The Energy and Emergy of the Internet

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ABSTRACT

Recent years have seen a flurry of energy-efficient networking research. But does decreasing the energy used by the Internet actually save society much energy? To answer this question, we estimate the Internet's energy consumption. We include embodied energy (emergy)—the energy required to construct the Internet—a quantity that has often been ignored in previous work. We find that while in absolute terms the Internet uses significant energy, this quantity is negligible when compared with society's colossal energy use.

Categories and Subject Descriptors

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

General Terms

Economics, Management

Keywords

Energy, Emergy, Consumption, Sustainability

1. INTRODUCTION

Amid global concerns over energy and climate change, researchers have flocked to the study of energy-efficient networking. Likewise, many prominent companies have ramped up their efforts to be branded as "green" via programs such as the Climate Savers Computing Initiative. These efforts have typically aimed to reduce the electricity use of networked systems. From the perspective of a company that operates its own data centers and networking infrastructure, saving energy translates to saving money. From the perspective of a mobile device consumer, saving energy translates to longer battery life. From these narrow points of view, research into energy-efficient networking is well-motivated. However, when we examine the broader goal of reducing *societal* energy consumption, does energy-efficient networking actually have a significant impact? To answer this we must address a more fundamental question: how much energy is required to construct, run, and maintain the Internet?

We begin our study with two pieces of the Internet's energy use. One is the Internet's electricity use, which is the standard metric for energy-efficient networking. The other is embodied energy (*emergy*)—the energy required to build the devices and infrastructure that comprise the Internet. Conventional research typically ignores emergy, since it does not directly affect a device's electricity consumption. Combining the two we provide, to the best of our knowledge, the first holistic estimate of Internet energy use. Although we are certain our answer is wrong, we hope to raise awareness on the study of this important topic.

Our emergy calculations help us understand the replacement energy cost of the devices that make up the Internet. An interesting consequence is that we can compute an estimate for the *power consumption* of the Internet in real terms—that is, in terms that include all energy costs regardless of timescale. We estimate that the Internet consumes between 170 and 307 GW.[1]

Is this a lot of energy or a little? Our answer is that it's both. Given the enormity of the world's energy consumption and impending global energy challenges [28], the Internet's usage is significant but still only comprises a small fraction of the total—between 1.1 and 1.9% of the 16 TW used by humanity [5]. Thus energy-efficient networking can have no more than a minor impact on world energy consumption. If we are concerned with saving energy on a global scale, and not just for individual companies, we should invoke Amdahl's law and use the Internet to provide substitutes for other functions of society that use much more energy (such as transportation). Specifically, what savings might we expect from oft-discussed substitutes such as video conferencing in lieu of travel? To this end, we estimate the savings that functional offloading can provide on a societal level.

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[1] We have made our calculations public and hope to keep them up to date with the community's help [27].

2. ESTIMATING THE INTERNET

We calculate the total energy used by the Internet and summarize our calculations in a pair of tables. The difficulty with such estimates is that there is no single authoritative data source that we can rely on, so we cannot claim that our results are accurate. Instead, our goal is to derive reasonable bounds. We use rounded values to avoid false precision.

2.1 Overview

Our approach is simple: we estimate two components of Internet energy consumption and then combine them. The first is the emergy of the devices that make up the Internet. In this, we adopt a broader definition and include end devices; the comparisons we make in Section 4 discuss how end-system applications would replace other aspects of societal energy use. The second is a power analysis of the Internet that includes both embodied power—the energy required over time to continually maintain devices as given by their emergy and replacement timespan—and wall-socket power.

We first take a census of the Internet's constituent parts. Given the paucity of data on this subject, we perform some estimates on our own, which correspond well with existing estimates for the number of each type of device and the installation size for other infrastructure components. Subsequently, we define a range of weight values—the amount a device is "part of the Internet"—as is often done in emergy studies where items are shared between different systems [26].[2] Weighting is necessary as determining how much a device participates in the Internet is an ontological question that we cannot answer precisely. Finally, we refer to existing studies where available to estimate the emergy of various components.

