*microjoules per bit* (mJ/b)). The reason for this is that in some cases it is possible to identify the power consumed by individual consumers; for example a user of a mobile phone or a tablet. Similarly, home WiFi will have one or two users making it relatively easy to identify the power consumption. In contrast equipment such as public WiFi and telecommunications networks are shared among many hundreds, thousands and millions of users. With such highly shared equipment it is more appropriate to use the quantity "energy per bit".

The CEET model calculates the power per user for their "busy hour" and then the total energy consumption for all users per day is estimated by accounting for the diurnal traffic cycle[1]. This method accounts for customer usage cycles. Energy consumption estimates are modelled on two scenarios based upon the number of wireless cloud users and the global monthly traffic forecasts for 2015. These forecasts suggest a range of values for the number of wireless cloud users and the monthly traffic for wireless cloud services. Using these forecasts, we have constructed two scenarios: The "Lo" scenario corresponding to "low take-up, low traffic" and "Hi" scenario corresponding to "high take-up, high traffic". The values in each scenario appear in table 1.

Scenarios for wireless cloud services in 2015	Users	Traffic
Low take-up, Low traffic (Lo)	1.6 billion	2.2 exabyte/month
High take-up, High traffic (Hi)	2 billion	4.3 exabyte/month

Table 1: Wireless cloud service scenarios take-up and monthly traffic scenarios for 2015. The low take-up, low traffic scenerio is labelled "Lo". The high take-up, high traffic scenerio is labelled "Hi".

The number of users for the low take-up case or 1.6 billion users is based on a conservative projection of the growth trend published by ABI Research [33]. The high take-up value of 2 billion users comes from a more aggressive growth projection using a mobile broadband subscriber forecast from Infonetics [39] and using the ABI Research report [33] to estimate the proportion of mobile users who will use wireless to access cloud services.

Another key parameter is the amount of traffic generated by wireless cloud services. The model adopts high traffic and low traffic estimates based on industry forecasts. The high traffic value of 4.3 exabytes per month comes from a forecast by Cisco corresponds to forecasts by Alcatel-Lucent for mobile traffic in 2015 [1,37]. Unfortunately there are very few reports on wireless cloud traffic apart from the Cisco Visual Networking Index. Therefore the low traffic estimate (2.2 exabytes per month) comes from forecasts by Nokia Siemens Networks [36] and Ericsson [38] using a ratio of wireless cloud users to mobile users derived from the Cisco Visual Networking Index.

There are additional estimates for the improvements in energy efficiency of various technologies in the CEET model. As the focus is on the wireless cloud, the total power consumption for end user devices is estimated as either a table with WiFi or a 4G LTE mobile phone. According to industry data the power consumption of a 4G LTE phone is approximately 3 W and for a tablet approximately 3.5 W [40,41].

There are a number of different broadband access technologies to connect to the wireless cloud. The CEET model considers the following:

[1] See Appendix Figure 4 for details.

- Local wireless: Home WiFi connection, using a Fibre-to-the-Premises (FTTP) broadband connection
- Public wireless: WiFi hotspot, using an FTTP connection
- Mobile wireless: 4G LTE mobile connection

Home WiFi connections commonly use an integrated modem/WiFi modem/router. Today these devices consume around 8 W, and by 2015 industry trends indicate this value will be approximately 5 W. The CEET model assumes 2 simultaneous users in the home with each spending approximately 45% and 70% of their online time accessing cloud services in 2012 and 2015 respectively [1].

Public wireless connections are generally provided via a WiFi modem/router connected to a fixed broadband network. As these connections are shared, and run at higher utilisation, an energy-per-bit description is more appropriate than a flat power consumption figure. Based on current industry values we expect the energy per bit for this technology to be approximately 0.4 micro-Joules per bit. (See Appendix for details.)

The base station dominates 4G LTE mobile wireless access power consumption. The estimated access energy per bit ranges from 73 to 136 micro-Joules per bit [42]. The earth report [42] lists a range of estimates of power consumption for mobile base stations; the CEET model adopts the more conservative figure of 73 micro-Joules per bit.

The metro and core telecommunications networks are estimated to use approximately 0.64 micro-Joules per bit, according to CEET modelling [43]. The energy consumption of the data centre is estimated as 20 micro-Joules per bit, based on internal CEET modelling. This value corresponds with recently released Facebook [44] and Google [45] energy consumption data that report per user energy consumption of 1 kWh and 2 kWh per year respectively. The CEET model gives an average per user data centre energy consumption of 2 kWh per year.

