Understanding the Environmental Costs of Fixed Line Networking

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ABSTRACT

In this paper, we calculate the power-per-line and the energy-per-bit associated with real-world communication networking. We highlight the key real-world network deployment issues, particularly legacy systems and utilization, which can have a strong bearing on the level of energy efficiency. We show how and why the real-world metric values differ from prior models of network energy use. We show how including embodied energy leads to the overall environmental impact being minimized only when legacy systems are maintained. We capture the full end to end impact of networking including an understanding of the data centre and home equipment. An accurate understanding is needed if claims around the potential carbon benefit of communications technologies are to be substantiated.

Categories and Subject Descriptors

C.2.3 [**Computer-Communication Networks**]: Network Operations

General Terms

Measurement, Performance.

Keywords

Network energy

1. INTRODUCTION

Reducing the likelihood of significant global warming leading to climate change and reducing energy dependence are key, inter-related problems for both industry and government [23]. It is claimed that communication products have the potential to provide a net carbon benefit– enabling customers to save up to five times the carbon emissions that provision of the product consumes [17]. For example, audio and video conferencing and teleworking lead to travel reduction, whilst electronic delivery of goods and services can also reduce the need to extract and process raw materials into end products. However, such benefits can only be achieved if the energy required to provide the alternative services is constrained. This paper therefore investigates the energy and carbon costs of communications based on the BT UK network.

BT, a major supplier of telecommunications services in the UK, uses over 0.7% of the UK's electricity supply and produces 316 thousand tonnes of CO2e each year to operate its UK network [5]. This energy use is significant; it is of a similar scale to the energy used within data centres worldwide. [13]. However, unlike data centres, this energy use is less visible, as the energy is not consumed in a few large locations, rather relatively small amounts of energy are consumed in thousands of exchange buildings around the country. Another area of energy use that is not always immediately apparent is the so-called embodied energy associated with creating the electronic devices and fibre cabling needed for network operation.

To achieve the full potential of telecommunications networks to reduce the likelihood of significant climate change and to help tackle energy security issues, we need to ensure that the communications industry is not causing more problems than it is solving. To understand this we need accurate quantification of the actual energy use associated with communications networks.

In this paper we develop an end-to-end view of the energy and carbon impacts of a real-world network, based on measurement data available from BT's network. We develop an understanding of the key metrics of "power per line" and "energy per bit" applied to the fixed network based on observed data, highlighting key real-world network deployment issues that can have a strong bearing on the level of energy efficiency. We show how and why the real-world metric values differ from prior models of network energy use. To understand the full impact of communication networking, we need to look beyond the equipment within our own network and understand the impact of resources used in the home, in data centres and in other networks. Our main focus is on the electrical in-use energy, but we go beyond this to also consider the embodied energy and carbon impacts associated with networks and the services that they deliver.

2. BACKGROUND

In [4] the authors presented a model to estimate the energy impact of optical IP networks based on data from commercially available network equipment. The model network topology is a fair reflection of modern network structure and the model aims to capture practical implementation factors from the concentration that is applied as traffic shares resources through to the impact of cooling overheads. The model also shows how to evaluate the impact of changing equipment efficiency. The authors use this model to generate an expression of the power per access line of the Internet, as a function of access rate for various network access technologies. Such modeling capability is useful as it allows comparison between different architectural solutions without

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needing to rely on full implementation. They have then used their model to develop an understanding of cloud computing [6] – a technology that is often promoted as a green technology by centralizing computing resources and so enabling these resources to be efficiently managed. To achieve this, a proportion of the power per line is allocated to the specific cloud use – in particular a metric of “joules per bit” is used for shared network resources.

A broadly similar approach to modeling networks was used in [8] to compare different network architectures. This extended the analysis to include an estimate of the energy embodied within a network. This paper notes that the energy embodied in optical fibres is not insignificant, and so an architecture that minimises operational energy use may not minimise the total energy impact.

In the above models, the metrics of “power per line” and “joules per bit” are key. In this paper we consider how these metrics can be developed and used in a real-world, deployed network context.

In [15] the authors examine the question of the real-world cost of networking. They use a top down approach based on total electricity consumption of a number of network operators. An advantage of our study is that we can use the top down analysis to verify a bottom up analysis based on deployed equipment. This enables us to understand the relative impact of different service types. It is also easier for us to understand, for example, the impact of leased lines and virtual private networks.

Many attempts to understand carbon abatement could be seen to under-estimate the impact of the explosion in ICT equipment that has occurred over the last twenty years. It appears unlikely that we would have the growth in laptop and tablet devices if we did not have the network infrastructure to support them, so an end-to-end model of energy/carbon impacts should consider this aspect. We have estimated the total carbon footprint of equipment in the home that exists partially or totally as a result of the communications infrastructure. The purpose of this is to capture the potential rebound effects of networking more completely.

