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Network energy use not directly proportional to data volume

The power model approach for more reliable network energy consumption calculations

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Abstract

It is commonly assumed that data volume and network energy consumption are directly proportional, a notion perpetuated by numerous studies and media coverage. This paper challenges this assumption, offering a comprehensive examination of network operations to explain why the relationship between energy consumption and data volume is nonlinear. The power model approach is explored as an alternative methodology for calculating network energy consumption providing a more reliable representation of network energy use. The power model demonstrates that simple energy intensity calculations, expressed as kilowatt hours per gigabyte of data, are insufficient for accurately estimating real-world network energy consumption.

KEYWORDS
computer industry, energy consumption, information and communications technology (ICT), internet, network energy, sustainable computing

1 | INTRODUCTION

Information technology (IT) or information and communication technology (ICT) can be defined broadly, but is generally comprised of connected devices, for example, laptops, phones, and IoT devices; access networks ("last mile to customer"), for example, mobile base stations and local network nodes; data transmission networks/core networks; and data centers (Malmodin & Lundén, 2016; Malmodin et al., 2023). For specific services such as video streaming and broadcasting in the entertainment and media (E&M) sector, additional devices are required such as televisions at the customer side and streaming servers located in data centers. For all these cases connectivity is usually facilitated through the global networks commonly referred to as "the internet" (excluding the user devices).

Although often referred to in the singular and lacking any formal definition, the term "the internet" was first used in the 1974 "Specification of Internet Transmission Control Program" as a shortened version of "internetwork" describing many interconnected computer networks (Cerf et al., 1974). Today, the internet is a crucial technology involved in all aspects of modern life—these networks are what enable millions of people to access digital services easily and cheaply as diverse as social media, collaboration software, online banking, trading, education, news, email, online gaming, and video streaming.

A common set of standardized global protocols exists to ensure data from a connected device is reliably transmitted to the destination. When accessing an online service such as YouTube, WhatsApp, or Amazon, the user's device or terminal transmits and receives electronic messages known as data packets. Even simple web browsing such as clicking a link or running a search can result in many hundreds or thousands of packets being transmitted and received, often over multiple networks owned and operated by different organizations, sometimes in different countries, under the sea or via satellites.

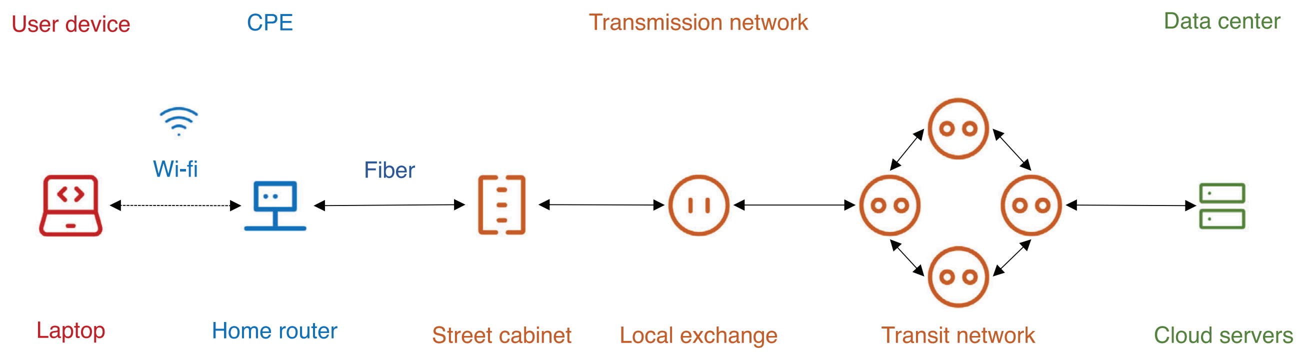

FIGURE 1 Illustration of the system described in the journey of a packet over the internet, from the user laptop device through the Customer Premises Equipment (CPE), transmission network (access and core networks), to the cloud servers running in a data center.

Over recent years, many articles with thousands of citations have been published on the assumption that there is a strong link between how much data is transmitted over a network and the amount of energy consumed by the network (Andrae & Edler, 2015; Belkhir & Elmeligi, 2018; Kishita et al., 2016). These claims are recycled in the academic literature (Madlener et al., 2022), think-tank advocacy reports (The Shift Project, 2019), workshops (Makonin et al., 2022), and review articles (Jones, 2018), and there are even those that acknowledge there is no such relationship, but then ignore it and publish based on that assumption anyway:

"In practice, energy use for data storage and transmission does not increase linearly with increased internet use. Our estimation disregards this nonlinearity and relies on average energy use per gigabyte of data…" (Obringer et al., 2021) (from the supplementary material)

These inaccuracies are perpetuated by mainstream media coverage (Griffiths, 2020) and form the basis for misleading analysis of the energy consumption of common services such as video streaming (Kamiya, 2020). At best, these result in recommendations for users to take ineffective actions (Boström & Klintman, 2019) such as deleting unwanted mail (Griffiths, 2020) and photos (IET, 2021), but are often used as arguments for regulation to cap usage, impose taxes, or make value judgments about "wasteful" behavior (Makonin et al., 2022). Repeated often enough, the myth has become reality through flawed methodologies for calculating the environmental impact of services and applications, for example, website carbon calculators, or unrealistic projections of the future energy consumption of the internet, for example, up to 20.9% of global electricity demand (Jones, 2018).

Data centers have historically been the focus of detailed analysis (Mytton & Ashtine, 2022), with the most recent credible analysis calculating a total energy consumption of 196 terawatt hours (TWh) for 2020 (Masanet et al., 2020) (excluding cryptocurrencies; Hintemann, 2020). However, networking is also an important component of the total energy footprint, estimated to be 272 TWh in 2020 (Malmodin et al., 2023). This is up from 240 to 250 TWh in 2015 (Malmodin & Lundén, 2018b), but at the same time network traffic grew by 600% (0.6 zettabytes in 2015 to 4.4 zettabytes in 2022) (IEA, 2023). The latest analysis from the IEA suggests that global data center electricity consumption in 2022 was 240–340 TWh and data transmission networks consumed 260–360 TWh in 2022 (IEA, 2023). Except for traditional fixed voice subscriptions, the number of users and connected devices has also continued to grow, but not at the same pace as the data traffic increase (Malmodin et al., 2023). This by itself demonstrates that there is only a weak link between energy consumption and data. So why is there a common assumption that network energy is proportional to data transfer?