The results from the CEET energy consumption of the wireless cloud modelling were derived from multiple interrelated calculations. Firstly, equipment energy per bit was multiplied by the capacity (in bits per second) of a customer's traffic through the equipment obtaining a measure of an individual's share (in Watts) of the power consumed by that piece of equipment for the time the equipment is used. To achieve this an estimate is required for the average traffic per customer on the wireless cloud. This value, based on Cisco projections for 2016, is approximately 19 kilobytes per second during the peak traffic hour.

Secondly, to estimate the total energy consumption of the wireless cloud in 2015, the proportion of traffic accessing the cloud from mobile or WiFi needs to be calculated. Cisco estimates that 33 percent of wireless device traffic will be offloaded to local small (femtocell) base stations [1]. The CEET model adopts this ratio for the number of customers who will access cloud services via WiFi connections. Of those using WiFi the model estimates the number of customers accessing the cloud via a public WiFi network, which is shared among many users and those that use in-home WiFi, with the power shared between one or two users. The CEET model assumes an average of 2 users sharing in-home WiFI. ABI Research estimates that 24 percent of wireless cloud users will be business users in 2016 [33].

05 THE ENERGY CONSUMPTION OF THE WIRELESS CLOUD IN 2015

Using the CEET model, as outlined in section 4, the total energy consumption of the wireless cloud is estimated to be between 32 Terawatt hours (TWh) (Lo scenario) and 43 TWh (Hi scenario) in 2015. The details of the modelling are presented in the chart below. For comparison, also included is an estimation of the 2012 wireless cloud energy consumption (9.2 TWh) based on demand figures for that year. This is an increase of 390% to 460% over 3 years.

This corresponds to an increase in carbon footprint from approximately 6 megatonnes in 2012 to around 30 megatonnes in 2015. [46]. This increase corresponds to adding and extra 4.9 million cars onto the roads [46].

The energy consumption of the wireless cloud estimated by the CEET model assumes take-up rates and technological improvements predicted by current industry forecasts. As shown in figure 3, in 2015 for wireless cloud services, data centres consume between 3 TWh and 4 TWh. This is the data centre power consumption incurred by wireless access traffic. Estimates of global data centre power consumption are much higher because those estimates include all data centres (many of which are old, lightly utilised, and not designed for energy efficient operation) as well as both cloud (wireless and wired access) and non-cloud traffic [16]. Additionally the energy consumption values for the access technologies and the metro and core telecommunications networks are for (wireless) cloud data traffic only. Using published global energy consumption trends for mobile networks it is expected that the global energy consumption of 4G LTE networks in 2015 will be approximately 80 TWh [47].

Figure 3 shows that the energy consumption of the wireless cloud is dominated by broadband access technologies. The energy consumption in the metro and core network is relatively insignificant, while the energy consumption of the data centres is not the dominant contributor to wireless cloud service power consumption. Wireless cloud energy consumption is dominated by 4G LTE and home WiFi access, together contributing 90% of total energy consumption of the wireless cloud in 2015. The energy consumption from data centres is approximately 9% of total consumption. In so far as addressing the sustainability of the wireless cloud services, it should be noted that wireless technologies consume significantly more energy than data centres.

It is important to note that the energy consumption forecast of 32 TWh to 43 TWh for wireless cloud in 2015 assumes all of the infrastructure used in the wireless cloud network is the latest generation (2015) technology. The cost of re-equipping the entire network with the latest technology each year will be prohibitive. Therefore, it is most likely the network infrastructure will be a mixture of new and older technologies. Assuming 2012 technology (no improvement with technology) with the 2015 Lo and Hi scenarios, the model predicts energy consumption of between 41.5 TWh and 58 TWh. Therefore we need to recognise the energy consumption range of 32 TWh to 43 TWh is a conservative estimate because there will be a range of newer and older equipment.