It should not be forgotten that, as noted earlier, ICT products have the potential to provide a significant net carbon benefit for customers [17], [14], [9]. The research presented in this paper will enable a more accurate estimate of potential net savings to be calculated and will also indicate how those savings can be maximized through improvements in communication system efficiency.

3. ENERGY USE IN TELECOMS

3.1 Network Platforms and Infrastructure

A real communications network that has been evolving for over 100 years is inevitably complex. Essentially, BT’s network is a conglomeration of a range of different underlying network platforms. For example, the Public Switched Telephone network (PSTN) is the telephony network that provides services worldwide, and some of its supporting equipment has been installed and operational for several decades.

Of a similar age is a private circuit network that is used primarily for leased line and early Internet Access services. Although this supports many data services, the underlying technology is circuit based, so this network provides many features that until very recently have been unavailable within IP-based networks. For example, because of the need to have accurate timing data, many mobile base stations in the UK have a leased line for handover signaling in addition to high speed IP/Ethernet connections for the data traffic. Typically, legacy networks remain in operation where they provide specific functionality or performance features that are not replicated by more modern network technologies. However, as customers gradually move to new ways of working supported by new technologies, the legacy networks will see steadily declining use, and steadily increasing under-utilization which has implications for energy efficiency of real-world network deployments to which we will return.

In recent years, we have deployed a range of access technologies including digital subscriber line (DSL), Asymmetric digital subscriber line 2 plus (ADSL2+), Fibre to the Cabinet (FTTC) and fibre-based Ethernet to provide ever greater access bandwidths to residential and businesses users.

The ADSL2+ , FTTC and Ethernet access networks have been supported by new (21C) backhaul, metro and core network infrastructure - a high speed network based on optical transmission, Ethernet switching and IP routing. Note that the BT infrastructure is used by many communication providers, so the Ethernet switching provides isolation between these different providers. Although the basic 21C network was deployed around 2005, it is seeing continual development to handle continuing traffic growth.

3.2 A Model of Energy Use

Energy costs BT over £250m per year, so is a significant expense. Saving energy brings both the environmental (carbon) benefits as well as the associated cost savings. The lion’s share of energy use is due to the electricity consumed by BT’s networks, which co-exist in around 6000 exchange buildings, for which electricity meter readings are available.

Given these drivers and the overall level of network complexity, it is important that BT has the ability to understand network energy use at a lower level of detail, so that usage hotspots and opportunities for energy reduction can be identified. We have therefore built an energy model that captures the electricity use of each network platform.

This model is primarily based upon records of deployed equipment with estimates of power use, supplemented with domain expert knowledge where necessary. The power estimates are usually based upon measurements made on sample equipment, either live or within network test facilities - this is particularly important for older equipment, where power data was traditionally provided solely for the purpose of power provision and so was typically a worst-case estimate. The model also estimates the energy overheads associated with equipment, such as the cooling required for the high density 21C core equipment. These estimates were made by first obtaining measurements at a small number of sites of the AC and DC loads at those sites. The DC load is solely associated with the network equipment. By comparing the AC and DC load, we can therefore quantify the overheads at those sites. These sites were chosen because they were of different types containing different ranges of equipment. The overheads were found to be platform dependent. The platform-specific overhead value was then applied to all equipment within each platform. The output of the model is then verified against electricity bills.

The energy model also includes an estimate of data centre energy, based on equipment records. Energy overheads are again estimated from a comparison of the AC and DC loads at each data centre.

The energy associated with running a business – offices and call centers is taken directly from billing information for each office building. Some buildings have shared use, for example office and telephone exchange. Where available, sub-meter readings have been used to quantify the office energy. This has provided data to enable us to estimate the split between office and exchange for buildings without such sub-meters. The model also includes overheads associated with network maintenance – IT systems to identify and monitor faults, the truck rolls to repair them, and the use of oil in generators to power the network during electricity failures. These factors are taken directly from fuel bills. Note that the model can also provide future projections based on network development plans.

3.3 Energy Use – the Big Picture

Figure 1 shows the energy footprint of BT's UK business based upon the BT energy model, providing the big picture of energy use in BT, dominated by in-use energy used to run the UK network infrastructure.

The figure could of course be translated into a carbon footprint using the relevant conversion factors. In fact BT has an agreement with its energy supplier that they will source 100% of BT's UK electricity from renewable sources, i.e. a matching number of units from renewable sources are fed back into the electricity grid for every unit BT consumes Thus the carbon emissions factor for BT's UK electricity use could be considered close to zero. However this does not negate the need for energy efficiency, since the UK faces electricity supply challenges nationally and energy prices will continue to rise steeply.