In this paper, we provide a primer for non-experts describing how networks work and what that means for calculating their energy consumption. We also explain the pitfalls of the common, energy intensity-based approach to calculating network energy consumption, and we present an alternative methodology for analysis to use instead—the power model, originally described by Malmodin (2020), and later used as an alternative analysis of alongside real-world data by the International Energy Agency (IEA) (Kamiya, 2020) and the Carbon Trust (2021).

The goal of this paper is to provide a straightforward method for non-experts to assess claims about the energy consumption of computer networking, but we also provide a detailed technical explanation of how to perform more reliable calculations. It is important to challenge the methodology of future work that claims to show a direct link between network energy and data transfer, so we also highlight red flags to be aware of when reading or reviewing existing or future publications.

That stated, it remains important to address the sustainability challenges with the expansion of global ICT services. The authors of this paper urge caution because exaggerated claims harm the credibility of the overall message and result in too much emphasis on increasing data volumes rather than serious issues such as material usage and the lack of circularity in the full ICT life cycle.

2 | THE JOURNEY OF A PACKET OVER THE INTERNET

Consider a simplified journey of a single data packet involved in the delivery of video to a user via an internet streaming platform (Figure 1). Data packets are small units of communication which represent data that has been broken down for ease of transmission, then reassembled at the destination. The journey begins with the user device, which in this example is a laptop computer connected to Wi-Fi, but could be a television, tablet, or other connected device. The data packet is generated by the laptop and begins its journey by being transmitted over a wireless network to the user's router.

In this example journey the router is connected to the internet via a high-speed broadband cable linking the user's home to a cabinet located nearby (possibly on the same street, but up to a couple of kilometers away in less densely populated areas). Depending on the technology used, this cable may be a direct fiber connection to the home (in the case of modern broadband services such as Fiber to the Premises, FTTx) or an older connection, for instance via a cable television (CATV) or a telecom copper-based (xDSL) network (in the case of older, slower connectivity) (Ofcom, 2022). The cabinet contains multiple pieces of network equipment known as routers and switches which direct and manage all the data packets so that they are correctly relayed to the next step in the journey. This allows a single cabinet to serve multiple users and households in the same area. For high-speed broadband connections, the cabinet is in this case connected via fiber cables to a broadband node (which might be in a telephone exchange; Ofcom, 2022; also containing routing network equipment).

So far in this simplified example, the data packet has traveled through two networks. The first is the local network between the user device and their router, known as the Customer Premises Equipment (CPE) or Residential Gateway (RGW). The street cabinet and local exchange make up the second, owned by the local internet provider, known as the access network. In this example, the ultimate destination is a data center somewhere else in the country, which is reachable through a high-speed network called the core network. This connects the local exchanges to transit networks all made up of fiber optic cables also connected via routers and switches. The total number of networks depends on several factors such as population density, network complexity, and the distance between the source and the destination, known as network hops. The different networks may also be referred to by various names, such as edge, metro, or core networks, with varying types of equipment deployed to provide different types of services. If the destination is in another country, multiple transit operators may be involved, as well as very large "Internet Exchange Points" (Internet Exchange Federation, 2023) involving undersea cables or satellite communication.

Having started from the CPE and traveled through the access network and the core network (collectively called the transmission network), the data packet finally arrives at the data center. These are located all over the world and range in size from small cupboards through to "hyperscale" warehouses containing many thousands of servers (Barroso et al., 2018). The data center has its own internal network which will route the packet to the destination—a server that will process the request and perhaps send a response. That response will take a similar journey across multiple networks until it returns to the original user, but not always following the same route.

2.1 Hidden complexity

The example above is simplified to illustrate the basic concepts, but reality is much more complex because the flow of traffic is non-deterministic. A core design principle of the internet is that it is operational 24/7 and resilient to failure, so each packet may take a completely different route over entirely independent networks. Each network is made up of different equipment, all with different power consumption and efficiencies. This is important to understand when representing the complexity with a single number. Such an architecture is possible because packets are only reassembled in the correct order once they arrive at the destination. Packets may be lost and requests for retransmission may be made. Each packet may also be compressed, and different algorithms may be involved with deciding how to route each packet. For example, routing may happen by simply finding the shortest path; however, some algorithms analyze state information about whether certain routes are operating correctly including deciding how to avoid any congestion. Traffic flows are constantly changing which makes modeling them more complex.

This also has an impact on how different network operators report the volume of data flowing through their network. There is no measurement standard, so when an organization reports a number, it could refer to aggregate, peak, or total data transfer (Lundén et al., 2022). Often it is unclear if reported data traffic is based on a single direction or goes both ways. Such differences could result in double counting or allocating traffic to the wrong provider.

Application developers may also take steps to optimize their architecture depending on business demands such as how they wish to prioritize latency, response times, and the volume of data being transmitted. How each is addressed is a function of whether improving the user experience or reducing the cost of the infrastructure is the end goal, and these decisions may affect how much energy is consumed.

For example, an application may be designed to temporarily store (cache) static content such as images on the user device so that they are only transmitted the first time the application is loaded (Google, 2019). This means the data transferred is reduced on subsequent requests. Content delivery networks may locate the content closer to the user, particularly for popular sites and videos, which reduces the overall distance between the user and the destination, speeding up the response times and reducing data transfer (Mozilla, 2023). Server-side processing may render page components before they are sent to the user to reduce the work the browser needs to perform (Abramov et al., 2020). Compression can be enabled to reduce the data volume (Google, 2023) at the expense of processor time to perform compression/decompression (Chen et al., 2010; Song et al., 2022). Newer devices have specialist processor cores which the operating system and browser can use to improve performance, minimize energy consumption, and improve battery life depending on the task being performed (Apple, 2020).

TABLE 1 Components within the system boundary of an example online application.