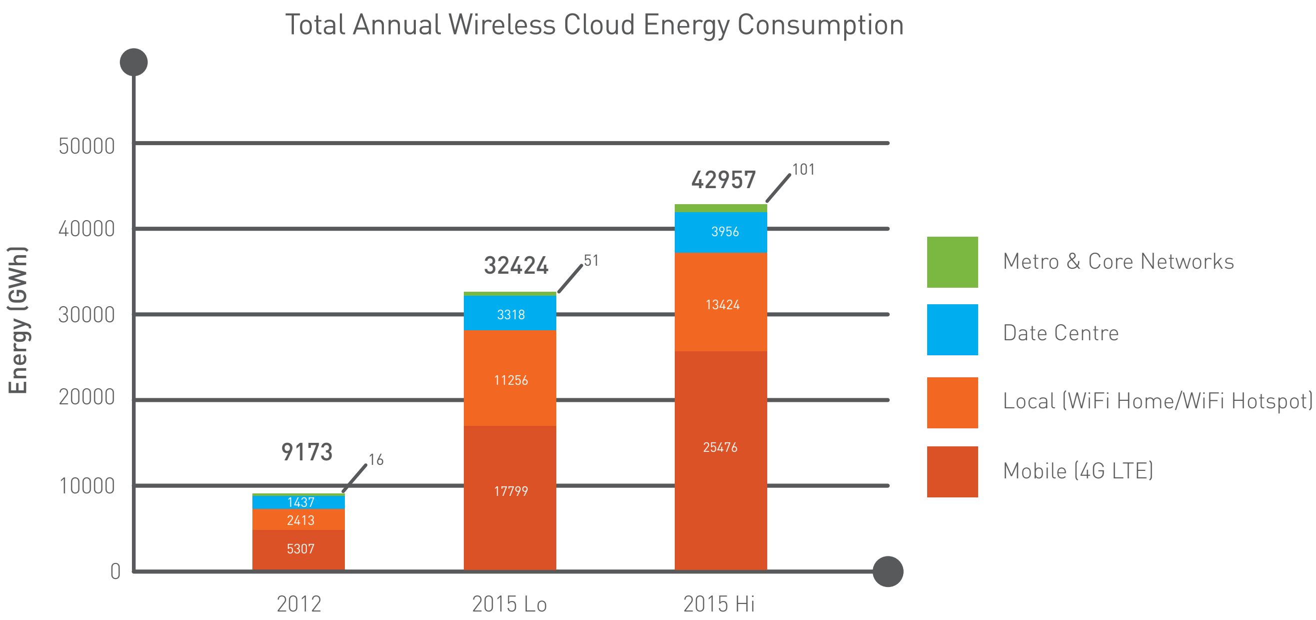


Figure 3 Estimate for annual energy consumption broken down into the various components of the wireless cloud ecosystem, 2012 and 2015 (Lo and Hi scenarios, see Table 1).

06 CONCLUSION

Cloud computing is widely viewed as the next major evolutionary step for the Internet and Internet-based services. The shift to wireless access is also continuing at a great rate. Cisco projects that cloud computing will represent approximately 34% of data centre traffic in 2015 [3], with approximately 20% of data centre traffic will be served by wireless access networks.

Wireless and cloud are converging trends supported by the increased availability of affordable, powerful portable devices, convenient and useful applications, and high-speed wireless broadband infrastructure. This convergence is expected to be a key driver of traffic growth on telecommunications networks in the future.

There is evidence to show that cloud services access via fixed-line networks could result in lower energy consumption relative to current computing arrangements, such as replacing powerful desktop computers with cloud services [9,10,11]. Greenpeace has highlighted the carbon footprint of cloud computing but focused on data centres as being the biggest contributor to energy consumption. When considering the energy consumption of the wireless cloud, all aspects of the cloud ecosystem must be taken into account, including end-user devices, broadband access technology, metro and core networks, as well as data centres.

This white paper analysed the various components of the wireless cloud ecosystem to identify the dominant energy consumers. The CEET model explored the impact of the wireless cloud, accounting for all aspects of the ecosystem including devices, broadband access technology, and metro and core telecommunications, in addition to data centres.

The predicted large-scale take-up of wireless cloud services will consume 32 to 43 TWh by 2015. The energy consumption of wireless access dominates data centre consumption by a significant margin.

To ensure the energy sustainability of future wireless cloud services, there needs to be a strong focus on the part of the ecosystem that consumes the most energy: wireless access networks. Further debate needs to move beyond the data centre to develop a holistic account of the ecosystem with this white paper being a step in that direction.