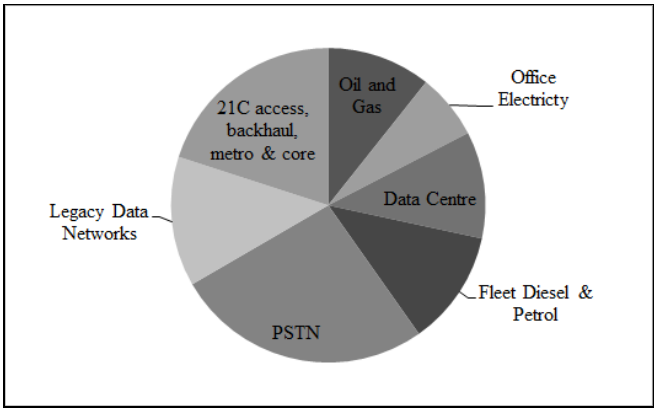


Figure 1 Energy Use within BT

3.4 Network Energy Efficiency Values

Typical network energy efficiency metrics that have proved useful are "power per line" (as used in [4]) and "energy per bit" (eg [24]). Power per line figures are an effective way to quantify the total environmental impact of networking whilst energy per bit is a generic metric that can be used to quantify the impact of specific services – for example a CD download which needs a known number of bits to be transmitted. Here we describe the method by which these metrics are calculated for our network, using the 21C network as the exemplar. Note that here we focus purely on network energy costs.

3.4.1 Power Per Line

The 21C network has three types of access port: ADSL2+, FTTC and Ethernet. There is one access port per line, thus the *power per access port* is easily calculated by dividing the total power of the relevant **access platform** (e.g. ADSL2+) by the total number of active lines it supports. Note that the platform energy, which is determined from the BT energy model, already includes all energy overheads such as AC to DC conversion losses and cooling. This method of calculating the power per line also fully captures the impact of any spare capacity.

Other types of resource, such as **backhaul or core network platforms**, are shared between users. Records are maintained that allow us to estimate the total provisioned bandwidth on each platform based upon the known number of users and the bandwidth provisioned per user. Typically, different types of user have different resources configured for them. For example, the backhaul bandwidth provisioned per FTTC user is greater than that provisioned per ADSL user. The energy consumption of such shared resources is allocated on the basis of the provisioned bandwidth per user divided by the total bandwidth provisioned on that platform. This most accurately reflects what drives growth in the network and therefore the energy use of the network, enabling an estimate of the power per line to be calculated.

It is normal to consider *essential* network equipment that is located physically within the home as part of the fixed network. We consider that the home energy of broadband lines includes the equipment used to terminate the access line and a wireless home router (these are often integrated into one unit). The energy use of the home router may depend upon its usage profile as some elements within more modern routers use less energy when not actively connected to the network. Colleagues [McDonald, personal communication] have measured the power draw of typical BT supplied home devices for each state of operation and also the typical activity levels (over multiple lines at one local exchange) and determined that on average a home router is actively connected to the network for 7 hours a day. This lets us estimate the weighted average power consumption of the home router – for example 6W for the ADS2+ modem. Note that the home energy associated with a PSTN user is assumed to be zero, since a basic phone is reverse-powered from the exchange.

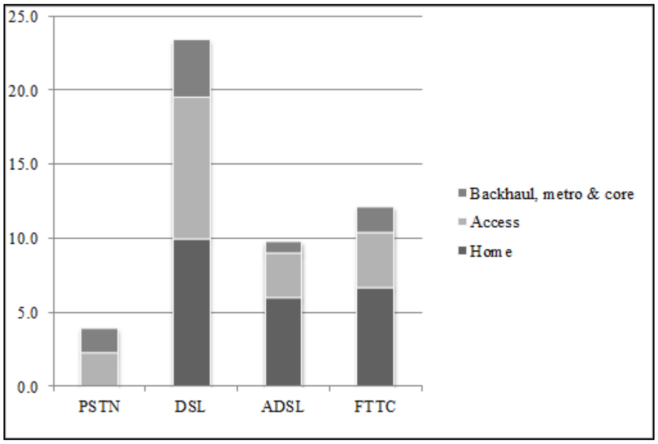


Figure 2 Power per line (W) for key access technologies

Figure 2 shows the power per line calculated as above for four key access technologies. We use data from the energy model for 2016, as at this time deployment of FTTC will be more established and the metric values therefore more stable – currently the power per line for FTTC is changing rapidly due to the high rate of network deployment and rapid increase in user base. (This choice of year does not materially impact the power per line calculated for the other technologies).

3.4.2 Energy Per Bit

To calculate the "energy per bit" metric, we need traffic statistics. Focusing on residential broadband customers, traffic measurements by colleagues [Soppera, personal communication], [Cathcart, personal communication] quantify the amount of data that is downloaded per line and how that depends upon line access type. We can then use this data to calculate the *energy per bit* for each of the different platforms. The energy per bit can be calculated as: the power per line multiplied by the number of seconds in a month divided by the bits per line in a month. Results are as shown in table 1.

Table 1. Energy-per-bit for various access types.