Component	Power profile
User devices E.g., a phone, laptop, TV, or other connected device	Power consumption of user devices is related to usage, particularly with large screens such as TVs. These devices consume power when in use but are generally turned off or are in a lower-power standby mode when not used. Of increasing importance are Internet of Things (IoT) devices. Consumer varieties such as smart-speakers or Bluetooth weighing scales may exhibit different power profiles—they are likely to be always-on in a standby/idle mode awaiting user interaction, e.g., with an active microphone waiting for a trigger command. In industrial settings, these devices may be always active, such as in factory monitoring contexts. The power consumption per device is relatively low, but the number of active devices is huge (12–50 billion devices in 2022; Pirson & Bol, 2021) and increasing in volume over time (Maistriaux et al., 2023).
Customer premises equipment E.g., a wireless router, set-top boxes, modems	Always-on. Consumes a baseline amount of energy regardless of activity, with minor fluctuations depending on load and the number of activated features (Malmodin, 2020).
Transmission network (fixed) E.g., access and core networks	Always-on. Consumes a baseline amount of energy regardless of activity, with minor fluctuations depending on load (Malmodin, 2020).
Transmission network (cellular) E.g., 4G and 5G radio base stations and access networks	The radio access network (RAN) generation determines the power profile. 4G networks are most common but are nowadays complemented with the newer generation 5G networks (25% of connections will be 5G by 2025; GSMA, 2022) at the same time as the older generations 2G and 3G are phased out. The older generations 2G and 3G can be considered as always-on with minimal fluctuation due to data traffic load (Lorincz et al., 2012). Both 4G and 5G generations can be considered always-on with a baseline amount of energy regardless of activity with minor fluctuations depending on load (less proportionality for 4G, more for 5G using sleep mode) (Golard et al., 2023). For 4G networks, the baseline component accounts for 70%–90% of the total energy consumption (Golard et al., 2023). 5G technologies include a more aggressive "sleep mode" functionality which can reduce the energy intensity by 8–12× compared to 4G (3–5× lower without sleep mode) (Golard et al., 2023), but make it more proportional to usage.
Data center E.g., a colocation facility or a cloud "region"	Power profile depends on the application architecture. Applications running in modern cloud environments can be more efficient with better resource utilization because they can scale to meet demand and shut down when not in use, particularly if they are able to use "serverless" components. Physical servers (or virtual machines running on top of physical servers) are less efficient but have seen improving power proportionality over time (Barroso & Hölzle, 2007; Barroso et al., 2018; Shehabi et al., 2016). The power profile is therefore more closely matched with the overall load.

All these optimizations, which differ by application, help to improve the performance and power profile of applications, but make modeling more difficult.

3 | POWER CONSUMPTION ALONG THE NETWORK JOURNEY

Each component in the journey described above has its own power consumption profile which contributes to the overall energy impact. In a detailed life cycle assessment of a network (Malmodin et al., 2014), all these components are combined and aggregated, cut offs due to system boundaries are well defined, and finally broken down into several subcomponents such as presented in Table 1, which is evidenced by recent real-world observational data of networking equipment (Malmodin, 2023).

3.1 | User devices and servers: Some power proportionality

Components at both ends of the system—the user device and the data center—exhibit a power consumption profile that is more closely linked to usage and/or system load. This is known as power proportionality (Barroso & Hölzle, 2007)—the theoretical goal is that power scales with usage resulting in close to zero power consumption at zero load, also called dynamic range (Vertiv, 2016). Over the last decade, there has been a particular focus on processor efficiency, such as the move to multi-core architectures and optimizations such as speculative execution, which has resulted in almost a two-fold improvement in the dynamic range (Barroso et al., 2018).

However, whether this power proportionality is relevant in modern cloud data centers is unclear. Hyperscale cloud providers have been able to increase the utilization of their infrastructure because economies of scale allow investments into specialized equipment and workloads can be more effectively scheduled across that equipment (Barroso et al., 2018). The result is a base load that is effectively always on, with capacity held in reserve for expected (or unexpected) demand. Individual customers can scale their usage to zero, but that does not mean those resources are "turned off" in a traditional sense.

As can be seen from energy reports for modern laptops (Apple, 2022) and phones (Google, 2022), consumer devices are closer to this goal than server equipment in the data center. This can be seen from device testing under different activities and is often cited by manufacturers as the number of hours a device can be in use, depending on the activity, for example, web browsing versus video streaming (Apple, 2023). However, variation within a specific activity such as when streaming 720p versus 1080p video resolutions, is in practice negligible (~2 W) (Schien et al., 2023). Low-power or standby mode also tends to result in lower power consumption, but not zero.

3.2 | Network: Power not proportional to data

In contrast, power and data measurements of network equipment show no or very little proportionality (Barroso et al., 2018). Network power consumption is related to the capacity of the network equipment (Masanet et al., 2020; Shehabi et al., 2016). Unlike consumer devices which may experience long periods of low/no usage, networks are typically always in use due to the different usage patterns in time as well as the requirements for low latency among users, so improving dynamic range has not been prioritized (Abts et al., 2010). Power cycling network equipment is generally inefficient because it requires not just restarting the device, but also taking various steps at the protocol layer such as renegotiation of data rate and buffering of traffic whilst the deactivated device becomes available again (Abts et al., 2010).

Network upgrades happen in a step function where older equipment is replaced with newer equipment that might often have a similar or in some cases a higher total energy consumption, but with significantly higher capacity. Networks must also be provisioned for both peak capacity and redundancy. They must be designed for and be able to respond to unexpected spikes in traffic. These might be caused by additional traffic but could also be caused by diverting traffic from a part of the network that is offline due to an outage or for maintenance.

For example, Cloudflare is a large, global network operator. They reported that traffic volume fell by 13% on November 24, 2022, 13:00–17:00 Pacific Time when many in the United States were having their Thanksgiving dinner, then by 22:00 rose to 15% more than the same time the day before (Tomé, 2022). These traffic variations occur within just a few hours, showing how the network is provisioned to be able to handle such spikes.