INDUSTRY MUST FOCUS ON THE REAL ISSUE, MORE EFFICIENT WIRELESS NETWORKS IN THE WIRELESS CLOUD ENVIRONMENT

APPENDIX: CEET WIRELESS CLOUD ENERGY CONSUMPTION MODEL

A1 POWER CONSUMPTION OF CLOUD SERVICES

Precisely forecasting the power consumption of the wireless cloud is extremely difficult due to the potential variation in the take-up rate of cloud services along with the diversity of possible future services, each involving a particular combination of equipment, data transfer and processing. To construct a model for the energy consumption for the wireless cloud this white paper developed an estimate of the global power demand based on industry predictions and scenarios for uptakes of cloud services in 2015. Although the model is an approximation, it transpires that this estimate is sufficient to assess the relative contributions of the various parts of the network to global mobile cloud service power consumption.

To construct an estimate of the energy consumption of the wireless cloud average power consumption per user and the number of users of the cloud service accounting for the diurnal variation in broadband traffic was determined. The diurnal cycle describes the fact that, for any given geographical region, the number of users simultaneously "online" cycles with the time of day in that region. A study of this cycle gives a characteristic shape typified by that shown in Figure 4.

We constructed the estimate for 2015 based on published projected take-up rates and service demand forecasts [1,2,3,4,28,29] recent reports from Facebook [44] Google [4,45], energy and cost model of a data centre [48], the Energy Aware Radio and network technologies ("earth") Project [42] and internal CEET modelling.

For devices that are used by single or a small number of users the power consumed by using the device data (e.g. a smartphone, tablet or home router) was identified. To determine the power consumed by equipment that is shared between many users (e.g. telecommunications equipment such as WiFi public hotspots and telecommunications networks) the energy consumed by each bit of data was estimated. Then, by multiplying the equipment energy consumed by each bit by the capacity of a user's traffic through that equipment, we obtain a measure a user's share of the power consumed by that piece of equipment in Watts.

In this model, the average capacity per user for cloud services to be between 12.5 kb/s and 21 kb/s during peak traffic hour, depending upon the scenario (see below for details).

A2 USER TRAFFIC PROFILES

Based on ABI Research estimates the percentage of mobile subscribers who also subscribe to wireless cloud services will increase from 1.1% in 2008 to 19% in 2014 [33]. Using these figures and projecting this growth rate out to 2015 we estimate 26% of mobile subscribers will use wireless cloud services.

Adopting this 26% forecast two take-up scenarios were constructed. A "low take-up" case (1.6 billion users) is based on a projection of the growth trend published by ABI Research [31]. The "high take-up" value (2 billion users) comes from a more aggressive mobile user growth projection using a forecast from Infonetics [39].

Similarly the model includes "low traffic" and "high traffic" forecasts for the monthly mobile cloud traffic. From the Cisco "Global Mobile Data Traffic" forecast VNI [1], in 2015 63% of mobile traffic will be cloud user traffic. By applying this percentage to Cisco's global mobile traffic forecast for 2015 (6.9 exabytes per month) we estimate 4.3 exabytes for wireless cloud traffic per month [1]. Therefore, we adopt a value of 4.3 exabyte for the "high traffic" scenario.

The "low traffic" scenario monthly wireless cloud traffic value of 2.2 exabytes per month is based upon traffic forecasts by Nokia-Siemens Networks [49] and Ericsson [50].

This monthly data demand is not uniformly distributed across the month, but is subject to variation according to time-of-day (diurnal) and to day-of-week. These cycles arise because for any given geographical region, the number of users simultaneously "online" cycles with the time of day in that region.

When dimensioning a network, the network provider will ensure that the network can accommodate the busiest hour traffic with minimal congestion or to the service level agreement level the provider has with their customers. Thus we need to relate the monthly traffic demand to a per-customer busy-hour connection speed by accounting for the diurnal cycle of Internet traffic. A study of this cycle gives a characteristic shape typified by that shown in Figure 4, where the busy hour occurs around hour 21. The total area under the curve in Figure 4 (between 0h and 23h) corresponds to the total traffic over a one day. Extending this to one month, the total area corresponds to the total traffic per month which, in total, will correspond to the "low traffic" and "high traffic" estimates given above.