μ joules / bit	**PSTN**	**DSL**	**ADSL**	**FTTC**
Home	0	183	56	35
Access	1716	176	29	20
Backhaul, metro and core	1200	70	8	9

We present an energy per bit metric that is time averaged over actual traffic load rather than maximum capacity. This gives a more realistic indication of the actual energy involved in communication. It can be seen that the energy per bit is actually minimized when traffic load is at its highest. This might imply that the most energy efficient way of using a network is to add load at peak times. On a longer timescale however, such behavior would drive the network provider to add more capacity, increasing the energy costs. The instantaneous cost of using the network off-peak is higher than average, but the long term cost is less. Hence we use a time averaged energy per bit value.

The PSTN and DSL access lines are connected to legacy backhaul, metro and core networks, hence they are less efficient as more recently-deployed equipment efficiency has improved over time.

The energy per bit used within the 21C backhaul, metro and core region is virtually identical for ADSL and FTTC customers, even though the latter has a higher power per line in that region. This is because the higher level of provisioning (and so energy) for the latter is compensated by higher usage (more bits), i.e. the provisioning is proportionate to usage. This is unsurprising since similar Quality of Service expectations exist.

Assuming similar usage and quality of service profiles across different types of network user, then we would expect all services using the 21C backhaul, metro and core network to have broadly similar energy per bit figures. Similarly, we would expect other services using the oldest circuit-switched network to have energy per bit figures similar to that of the PSTN.

The aggregated energy per bit for the broadband networks is 113 μj/bit which, assuming download speeds of nearly 15Mbps [20], is approximately ten times greater than some prior models have suggested for communication across the Internet [4]. Before we consider additional costs (outside of BT) we first identify why communication costs in a live network may be higher than modeled costs.

3.5 Issues Affecting Energy Efficiency

There are a number of reasons why the power per line and energy per bit figures of real-world deployed networks are higher than might be otherwise estimated by models, including issues associated with legacy networks, provisioning and utilization.

3.5.1 Legacy Momentum

The effects of efficiency improvements take a long time to be fully incorporated into the network. Equipment remains in the network for as long as it is needed. For example, DSL equipment which is now being removed has been in place for around ten years or more, whilst the PSTN equipment is over twenty five years old. Whilst specific network devices may be replaced to provide increased capacity, if the old equipment is still viable, it is likely to be re-used elsewhere within the network. Note that this reduces the impact of embodied energy which can be an important factor in overall energy/carbon footprint (discussed later).

BT has been monitoring its network energy use for many years and can make traffic estimates for its network over the same period. These estimates are based upon usage patterns (the typical call times per voice line and the average data volume downloaded per broadband line) for each particular year. Where the data is not available (such as for private networks) we make the assumption that the utilization levels will be similar to those on other networks. This has allowed us to estimate our observed aggregated network efficiency as shown in Figure 3, which here excludes the home element. This shows that network efficiency does indeed improve over time. This improvement occurs because new equipment needs to be added to the network to address traffic growth. To support the higher data rates that are needed because of traffic growth, each new generation of network equipment is implemented with silicon that has a smaller gate size, with a fortuitous reduction in energy. Historically, a two times increase in speed caused by a decrease in gate size is accompanied by a 1.4 times increase in power consumption. Since speed doubles approximately every 18 months, the energy per bit for equipment reduces by about 0.8 a year [16].

The observed network efficiency improvement rate is around 0.16 - slightly slower than the technology efficiency improvement noted by [16]. We note also that by the time equipment is deployed it is inevitably already behind the most efficient systems.

3.5.2 Provisioning and Utilization

Traffic levels vary tremendously during the day, as can be seen in figure 4 which shows average traffic as downloaded by ADSL and FTTC broadband users. Further, as users migrate to new networks, this effect is getting stronger, i.e. the difference between average demand and peak demand is increasing.

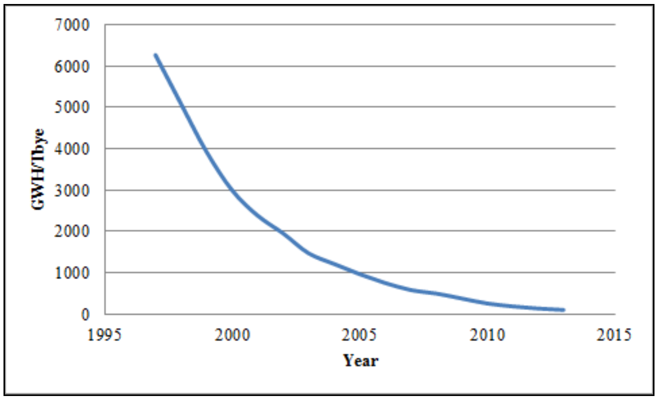


Figure 3 Observed network efficiency

There is a lack of adaptation within most network equipment to enable it to respond to variable traffic levels, i.e.the power drawn does not typically go down as traffic decreases. Based on a comparison of peak bandwidth and actual utilization levels, we estimate that if the energy consumption of the network were able to fully track the utilization, then we would save 55% of network energy.