4 | CHALLENGES WITH THE ALLOCATION/AVERAGE APPROACH

The most common method for presenting the power consumption of a network is as average energy per unit of data. Total network energy is allocated to total data transfer resulting in a number usually reported as kilowatt hours per gigabyte (kWh/GB). It is accurate for historical reporting or accounting because the total energy consumption and total data volume is known. It has been shown that energy intensity of fixed line networks in some developed countries has been falling by 50% every 2 years (Aslan et al., 2018).

A simple analogy can be used to describe this approach. Imagine a train which travels a particular route and consumes energy in the form of electricity to power the motors. At the end of the route, the total distance and total energy is known. This can be allocated to the total number of passengers to calculate the energy per passenger kilometer. For example, if the train travels 100 km and consumes 1000 kWh of electricity to transport 100 passengers, the energy intensity is 1000 kWh / 100 km / 100 passengers = 0.1 kWh per passenger per kilometer.

The limits of this approach become apparent if the average is used for estimating different usages of the train route, for example, projecting an increased number of passengers in the future. If we expect an additional 100 passengers over the same distance, using the same energy intensity gives us a total energy consumption of 0.1 kWh × 200 passengers × 100 km = 2000 kWh. Although there is indeed an increase in energy to account for moving the weight of the additional passengers, the increase is marginal and does not follow a linear model. Measurements would reveal that the total electricity consumption of the train varies only by a tiny amount for 100 versus 200 passengers because the marginal energy for an additional passenger is almost zero (Wee et al., 2005) whereas the intensity (per passenger kilometer) varies by occupancy (Dalla Chiara et al., 2017).

The train analogy is a useful illustration, but the magnitude of the passenger increase—doubling—does not accurately represent the type of increase seen in the IT sector. Network data volumes can easily increase by 10 or 100 times without the power going up more than 10%. A more accurate analogy might be a library building or physical mail sorting facility which would have a stable electricity consumption regardless of how many books are borrowed or letters processed. If we measure "use" by the quantity of "text" inside a book or letter (which we could call "text data"), the energy consumption is not proportional to this "text data." If the books or letters were then replaced with images, music, or video stored on physical media that increases in capacity with respect to the amount of data per physical volume, it is easier to understand how a library or mail delivery facility can deliver 10, 100, or 1000 times more data with a similar energy consumption. In this analogy, the library is like the data center, the mail sorting facility is like core networks, and delivery routes are like access networks.

It is important to note that any viable allocation method must never exceed the total power across all time periods and must not exceed the maximum power. As discussed above, network equipment is always on and operates at a baseline power consumption regardless of activity. Yet using the average energy intensity to predict the energy of a particular workload would break both rules.

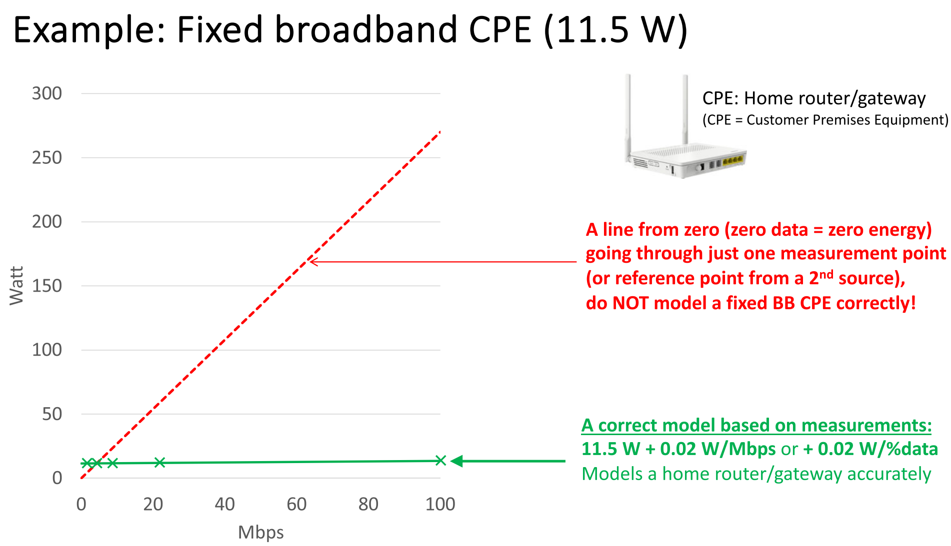

FIGURE 2 Representative illustration of a linear power model where zero data results in zero energy consumption based on data from Malmodin (2020, 2023).

For example, consider a 100 Gb network switch which has a 100 W max power rating (1 W/Gbps) and at 0% utilization, but fully connected it draws 90 W. If we then take a measurement at 10% utilization, we would see 10 Gbps of throughput drawing 91 W and calculate 9.1 W/Gbps. If this average energy/data number were then used to calculate 100% utilization it would show 900 W, but the maximum power is actually 100 W. In reality, switches are even more efficient with the new 24-port switch from 2015 measured at 0.322 W/Gbps (Malmodin, 2023).

Using a kWh/GB average implies a simple linear power model which starts at zero power for zero data. This is easy to prove incorrect by measuring the power consumption of a network router with zero network traffic—the measurement will not be zero (Figure 2). If the average is based on a low data rate reference point, then it will overestimate high data use. Equally, if the average is based on a high data rate reference point, it will underestimate low data use.

4.1 | Extreme projections

We can only know the energy intensity of any data transfer in hindsight because the calculation depends on knowing both total energy consumption and total data transfer in the given period.

A common abuse of kWh/GB averages is to extrapolate projections for future growth in data transfer to produce an extreme scenario of the future energy consumption of networks. It is very difficult to produce accurate estimates even a few years into the future because of how rapidly technology changes (Mytton & Ashtine, 2022). Energy intensity is based on the characteristics of a specific network so should not be used to extrapolate to different networks, particularly from small scale to large scale networks. Using historical averages to suggest very high energy consumption 5–10 years into the future, even with adjustments for possible improvements in energy efficiency, results in implausible numbers that should not even be presented as a potential forecast.

To put it short: If a static kWh/GB is applied to estimate future electricity consumption based on expected exponential data volume increase, any embedded error will also be exponentially extrapolated.