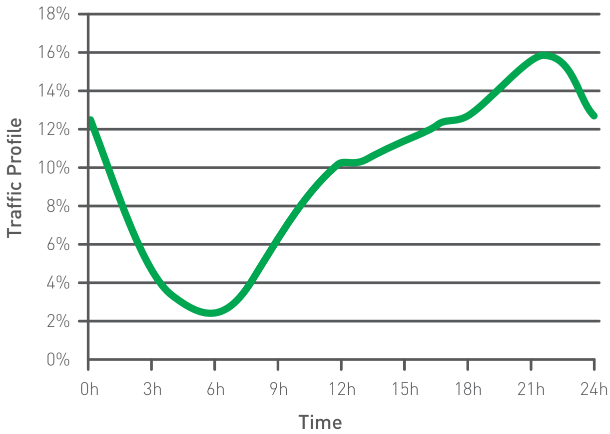


Figure 4: Typical diurnal cycle for traffic in the Internet. The scale on the vertical axis is the percentage of total users of the service that are on-line at the time indicated on the horizontal axis. (Source: [21])

To construct this relationship, we use the projections above to estimate the average monthly capacity per user for each of the four scenarios. These results are in shown in Table 2.

Total monthly capacity per user	Low traffic (2.2 exabyte/month)	High traffic (4.3 exabyte/month)
Low take-up (1.6 billion users)	1.3 GBytes/month (Lo scenario)	
High take-up (2 billion users)		2.1 GBytes/month (Hi scenario)

Table 2 Total monthly traffic per user for the wireless cloud service scenarios.

Using the traffic profile shown in Figure 4, we can determine the ratio of the average user busy hour traffic (in Mb/s) to total monthly capacity per user. Today, the ratio (which is relatively consistent across different networks studied) indicates 1 Mb/s average busy hour access rate for every 196 gigabyte/month of traffic volume.

By 2015, with a shift in the types of applications being used, the ratio of peak to average data rate is expected increase by 25% [51]. Consequentially, in 2015, the ratio for relating monthly traffic volume to average peak hour data rate is projected to be 157 gigabyte/month for a 1 Mb/s average data rate during the busy hour.

Using this ratio, we estimated the average user access speed required to service the traffic demand of wireless access to cloud services for the four scenarios listed in Table 2, averaged over the busy hour. However, there will be short term variations in the traffic over the busy hour; therefore to reduce the possibility congestion during the busy a "safety factor" is included in dimensioning the wireless base stations. We adopt a safety factor of 1.5. This corresponds to the average base station load during the busy hour being 60% of its maximum load.

The resulting per user average access speed during the busy hour for each scenario is show in Table 3. There may be users who, during the busy hour, individually experience higher speeds than those show in the table, however there will also be users who experience speeds less than this during the busy hour.

Average per user busy-hour access speed	Low traffic (2.2 exabyte month)	High traffic (4.3 exabyte/month)
Low take-up (1.6 billion users)	12.5 kb/s (Lo scenario)	
High take-up (2 billion users)		21 kb/s (Hi scenario)

Table 3 Average busy hour access speed per user for the wireless cloud service scenarios.

A3 USERS' DEVICES

Over recent years, there has been a strong move towards accessing cloud services via small, portable devices such as notebooks, netbooks, tablets and smartphones. These devices can connect to the Internet using one or more of access technologies such as a cable (Ethernet or PON) or wireless (WiFi or 4G LTE).

To enable comparison Table 4 shows typical power consumption values for a range of devices that may be used to access the Internet. Because this white paper focuses on wireless cloud services, it will use the power values for tablet and mobile phone. The other values are included for comparison with other common user equipment. With the growing popularity of tablets and their low power consumption, we estimate that, by 2015, typical consumer and enterprise users will access a wireless cloud service via a wireless connection (4G LTE or WiFi) rather than a wired connection [2]. Further, growth trends indicate a dominant increase in traffic from smartphones (4G LTE) and tablets [1]. (As seen in Table 4, the power consumption of a 4G LTE phone and a tablet are relatively equal.)

User device	Power consumption (Watts)
Tablet	2.5
Mobile phone (4G LTE)	3
Mid-range PC	70
Laptop	15
Netbook	11

Table 4 Power consumption of various devices that can be used to access cloud services

A4 BROADBAND ACCESS TECHNOLOGY

In a recent survey of the energy efficiency of access technologies, it was shown that among the access technologies available, wireless based technologies consume the most power [52].

In the present study, we consider the following scenarios:

1. 4G LTE connection via the mobile network.
2. WiFi connection
    a. Via in-home WiFi.
    b. From a WiFi hotspot area with many WiFi users accessing the cloud via the hotspot. (For example, public WiFi in an airport.)