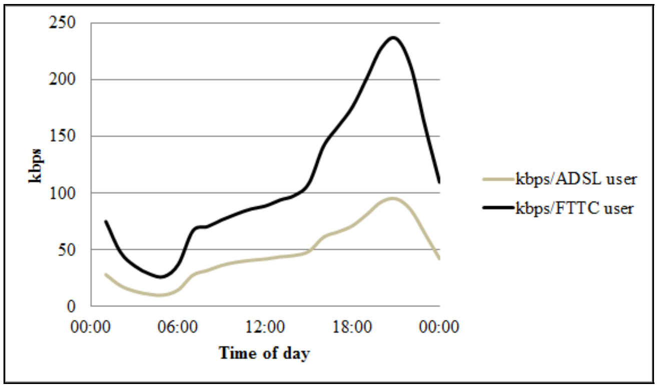


Figure 4 average traffic by time of day from residential broadband users

Note that traffic with a less variable demand level could achieve a significantly lower *energy per bit* value, as relatively fewer resources would need to be provisioned to support the same quality of service and total volume of traffic (since peak demand drives the level of provisioning), but at present we see no evidence to support a suggestion that smoother traffic profiles are commonplace within our network.

The provisioned resources will be greater than the peak required bandwidth in order to ensure that there is sufficient headroom to ensure good quality of service. Further, because it can take time to provision new resources, there will be sufficient headroom to ensure that the quality of service does not degrade as traffic grows – current rate of growth is observed to be around 25-30% a year within the UK. Finally, to maintain reliability levels, most resources have a level of redundancy associated with them.

3.5.3 Rollout of New Access Technologies

Utilisation can also be low because of the effects of granularity associated with the rollout of new access technologies. Take for example a typical VDSL cabinet. For a cabinet serving between 1 and 48 VDSL users, it must be provisioned with a 48-port line card. Even with lower power modes operational for ports that are not connected the power for one user is over 100W, falling to 2.2W as number of users rises to 48.

Then, the utilisation of any fibre gigabit Ethernet (GE) links back to the exchange will be significantly less than 100 percent, even at peak times. If there is only one use on a cabinet, with a service of up to 80Mbps being provided, a whole GE link must be provided. This difficulty in matching link bandwidth or switching capability to the required capacity continues through the network.

3.5.4 Regulatory Constraints

BT's network supports many different communication providers via a range of wholesale and access line products in a manner defined by regulation. This has led to a network design that contains additional electronic switching points at regulated points of interconnect. Today, as competition becomes established within the UK, some of these switches may be removed if they are no longer providing interconnect.

3.5.5 Summary of Energy Efficiency Issues

Figure 5 shows our cumulative estimate of the impact of all of the above factors on the network (excludes home impact).

The first bar shows the aggregate network efficiency today; the second bar shows the efficiency of the most modern FTTC/21C platform (from Table 1).

We separated "adaptation to redundancy and granularity" from "adaptation to utilization", since any adaptation to these will take place on different timescales. Adaptation to changes in utilization levels would need to take place in nano-second timescales to avoid impacting network quality of service, whereas reaction to, for example, network failure, can occur in a milli-second timescale. We estimated earlier that complete adaptation to utilization would save up to 55% of network energy use. Similarly, we can estimate the maximum savings that can be made with slower adaptation based on the number of spare access ports that are available and the amount if capacity that is provided for redundancy purposes.

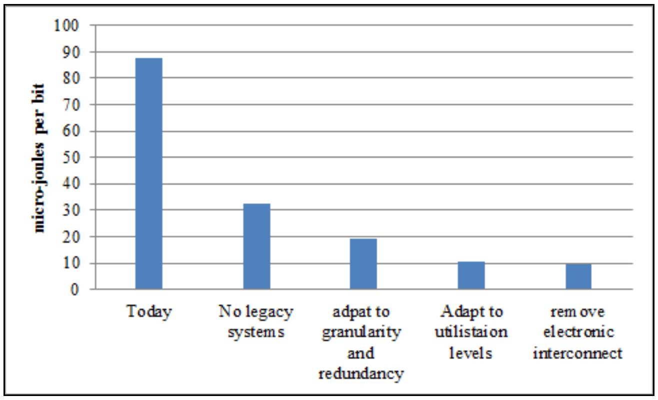


Figure 5: Impact of real-world on network efficiency

We note that legacy networks have the biggest impact; these are today also the networks with the greatest number of users. However the ability to adapt the network energy use to traffic load could have a significant impact on network energy consumption and so is an interesting area for further research.

3.6 Energy Use Beyond BT's Network

As we wish to understand the full end-to-end energy impacts of networks and network services, it is also important to consider those elements that lie beyond BT's own network, but which are required for a network service. These are discussed below.

3.6.1 Internet Energy Use

The total energy cost of communications needs to include the energy in other parts of the Internet network, beyond BT's own network. Analysis of our traffic suggests that around 80-90% percent of traffic on our network is coming from data centres which are external to BT [Soppera, personal communicaton]. These data centers are typically those which are providing video, news or host e-commerce sites.