Challenges remain with the transparency of private network operators, but many network operators now publish data as part of their annual sustainability reporting (Malmodin et al., 2023). This allows us to compare actual numbers against projections. For example, in 2019 The Shift Project (The Shift Project, 2019) released a widely cited report which claimed that the energy consumption associated with digital technology would be between 3% and 7.5% of global energy consumption by 2025. This included user devices, networks, and data centers, and was based on previously published calculations with data up to 2013 (Andrae & Edler, 2015) combined with their own calculations up to 2017 to project an average 9% annual growth in energy consumption.

The model behind the network calculations assumes a direct relationship between data traffic and energy consumption, that is, it applies an annual energy intensity to the data volume for that year to calculate the total energy consumption. Although their model adjusts for efficiency improvements over time, the projections are still high. Using The Shift Project model to estimate Telefónica's 2020 energy consumption would result in an estimate of 26.8 TWh whereas Telefónica reported their actual 2020 energy consumption as 6.2 TWh (Table 2) (Telefónica, 2021). Over the period 2015–2021, Telefónica reported a 565% increase in network traffic against a 7.2% decrease in total energy consumption.

TABLE 2 Comparison of actual network energy intensity (terawatt hours per exabyte) and total energy consumption (terawatt hours) values reported by Telefónica (2021) and the projected values using The Shift Project model. This shows how using the energy intensity (TWh/EB) is falling over time and that using it to make future projections (shown in TWh) generates extreme (incorrect) results. The projection is calculated using the fixed wired energy intensity value from The Shift Project "expected" scenario multiplied by the data volume reported by Telefónica. See the Supporting Information S1 for the workings.

	Unit	2015	2020
Telefónica—Actual	TWh/EB	0.39	0.07
Shift Project—Fixed wired	TWh/EB	0.53	0.31
Shift Project—Cellular	TWh/EB	2.02	0.18
Telefónica—Actual	TWh	6.58	6.27
Shift Project—Projection	TWh	9.04	26.84

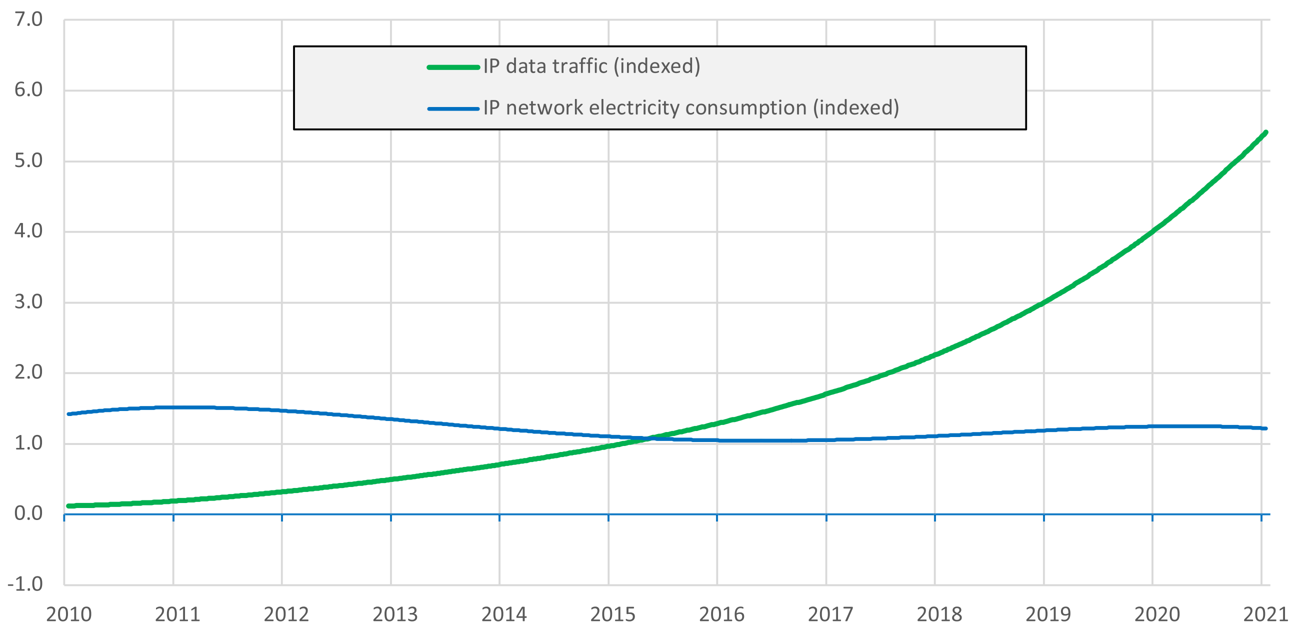

FIGURE 3 Electricity consumption indexed against IP data traffic for the global IP backbone provider, Arelion, for the period 2010–2021. A fourth order polynomial filter has been applied on the dataset due to seasonal IP traffic variations, mainly during the Covid period. From internal data provided to the authors. See Supporting Information S2 for the indexed values.

Arelion, formerly known as Telia Carrier, is a large, global backbone provider of IP connectivity. Starting in Sweden in 1993, the network has since expanded to provide global connectivity. The authors of this paper have been provided with internal data about the operations of the network which show the relationship between electricity consumption and IP traffic trends (Figure 3). The reported data traffic is growing much in line with Moore's law. At the same time, the electricity consumption has remained almost flat even though the physical network and the number of network points of presence (PoPs) have both increased. The available data goes back over a decade and shows how the electricity consumption has become decoupled from data traffic. Total electricity consumption is expected to decrease due to planned decommissioning of legacy network operations.

Other companies have reported a similar disconnect between energy consumption and network traffic. Cogent reported a 2017–2021 compound annual network traffic growth rate of 32.7% but a decrease of 16.6% for electricity consumed (Cogent, 2022). Virgin Media reported a 29.9% reduction of energy consumption per unit of data in 2021 compared to 2020 and 88% compared to 2015 (Virgin Media, 2022). In France, The Regulatory Authority for Electronic Communications, Postal Affairs and Print Media Distribution (Arcep) reported that fixed network power consumption has fallen by 14% between 2021 and 2022 (Arcep, 2024).