A5 NUMBER OF USERS

The number of users for each of the different access technologies needs to be estimated. To do this, we note that the Cisco Global Cloud Index white paper [3] estimates that in 2011:

"Globally, 33 percent of handset and tablet traffic was offloaded onto the fixed network through dual-mode or femtocell in 2011."

Adopting WiFi power as typical of such a cell, we can set approximately 33% of wireless cloud users accessing the cloud via WiFi and 67% via 4G LTE. We need to account for the fact that some WiFi access users do so using home networks and some use public WiFi hot spots. ABI Research forecasts that in 2015 there will be 240 million business customers of wireless cloud services [33]. This is 24% of their forecast of a total of 998 million cloud users. We adopt this percentage to split WiFi customer numbers between hot-spot (which are taken to be the 24% who are business customers) and in-home (the remaining 76%). Therefore, of wireless cloud users we have:

- 67% access the cloud via 4G LTE using a mobile phone (business and consumer)
- 25% (= 76% of 33%) access the cloud via home WiFi using a tablet (consumer)
- 8% (= 24% of 33%) access the cloud via a WiFi hotspots using a tablet (business)

		Cloud	
		Business	Consumer
Wireless	WiFi + offload	8% (WiFi Hotspot)	25% (WiFi Home)
	4G LTE	67%	

Table 5 Split of mobile cloud users into categories based on percentages reported in surveys and projections. (See text for details)

A6 ACCESS TECHNOLOGY

Access speed per user and the number of users for the various access technologies was estimated. To calculate their contributions to total wireless cloud power consumption, the model requires estimates of the energy per bit consumed by the network equipment used to provide wireless cloud services. This energy per bit is then multiplied by the number of bits per second to obtain the power consumption.

The model first calculates the 4G LTE wireless connection between the user's phone/tablet. Under typical circumstances, with 2010 technology, the energy consumption of a 4G LTE wireless access link ranges between 328 micro-Joules per bit and around 615 micro-Joules per bit [42]. The current annual energy efficiency improvement for wireless systems is approximately 26% [52]. Therefore, the 2010 values need to be adjusted to represent the expected energy per bit in 2015. This gives values of 73 micro-Joules per bit and 136 micro-Joules per bit. This paper adopted the lower value of 73 micro-Joules per bit.

For a WiFi home network, a WiFi router is typically attached to (or integrated into) a PON or ADSL modem. The power consumption of the integrated router/modem today is around 8 Watts per user assuming one user per home [53]. Applying an annual energy efficiency improvement of 10% [54], we estimate that this will fall to 5.2 W per user in 2015. The model needs to account for the fact that not all traffic through a home WiFi router will be cloud traffic. To adjust for this the 5.2 Watts is scaled by 71%, estimated to be the proportion of home WiFi traffic that is cloud related; this figure is based upon the proportion of mobile traffic that is cloud [1].

For public hot-spot WiFi the WiFi system is expected to deal with many customers and provide a much higher throughput over a large area. Further, in public spaces such as an airport, there will be a network of WiFi routers connected to a central Ethernet switch. Using power figures for current generation outdoor high power WiFi equipment (802.11.n using 2x2 MIMO, 300 Mb/s capacity at 30% network load), we find that the energy per bit for a commercial WiFi system is approximately 0.4 micro-Joules per bit [55]. The Ethernet switch adds around 0.007 micro-Joules per bit [56] giving a total of approximately 0.4 micro-Joules per bit. These data are summarised in Table 6.

Access technology	Power per user
4G LTE [42]	73 micro-Joule/bit x (12.5, 21) kb/s = (0.9, 1.5) W (Refer to Table 3 for listed bit rates)
Tablet with WiFi (in home) [53]	3.6 Watts*
Tablet with WiFi (hotspot) /nano-cell [57]	0.4 micro-Joules per bit x (12.5, 21) kb/s = (5, 8.4) milliWatts (Refer to Table 3 for listed bit rates)

Table 6: Cloud access technologies and their corresponding power consumptions.
* This power is based on 2 users per household and 30% of each customer's time is on non-cloud applications.