To estimate the energy costs associated with networking (beyond BT's network) to the data centre we first make the assumptions that it exhibits similar efficiency to BT's network and that the energy use of the network is proportional to the number of IP switching hops within it. We have then used traceroute to examine the routes most commonly taken by traffic that terminates on our network to estimate the number of hops both on and off the BT network. As an example, 20% of traffic for our residential customers is from YouTube; this requires only an additional three IP hops to reach the data centre server after the exit from BTs network (a total of 17 IP hops including the home router).

We found that for many popular (in terms of either traffic volume or web page hits) sites the traffic is traversing only a few hops outside of the BT infrastructure. Whilst some popular sites have noticeably longer routes, these tend to be responsible for relatively low amounts of actual traffic. Typically we find that the routes that are heavily used are short.

Based on the average IP hop count of the sample of routes investigated, we can estimate the additional energy needed to connect from the BT network to the data centre. Using a simple pro-rata approach based on this hop count, we estimate that about three quarters of the energy used to transmit data from the data centre to a BT customer is used within the BT network. Note that we exclude the energy associated with the home router in this calculation. Note also that this result will differ between service providers.

3.6.2 Data Centre Energy Use

The energy used within the data centre itself should cover devices to manage connectivity between the internet and the data centre (including Ethernet access termination for example) and internal networking energy, as well as energy for servers and storage. At present we have only been able to sample the energy costs associated with data centres, gathering data from three major data centres: Facebook as an example of a social media provider, Google which provides search engine and YouTube video and Akamai, a content distributor which supports a wide range of sites such as for news and internet shopping sites.

Facebook estimates that it uses 532GWH a year [10]. It is estimated that it is responsible for between 1.3 and 3 percent of Internet traffic [21]. We assume that the total Internet traffic is 31339 PBytes a month, as given by [7] for 2012. This implies of order 20 to 50 μj per bit.

Similarly, Google is responsible for around 20% of all traffic (YouTube plus other services, [21]) and uses 3,325 GWH a year [11]. This leads to an estimate of around 20μj per bit.

Finally, Akamai estimates its energy use as 216 GWH a year [2] and that it delivers 15% to 30% of Internet traffic [1]. This leads to an estimate of 0.9 to 1.7 μjoules per bit.

This suggests a large range in the performance of data centres, from 1 to 50 micro-joules per bit from any particular data centre. At first glance it is likely that this is linked to the general complexity of the data center.

To estimate the power cost per line associated with data centres in general, we use the fact that traffic analysis suggests that 80 to 90 percent of traffic on any one line is coming from a data centre. Since the weighted-average traffic over broadband lines is of order 300Gbits a month per line, thus we can estimate that the users on a single broadband line use between 243 and 13680 kjoules per month in data centre energy (across all data centres touched by the user). This is equivalent to 0.1 to 5 W per access line.

3.7 Embodied Energy of Networks

The energy embodied in the network includes the energy used in the fabrication of optical fibres and routers, as significant components.

A study on behalf of BT by Small World Consulting estimated that the carbon footprint of BT's supply chain is around 64% of the total BT carbon footprint [22]. This is based on an Environmentally Extended Economic Input-Output (EEIO) analysis – thus it is based upon BTs spending levels in different industry categories. This approach uses knowledge of the direct emissions associated with each category of industry and assumes that every unit of expenditure in any industry category has the same emissions intensity. The approach used is in fact a hybrid Environmentally Extended Input Output (EEIO) method, in that corrections have been made where the assumption can be proven to be invalid.

An alternative analysis has been carried out using a "process sum" approach to estimate embodied energy in a network [8]. This is a bottom-up approach which aims to estimate the emissions that take place at each stage of product manufacture. This again suggests that the embodied energy within a network is around twice the in-use energy.

Given the high embodied energy costs of networking, it may be considered that the net environmental impact of a network may be minimized if legacy systems were maintained. Figure 6 shows the cumulative energy used for a router replaced every year, eight years and 25 years. It uses the data for a CSR1 router from [8] assuming that equipment efficiency improves at 20% a year [16], with no change in embodied energy or equipment capacity.

The figure shows that the cumulative energy is lowest when equipment is replaced every eight years. This suggests that the optimal lifetime for network equipment is around eight years. Re-running the calculations with the assumption that the capacity of the equipment when replaced will need to be upgraded to handle traffic growth of 30% a year, the optimal lifetime increases to around twelve years. An optimization model is left for future work.

It is worth maximizing the life of fibre as this requires no in-use energy but has a high embodied energy cost. Fibre lifetimes of twenty five years are not uncommon. Using the data from [8], two routers would have a total embodied energy of 1.3 TJ and use 0.9 TJ per year. If these routers were interconnected by 40km of fibre, the embodied energy of the fibre would be 7 TJ. The EEIO analysis of [22] also shows the embodied energy associated with cables and fibre to be higher than that of the electronic equipment. A network is therefore minimizing its total environmental footprint when it is not constantly being upgraded, driven by a desire to minimize its in-use energy consumption.