It is unclear whether the system boundary is consistent across each company, for example, Cogent's numbers are related to its optical fixed wired network backbone whereas both Telefónica and Virgin Media have a significant cellular network. However, all companies report improving energy efficiency even as the average might be influenced by blending less energy intensive fixed wired with more energy intensive cellular networks, a distinction that the Arcep report specifically comments on with rising mobile network energy consumption. Sprint does provide a breakdown explaining that networks make up 91% of total energy consumption which has remained flat (~1.9 MWh for each of 2014 to 2019) even as

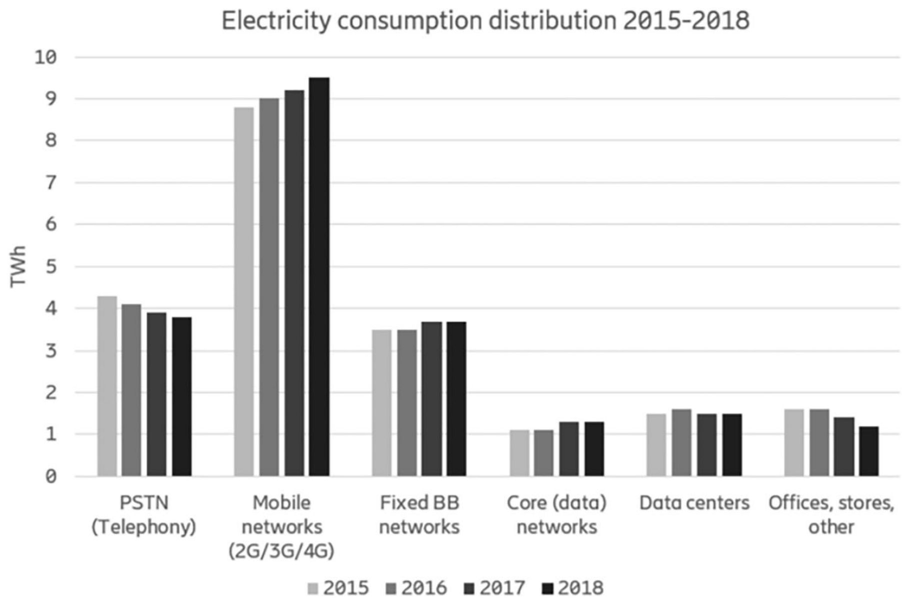

FIGURE 4 European Telecommunication Network Operators members total aggregated electricity consumption and trends per network type and overhead activity for the reporting operators of 2015–2018. These numbers exclude the electricity supply chain and distribution losses. From Lundén et al. (2022).

network data usage has increased (Better Buildings, US DOE, 2023). Indeed, Sprint's energy intensity reduced by 85% from 2.2 MWh/TB in 2014 to 0.3 MWh/TB in 2019.

4.2 | Location variations

The average global power consumption of a fixed broadband line is 160 kWh/18 W and for a mobile connection 20 kWh/2 W as of 2020 (Malmodin et al., 2023). However, these averages change depending on the location. For instance, Finland reports about 40 GB/month per mobile subscriber and that is one of the least densely populated countries, but the power per mobile subscriber is only about 4.7 W. The main reason for the higher power is not 4× higher data, it is mainly due to less than half the number of subscribers per base station in Finland. The average for Sweden is about 3.9 W, 17% lower than in Finland mainly due to population density in Sweden being 35% higher. The mobile data traffic in Sweden is only 40% compared to a Finish subscriber, which mostly depends on a much higher fixed broadband penetration than in Finland.

From a global perspective, there is also wide variation across regions: 75 kWh/connection in North America, 18 kWh/connection in Asia Pacific, and 15 kWh/connection in the Middle East and North Africa (GSMA, 2024). However, the common theme is that intensities have been falling by an average of 10%–20% per year since 2019 (GSMA, 2024).

An analysis of real-world observations across three cellular network operators in Belgium (Golard et al., 2023) supports this view. The static energy component of radio access networks makes up most of the energy profile and there is a linear relationship between the network capacity and the power consumption. However, the same paper projects an increase in total energy consumption over time due to increased total data volumes—with 5G deployed, energy consumption is projected to increase 27% (assuming sleep mode is used) against a 300% increase in data volume in 2025. This is primarily because 4G is unlikely to be decommissioned by this time so the baseline energy consumption of 5G is stacked on top of the 4G energy consumption, at which point the projected energy intensity is 12 kWh/subscription. If 4G were to be completely replaced by 5G, energy consumption would decrease by 64% (again with sleep mode deployed).

Similar analysis for Finland shows that the relatively high energy consumption of the legacy 3G network means it remains a large proportion of total energy consumption even as workloads transition to newer 4G and 5G networks (Huttunen et al., 2023).

Finally, survey data from 15 telecom network operators headquartered in Europe and covering 21 European countries reported that electricity consumption increased slightly from 20.8 TWh in 2015 to 21.0 TWh in 2018 (Lundén et al., 2022) (Figure 4). The total average electricity consumption (networks only) per subscription also remained mostly flat (19 kWh/subscription in 2015 to 21 kWh/subscription in 2018). When split out by network type, the mobile (cellular) average was 18 kWh/subscription in 2015 and 21 kWh/subscription in 2018 (mobile average networks only). These trends are despite data traffic increasing 2–4× between 2015 and 2018.

5 | ACCURATE NETWORK ENERGY CALCULATIONS USING THE POWER MODEL

Having demonstrated the problems with the allocation/average approach to modeling network energy, we now present an alternative methodology—the power model. Originally proposed in Malmodin (2020), and discussed in Carbon Trust (2021), here we define the model to allow easy calculation of energy values and offer examples of such calculations.

Focusing on network energy, the model contains two components: Transmission (core network) and CPE, both for fixed and cellular/mobile 4G traffic. The data center and user devices at either end can also be included but are covered in detail elsewhere (Barroso et al., 2018; Carbon Trust, 2021; Mytton & Ashtine, 2022). See Table 1 for a description of each of these.