A7 METRO AND CORE NETWORKS

User traffic passes through the Metro and Core networks between the user and the data centres that provide their cloud services. In the core network, traffic for many hundreds or thousands of users is aggregated. The consequence of this is that, although the network equipment that deals with this traffic may be quite large and consume significant amounts of energy, the energy per bit is relatively small in comparison with that in the access network. We adopt a figure of 0.64 micro-Joules per bit for the Metro and Core networks [43].

REFERENCES

[1] Cisco white paper, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2011 - 2016", 2012

[2] Cisco white paper, "The Zettabyte Era", 2012

[3] Cisco White Paper, "Cisco Global Cloud Index: Forecast and Methodology, 2010 – 2015", 2011

[4] Google White Paper, "Google's Green Computing: Efficiency at Scale", http://static.googleusercontent.com/external_content/untrusted_dlcp/www.google.com/en/us/green/pdfs/google-green-computing.pdf

[5] Greenpeace, "How Clean is Your cloud" Greenpeace, Apr. 2012

[6] A. Beloglazov et al. "A Taxonomy and Survey of Energy-Efficient Data Centres and Cloud Computing Systems", Advances in Computers, Vol. 82, p.47, 2011

[7] J. Baliga, R. Ayre, K. Hinton, R. Tucker, "Green Cloud Computing: Balancing Energy in Processing, Storage and Transport", Proceedings of the IEEE, Vol. 99, No. 1, p.147, 2011

[8] P. Mell, T. Grace, "NIST Definition of Cloud Computing" National Institute of Standards & Technology (US Dept. of Commerce), Special Publication 800-145, Sept. 2011

[9] Carbon Disclosure Project Study 2011, "Cloud Computing – The IT Solution for the 21st Century", 2011

[10] Accenture white paper, "Cloud Computing and Sustainability: The Environmental Benefits of Moving to the Cloud", Accenture, WSP Environment and Energy, 2010

[11] WSP Environment and Energy report for SalesForce.com, "SalesForce.com and the environment: Reducing Carbon Emissions in the Cloud", 2011

[12] Pike Research, "Cloud Computing Energy Efficiency: Strategic and Tactical Assessment of Energy Savings and Carbon Emission Reduction Opportunities for Data Centers Utilizing SaaS, IaaS and PaaS", 2010

[13] L. Liu, et al. "GreenCloud: A New Architecture for Green Data Center", Proceedings of the 6th international conference industry session on Autonomic computing and communications industry session, p.29, 2009

[14] M. Ali, "Green Cloud on the Horizon", CloudCom 2009, LNCS 5931, p.451, 2009

[15] Y. Gu, V. March, B. S. Lee, "GMoCA: Green Mobile Cloud Applications", HP Laboratories, HPL-2012-79R1, 2012

[16] J. Koomey, "Worldwide electricity used in data centres" http://www.koomey.com/post/8323374335

[17] Greenpeace, "How dirty is your data? A Look at the Energy Choices That Power Cloud computing", March 2010

[18] Greenpeace, "Make IT Green: Cloud computing and its contribution to climate change" Mar. 2010

[19] The Climate Group, GeSI, "SMART 2020: enabling the low carbon economy in the information age", 2008

[20] See CBS News TechTalk, "Greenpeace claims Apple, Amazon guilty of dirty cloud computing" 18/04/2012 www.cbsnews.com, Network World, "Greenpeace's sign to Amazon, Microsoft: 'How clean is your cloud?" 19/04/2012, www.networkworld.com

[21] A. Beloglazov, J. Abawajy, R. Buyya, "Energy aware resource allocation heuristics for efficient data centres for cloud computing", Future Generation Computer Systems, Vol.28, p.755, 2012

[22] P. Johnson, T. Marker, " Data Centre Energy Efficiency Product Profile", Report No. 2009/06, Pitt & Sherry

[23] http://www.datacenterknowledge.com/archives/2011/12/20/norways-fjord-cooled-data-center/ Accessed on 19/06/2012

[24] For example, see: http://www.google.com.au/intl/en/chrome/devices/chromebooks.html, http://www.samsung.com/global/microsite/galaxytab/10.1/spec.html, http://www.apple.com/au/ipad/specs/

[25] http://www.apple.com/pr/library/2011/06/06Apple-Introduces-iCloud.html Accessed on 19/06/2012

[26] http://windows.microsoft.com/en-AU/skydrive/home Accessed on 19/06/2012

[27] https://drive.google.com/start?utm_medium=docspromo&utm_source=link&utm_campaign=docsgaia#home Accessed on 19/06/2012