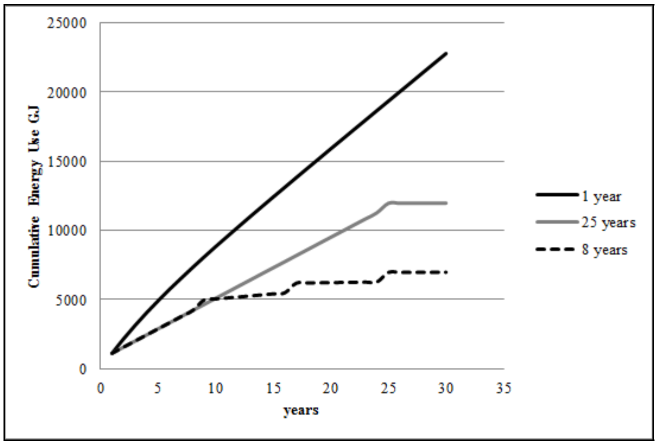


Figure 6. Cumulative energy used for a router with different replacement strategies

We observe however that the understanding of embodied energy of networks is still somewhat in its infancy and therefore currently lacks consensus.

4. HOME NETWORK EQUIPMENT

As we are seeking to develop a full end-to-end view of the energy and carbon impacts of real-world networks, it is necessary to consider the impacts of home equipment associated with telecommunications networks. The devices that we consider important to include are laptops, PCs, smartphones, games consoles, e-readers and tablet computers.

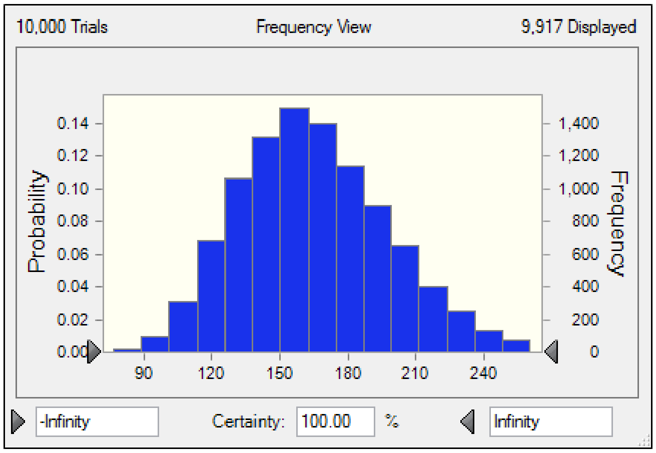
We do not include TVs and various TV-related set top boxes or music players in this analysis, since it appears that these devices have been subject primarily to substitution, as opposed to a growth in devices triggered by new network based services. For example, an internet-enabled music player often replaces a portable cassette or CD player.

We have gathered data on the penetration of different device types within the home [18], typical power consumption, lifetime energy use and embodied energy for each of these device types [3][25]. Because of the inherent uncertainty in much of the data, to build an understanding of the energy and carbon impact of networked home devices, Monte-Carlo simulation was used as a modelling tool.

We have allocated a share of the in-use and embodied energy as a network cost, the share being device dependent. For laptops and PCs, we have compared the total device use time (which we calculated from lifetime energy use and typical energy consumption) to the time spent on the network [18]. For devices such as an e-readers, 100% of the cost is allocated against the network as these devices fundamentally rely upon the network connectivity. A smartphone is 50% allocated to the fixed network and 50% allocated to a mobile network.

Table 2 shows the key parameters used in the model. The model output does depend strongly on these parameter values and on the expected lifetime of devices (we assume 4 years for the larger devices and 3 for the smaller devices). Figure 7 then shows our estimate of the likely carbon impact of home networking in an average UK household, in kg CO2 per household (the sum of in-use and embodied carbon per year). Based on the estimates of in-use and embodied carbon in Table 2, the model also generates separate results for in-use and embodied carbon as 54 ±16 kg CO2 and 104± 24 kg CO2 respectively. *We note that, due to the data available on the environmental impact of home electronics, we have switched from considering "energy" to "carbon" in this model.*

To convert these carbon figures to an average power per household and average energy per bit figures (for ease of comparison to the data in the other sections), we assume a global average of 0.0858 tCO2 = 1 GJ, based on worldwide energy use and carbon emissions [12].



Certainty: 100.00 %

Figure 7 Model results for environmental costs of home networked devices, kg CO2 per year per home

This gives the effective in-use power draw of home equipment as around 20W per household. This number may appear small given the number of devices often simultaneously in-use, but reflects the large improvements in energy efficiency especially in battery powered devices, usage patterns and the assumption that the devices will otherwise be switched off or in energy saving modes [13].