5.1 | Transmission (core network)

The fixed core transmission network is modeled through a fixed, baseline power of 1.5 W plus a variable 0.03 W per megabit per second of installed capacity. For cellular 4G connections, the baseline is 0.2 W with a similar variable component. Values are from Malmodin (2020) and the supplementary material of Malmodin & Lundén (2018b).

5.1.1 | Fixed line example

Given a 100 Mbps capacity:

Fixed transmission power = 1.5 W + (0.03 W × 100 Mbps)

Fixed transmission power = 1.5 W + 3 W

Fixed transmission power = 4.5 W

5.1.2 | Cellular 4G example

Given a 1 Mbps usage:

Cellular 4G transmission power = 0.2 + (0.03 W × 1 Mbps)

Cellular 4G transmission power = 0.2 W + 0.03 W

Cellular 4G transmission power = 0.23 W

5.2 | Transmission (access network)

The fixed line access network is modeled at a fixed 5 W per subscriber (line or household). The range calculated in Malmodin (2020) was 2–10 W with only a small variation (on the order of 0.1 W), included as part of the CPE calculation below.

For cellular 4G, the access network is modeled at 2 W per subscriber as a baseline, plus a range of 1.5 to 10 W/Mbps.

5.3 | Customer Premises Equipment

The CPE is modeled through a fixed, idle power of 11.5 W plus a variable 0.02 W per used percentage of capacity. This must be allocated across the number of users in a household and the number of simultaneous users of the service to be able to apportion the point in time usage. For cellular 4G connections, the baseline is 7 W, but this can range from 4 to 10 W. It is assumed that a single cellular 4G connection services a single user, so no allocation is required. Values are from Malmodin (2020) and the supplementary material of Malmodin & Lundén (2018b).

5.3.1 | Fixed line example

Given a 100 Mbps capacity broadband connection used at 100% by a single-user household:

Fixed CPE power = (11.5 W / Household users) + (0.02 W × 100 Mbps / 100%) / Data users)

Fixed CPE power = (11.5 W / 1) + (2 W / 1)

Fixed CPE power = 13.5 W

5.3.2 | Cellular 4G example

Given a 1 Mbps usage:

Cellular 4G CPE power = 7 W

5.4 | Total energy

Calculating the total energy simply requires multiplying these values by the usage time.

5.4.1 | Fixed line example

Given 1 h of usage:

Energy = (Transmission power (Core + Access) + CPE power) × Time

Energy = (4.5 W + 5 W + 13.5 W) × 1 h

Energy = 23 Wh

5.4.2 | Cellular 4G example

Energy = (Transmission power (Core + Access) + CPE power) × Time

Energy = (0.23 W + 2 W + 7 W) * 1 h

Energy = 9.73 Wh

5.5 | Usage energy

Note that the above total energy is primarily composed of the baseline power which would be required regardless of whether the equipment was in use or not. It is therefore important to split the values into usage and idle to be able to demonstrate the marginal energy from the service usage, for example, to answer the question of how much energy is consumed when video streaming versus not.

5.5.1 | Netflix video streaming example

Assuming a 1-h video streaming session with 4 Mbps of data transmission over a 100 Mbps fixed line network in a single-user household:

Fixed transmission (core) power = 1.5 W + (0.03 W × 4 Mbps)

Fixed transmission (core) power = 1.5 W + 0.12 W

Fixed transmission (core) power = 1.62 W

Fixed transmission (access) power = 5 W

Fixed CPE power = 11.5 W + (0.02 W × (100 Mbps / 4%[1]))

Fixed CPE power = 11.5 W + 0.08 W

Fixed CPE power = 11.58 W

Total power = 1.62 W + 5 W + 11.58 W

Total power = 18.2 W

Total network energy (1 h) = 18.2 Wh.

[1] This could also be 4 Mb instead of 4%.

TABLE 3 Comparison of energy consumption by component, this paper (power model) versus Carbon Trust report (average energy intensity model).

	This paper (Wh/h)	Carbon Trust report (Wh/h)
Network	5	20
Customer Premises Equipment	11.58	71

This total is composed of a baseline of 1.5 W from transmission (core), 5 W from transmission (access), and 11.5 W from CPE for a total of 18 W of energy consumption regardless of usage. The Netflix video streaming session caused an additional 0.2 W (the marginal impact).

Comparing this to the calculations in the Carbon Trust (2021) report, we estimate lower CPE and network energy consumption (Table 3). The Carbon Trust methodology is well reasoned and includes provider data for some components (for a 2021 European average), but this highlights the differences when using averages versus the power model and shows the importance of accurate equipment energy consumption values. Future comparisons should ensure consistency of equipment values when comparing methodologies.

5.5.2 | Data center and user device

To provide a complete footprint, we can add the energy consumption of the data center and user device. Taking the values from the Carbon Trust report (this paper is not proposing anything related to data centers or user devices), for 1 h of Netflix video streaming the data center component is 1 Wh and 96 Wh for screens plus peripherals.

Total data center energy (Carbon Trust) = 1 Wh

Total CPE and network energy (this paper) = 18.2 Wh

Total device energy (Carbon Trust) = 96 Wh

Total energy for 1 h of Netflix video streaming = 115.2 Wh.

6 | SUGGESTED USE OF THE POWER MODEL

The average/allocation model should be used when analyzing a specific network where total data transfer and total energy consumption over a given period are known. It is useful to understand how the network is evolving over time and can be used to analyze energy efficiency.

In all other scenarios, the power model should be used. For example, analyzing the energy consumption of a particular application, examining the difference between different application configurations (such as how video quality and bitrate might affect energy consumption), and calculating energy consumption in the present or making future projections (only of a short future timeframe—projections get significantly less accurate the further out they predict) are all suitable uses of the power model.

It is important to break down the network segments into the components as described in Table 1 because they each exhibit different behavior. All models are simplifications, so we also recommend highlighting limitations such as the variance in equipment across multiple networks. The application architecture and associated network topology should also be considered, particularly for popular applications such as video streaming where edge caching strategies will have a significant impact on overall data volumes.