[28] DataLogic Mobile white paper, "Cloud Computing and Mobility", www.mobile.datalogic.com

[29] J. Anderson, L. Rainie, "The future of cloud computing" Pew Research Centre's Internet & American Life Project, http://pewinternet.org/Reports/2010/The-future-of-cloud-computing.aspx , 2010

[30] Garnter: http://www.gartner.com/it/page.jsp?id=1278413 Accessed on 06/07/2012

[31] IDC "Top 10 Predictions 2012: Competing for 2020", 2011

[32] Gartner Special Report "iPad and Beyond: What the Future of Computing Holds," 2011

[33] ABI Research, "Mobile Cloud Computing" 2009

[34] S. Ried, H. Kisker, "Sizing the Cloud – Understanding and Quantifying the Future of Cloud Computing" Forrester, April 2011, www.forrester.com

[35] Juniper white paper, "Mobile Cloud Applications & Services: Monetising Enterprise and Consumer Markets 2009 – 2014 report", 2010

[36] Nokia Siemens Networks, white paper, "Liquid Radio – Let traffic waves flow most efficiently" 2011

[37] Alcatel-Lucent, strategic white paper, "Metro Cells", 2011

[38] Ericsson, "Traffic and Market Report – On the pulse of the networked society", 2012

[39] Infonetics Research, "Total Fixed and Mobile Subscribers Pivot", 2012

[40] P. Somavat, V. Namboodiri, "Energy Consumption of Personal Computing Including Portable Communications Devices", Journal of Green Engineering, Vol.1, No.4, p.447, 2011

[41] D. Barretta, "Tablet PC power consumption analysis", http://risorse.dei.polimi.it/vcampus/download/Power.pdf

[42] G. Auer, et al. "Energy efficiency analysis of the reference systems, areas of improvements and target breakdown", Deliverable 2.3, Energy Aware Radio and network Technologies (earth), 2010

[43] J. Baliga, R. Ayre, K. Hinton, W. Sorin, R. Tucker, "Energy Consumption in Optical IP Networks", Journal of Lightwave Technology, Vol. 27, No. 13, p. 2391, 2009

[44] "Facebook's Carbon & Energy Impact" https//newsroom.fb.com/News/Sharing-Our-Footprint-19c.aspx

[45] "Google Apps: Energy Efficiency in the Cloud" Google white paper:http://static.googleusercontent.com/external_content/untrusted_dlcp/www.google.com/en//green/pdf/google-apps.pdf

[46] Environmental Protection Agency (EPA) Greenhouse Gas Equivalencies Calculator see http://www.epa.gov/cleanenergy/energy-resources/calculator.html

[47] G. Auer, et al. "How much energy does it take to run a wireless network?" IEEE Wireless Magazine, Oct. 2011, p.40, 2011

[48] James Hamilton "Perspectives" blog: http://perspectives.mvdirona.com/2010/10/31/DatacenterNetworksAreInMyWay.aspx October 2010

[49] Nokia Siemens Networks, white paper, "Liquid Radio – Let traffic waves flow most efficiently" 2011

[50] Ericsson, "Traffic and Market Report – On the pulse of the networked society", 2012

[51] Cisco white paper, "Cisco Visual Networking Index: Forecast and Methodology, 2011 – 1016", 2012

[52] J. Baliga, R.Ayre, K. Hinton, R. Tucker, "Energy Consumption of Wired and Wireless Access Networks", IEEE Communications Magazine, June, p.70, 2011

[53] Based on Netgear DGN2200 Combined WiFi, ADSL2+ modem with 4 Ethernet ports. See: http://www.expertreviews.co.uk/wireless-routers/1283383/netgear-dgn2200/specifications

[54] D. Neilson, "Power dissipation limitations to the scalability of network elements", Paper Th 12.A.2, ECOC 2011

[55] For example: ZoneFlex 7762 Dual Band 802.11n Smart WiFi Outdoor AP or Tropos 3320/3310 Indoor Mesh Router.

[56] Based on a Netgear ProSafe Plus Switch, 24-port Gigabit Etherent JGS524E operating at 1 Gigabit Ethernet consuming approximately 90 W and allocating 20 downlink ports and 4 uplink ports.

[57] WiFi router: Netgear ProSafe Dual Band Light Wireless WAG102) plus Ethernet switch: Cisco 4500

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