Table 2 Home network energy model parameters

Parameter	Value per year
Laptop Device Penetration	61 %
Laptop embodied carbon	97 kg CO2 ± 30
Laptop in-use carbon	24 kg CO2 ± 10
% of laptop allocated to network	52 – 100%
Games machine Device Penetration	52%
Games machine embodied carbon	102 kg CO2± 10%
Games machine in-use carbon	59 kg CO2± 10%
% of games machine allocated to network	35 – 100%
PC Device Penetration	44 %
PC embodied carbon	108 kg CO2 ± 40
PC in-use carbon	99 kg CO2 ± 40
% of PC allocated to network	26 – 100 %
Smartphone Device Penetration	39 %
Smartphone embodied carbon	19 kg CO2 ± 6
Smartphone in-use carbon	4 kg CO2 2
% smartphone allocated to network	50%
Small games Device Penetration	32 %
Small games device embodied	13 kg CO2 ± 4
Small games in-use carbon	1 kg CO2 ± 0.4
% of small games allocated to network	47 – 100 %
E-reader Device Penetration	14 %
E-reader embodied carbon	13 kg CO2 ± 4
E-reader in-use carbon	1kg CO2 ± 0.4
% of e-reader allocated to network	100%
Tablet Device Penetration	18 %
Tablet embodied carbon	35 kg CO2 ± 10
Tablet in-use carbon	9 kg CO2 ± 4
% of tablet allocated to network	47 – 100 %

Using average data volumes as before, we can then estimate the (in-use) energy per bit as 174 μjoules. The embodied energy is found to be almost twice the in-use energy. We note that this is an average across all device types. Portable devices in particular can be seen to have a much higher ratio of embodied to in-use energy than wired devices. We further note, as highlighted in [13], embodied energy estimates are still uncertain.

5. CONCLUSIONS

ICT has the potential to provide a net carbon benefit, enabling users to save more carbon through activities such as video-conferencing than the provision of ICT services uses. However, the energy and carbon cost of networking is not trivial - BT alone uses around 0.7% of the UKs electricity.

To achieve the full potential of telecommunications networks to reduce the likelihood of significant climate change and to help tackle energy security issues, we need to ensure that the ICT industry is not causing more problems than it is solving. To understand this we need accurate quantification of the actual energy use associated with communications networks.

In this paper, we calculate the power-per-line and the energy-per-bit associated with real-world communication networking. These parameters give us an overall understanding of the total energy cost of networking, and a means to calculate the energy use of any specific service.

Table 3 shows the in-use energy impact of fixed line networking. The figures for broadband represent an average across the different network types, weighted by the number of users of each system.

Additionally, we have examined the information currently available on embodied energy costs. Within the home environment it appears that (using current equipment lifetimes) embodied energy is approximately twice the in-use energy. Within the fixed network electronic equipment, cumulative in-use energy and embodied energy are approximately equivalent if systems are replaced every eight to twelve years. The total environmental impact of a network is minimized if systems are maintained for eight to twelve years, even though this means that the in-use energy will be significantly higher than might be estimated from state of the art equipment. Network lifetimes of twelve to twenty-five years are currently not unusual, with copper and fibre cable lifetimes often significantly longer. The embodied energy costs associated with the cable infrastructure is not insignificant. The net effect is that the environmental impact of the fixed network could be four times the in-use estimate. However, as noted earlier this needs to be treated with caution as there is not currently consensus on the level of embodied carbon in networks.

We showed that the typical in-use energy per bit figures for real networks are often higher than those predicted by modelling alone. The primary reasons for this are firstly that the impact of legacy systems is not fully recognized and secondly that network utilization is much lower than often assumed within a model. Low utilization is driven equally by the need for redundancy, to ensure quality-of-service and the need to provision for peak traffic load. The impact of low utilization could be addressed if equipment could adapt its energy consumption to the current traffic level.

Table 3 Typical figures for network energy use

	Energy, μjoules / bit	Power, W / line
Home Devices	174	20
Legacy Network	2916	4
Broadband Access (including network termination in home)	116	11
Broadband Core (including access to data centre)	17	1.5
Data Centre	1 - 50	0.1 – 5

We note that the impact of the equipment in the home is limited. This can be attributed to rapid improvements in the energy efficiency of home equipment over the last few years. Of course the rapid update of home electronics carries an embodied energy implication.

We also see that although data centres receive significant, often negative, publicity about their energy consumption, the energy consumption of other elements in the communication chain can be as significant. These figures suggest that remote location of data centres (for example to enable access to a low-carbon energy source) may not always be effective, end-to-end. This is because it would increase the network distance traversed, typically requiring more network routing and additional fibre lengths.

We conclude that to understand the full environmental impact, the full end-to-end implications need to be understood. Although data on embodied energy is still poorly understood, the evidence suggests nevertheless that any end-to-end energy estimation needs to take embodied energy into account. Future work therefore should seek to understand the embodied aspects more thoroughly, considering not only equipment manufacture but also the equipment decommissioning. An optimization could then be made between in-use and embodied energy to understand the system lifetime that minimizes environmental impacts. Additionally, further research is needed to understand how to make a network adapt its energy use to the actual traffic demand as this would have a significant impact on operational energy use in a practical deployment.

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