6.1 | Limitations and proposal of additional research

The main limitation of the power model is the sensitivity to the power values for the equipment. The model relies on accurate values for both the fixed baseline, idle equipment state, and the variable per capacity component. These will vary based on the equipment deployed within each network which will change over time as the operator deploys new capacity, upgrades equipment, decommissions old systems, and switches to new technologies (such as from copper to fiber optic or 4G to 5G).

As an example, real-world measurements presented in Malmodin (2023) reveal different figures for a connection in Sweden:

Fixed transmission (core) power = 2 W baseline with 0.1 W variation.

Fixed transmission (access) power = 2 W + 3 W.

Fixed CPE power = 12.5 W, +2.5 for a good Wi-Fi signal, but +5.5 W for a poor Wi-Fi signal.

Based on these observations, for video streaming using Netflix as an example with an estimated average quality (5 Mbps), the calculations look like this:

Fixed transmission (core) power: 2 W + 0.03 W/% = 1.5 W + 0.03 × 1 = 2 W + 0.03 W = 2.03 W

Fixed transmission (access) power: 5 W

Fixed CPE power: 12.5 W + 0.025 W/% = 12.5 W + 0.025 × 1 = 12.525 W

Total: 12.52 + 5 + 2.03 = 16.555 W (1% utilization, 5 Mbps)

As the largest component of the power model calculations comes from the idle power portion, it is important that this is kept up to date. The power values in this paper are based on analysis of equipment for 2010–2015 from a technical report (Malmodin & Lundén, 2018a) and the supplementary material of a journal publication (Malmodin & Lundén, 2018b). Please be aware that the defined values (for the cellular 4G as well as fixed core network) are relevant for now but will evolve over time. In particular, the "W per megabit per second of capacity" factor requires regular review.

Although it has been difficult to get accurate numbers in the past, programs such as the Code of Conduct on Energy Consumption of Broadband Equipment from the European Union (Bertoldi & Lejeune, 2021) now publish detailed power consumption targets for new equipment and have committed to regular (annual) published updates. However, these apply only to new devices (Bertoldi & Lejeune, 2021).

There is only a limited set of literature related to the power consumption of the wide range of network devices deployed in real-world networks, so this is an area of opportunity for future research.

6.2 | Red flags for reviewers

Reviewers of publications should look out for several red flags when reading papers that claim to calculate the energy use of network services today or future energy related forecasts.

- **Are network components modeled individually?** As described in Table 1, each component has its own energy profile. User device energy consumption is related to usage and makes up most of the total energy consumption for a particular application, so must be calculated separately from the power consumed by the network. Detailed advice for the data center component can be found elsewhere (Mytton & Ashtine, 2022).
- **Is the energy consumption calculated by multiplying data transfer by an energy value such as kWh/GB?** This is only valid when allocating historical usage for a specific network with known total data and energy consumption.
- **Is there a linear relationship between data transfer and energy consumption?** The power model demonstrates that most of the total power consumption is unrelated to usage, that is, data transfer.
- **Do future projections account for improvements in energy efficiency?** As can be seen from network operator reports (Malmodin et al., 2023), significant increases in data transfer have not resulted in a similar increase in energy consumption.
- **Is the source data reasonably up to date? Is the intensity factor for the year analyzed (either as published in the source or with appropriate adjustments for efficiency improvements over time)?** As has been seen in many published articles (Mytton & Ashtine, 2022), tracing back through multiple cascading citations can reveal very outdated sources. Sources more than 3–5 years old should be considered unreliable unless otherwise adjusted or their relevancy justified. In addition, since the efficiency factor varies among different network devices in a network topology, the individual device efficiency factor might vary as well.

7 | CONCLUSIONS

When network energy intensity numbers are presented in kilowatt hours per gigabyte of data (kWh/GB) it is understandably tempting to use the values to calculate present or future network energy. However, such a simple methodology should be a red flag because it is rare for simple calculations to truly represent the systems they purport to represent. Energy intensity numbers are useful only for retrospective analysis where total data transfer and total energy consumption are known. Such numbers allow for efficiency analysis over time but cannot be used to calculate the energy consumption of real-world applications.

Besides a lower power consumption compared to fixed, mobile networks allow subscribers to potentially access its services around the world depending on coverage and roaming agreements between operators. A fixed broadband subscription is limited to just one spot (household) and where LAN cables and Wi-Fi reach. It is, however, also possible to connect as a guest to an enterprise network or a Wi-Fi router connected to a fixed broadband. Over the past decades, networks have grown significantly. This brings inherent complexity which means each component must be analyzed and modeled individually. Even then, the scale at which modern applications such as video streaming operate means it is even more unlikely that a single energy intensity number can provide an accurate description.

In the power model presented in this paper, we provide a new methodology for calculating network energy that considers the complexity and characteristics of all components of the network. When used with the latest values for the equipment power consumption, it allows for accurate modeling of an end-to-end network separating the components that have more power proportionality from those that do not. However, access to up-to-date data about the power consumption of network equipment is still lacking. This is an area for future research—collecting measurements from real devices—which can be performed in lab conditions but would also benefit from support from device manufacturers. Publishing not just the maximum power specification, but values representing different load profiles, would be beneficial. Reporting of energy intensity per subscriber and/or household in addition to the current average per unit of data would go further to help avoid confusion.

There is now sufficient evidence from many organizations from a range of different geographies to demonstrate the lack of a connection between network usage and total energy. Combining this with a commonsense approach that total energy of a network device cannot exceed the total maximum power of that device and an understanding of how networks are provisioned for redundancy and peak capacity proves that network energy use is not directly proportional to data volume.

AUTHOR CONTRIBUTIONS

Conceptualization: David Mytton; Methodology: Jens Malmodin; Validation: Dag Lundén and Jens Malmodin; Formal analysis: David Mytton and Jens Malmodin; Writing—original draft: David Mytton; Writing—review and Editing: David Mytton, Dag Lundén, and Jens Malmodin; Visualization: David Mytton, Jens Malmodin, and Dag Lundén; Project administration: David Mytton.

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CONFLICT OF INTEREST STATEMENT

David Mytton has a financial interest in StackPath, LLC, an edge computing company, and was engaged by the Uptime Institute as a Research Affiliate from December 2020 to November 2021. All other authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available as described for each figure. No new data were created.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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