To compute the power consumption of the Internet, we estimate the replacement cycle of the devices and infrastructure in question and divide the emergy of each component by its replacement timespan to yield its embodied power: the amount of power (energy over time) consumed in keeping that component in the Internet. To this value we add the ordinary wall-socket power consumption of the device, which we also estimate from a variety of studies, to yield the total estimated power consumption of the Internet.

2.2 Census

Before we can compute a global emergy value, we must first begin with a non-exhaustive Internet census, which we summarize in Table 1. First, we consider end systems. During the 1990s, most would not have considered end devices as integral to the Internet, but the rise of peer-to-peer applications and cloud-based services strongly argues for including end systems in the census. Desktops and laptops are the most obvious end systems; we estimate 750 million of each [9]. Since we anticipate that laptops are more frequently used with Internet access in mind, we select higher weights for them. Cloud servers represent always-on data center servers (typically fairly high-powered, rack-mount machines); we estimate 50 million of these [17] with high weights as they are generally for Internet use. We estimate 1 billion smartphones (including proto-smartphones that have some Internet functionality) [20] with a wide range of weights as data use is growing but varies widely [36]. Finally, servers represent ordinary machines that are not user-facing and not in the cloud; we estimate 100 million of these [31] with lower weights than for other devices, as many such servers are likely restricted to internal use.

Second, we consider infrastructure devices: routers, LAN devices, and cellular and telecom infrastructure. We estimate 1 million routers and router-like devices [13] with high weights. LAN devices encompass a range from cable modems to hubs and switches to WiFi access points—all of the devices in this category operate at the edges of the Internet at a smaller scale than routers; we estimate 100 million such devices considering an average of about 20 used ports (hosts serviced) per device, and we assign high weights. Cell towers and telecom switches are more difficult to estimate. Cell towers represent a contribution because they provide service to smartphones; we estimate 5 million towers [7] and assign fairly low weights. Telecom switches are similar; they provide some service for modem users. We estimate 75 thousand switches with low weights [2]. Finally, we estimate 1.5 billion km of fiber optic cabling [18] and 3.5 billion km of copper cabling [3] for global telecommunications; we assign lower weights for the latter than the former as it is less responsible for carrying Internet traffic.

2.3 Emergy

The calculation of emergy is a complex process that involves considering the energy used during the manufacture of devices, the contribution from components and materials of the device, and recursively the embodied energy of those components and materials.[3] The Total emergy column in Table 1 equals Count × Weight × Per-unit emergy. Our goal is not to be perfectly accurate, were that even possible, but rather to glean rough estimates from available data.

We estimate the emergy of devices and infrastructure based upon a variety of studies. Once again, we begin with end systems. Surprisingly, there exist few studies on the embodied energy of desktops; an oft-cited study concluded that an ordinary desktop has an emergy of about 7.5 GJ [35]. A more recent study found that a modern laptop has an emergy of about 4.5 GJ [10]. There exists better data for modern

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[2] The basic idea is that if a device has two equal uses, one that depends on the Internet and one that does not, then the device's weight is 0.5—that is, we "charge" half of the device's emergy to the Internet. Setting all weights to 1.0 would yield an estimate for all of computing (excepting private/secret systems).

[3] We do not fully leverage Odum's emergy concept in this paper, but rather use it in its simplest form—as a measure of embodied energy due to manufacturing and related inputs [26]. A full exploration of the networking device ecosystem—particularly with Odum's notions of self-organization and energy transformation hierarchies—has the potential to reveal significant insights.

Category	Count	Weight		Per-unit emergy	Total emergy		Replacement timespan
		Min	Max		Min	Max	
Desktops	750×10^6	0.5	0.95	7.5 GJ	$2,800 \times 10^6$ GJ	$5,300 \times 10^6$ GJ	4 years
Laptops	750×10^6	0.75	1.0	4.5 GJ	$2,500 \times 10^6$ GJ	$3,400 \times 10^6$ GJ	3 years
Cloud	50×10^6	0.8	1.0	5 GJ	200×10^6 GJ	250×10^6 GJ	3 years
Smartphones	$1,000 \times 10^6$	0.25	0.9	1 GJ	250×10^6 GJ	900×10^6 GJ	2 years
Servers	100×10^6	0.5	0.95	5 GJ	250×10^6 GJ	480×10^6 GJ	3 years
Routers	1×10^6	0.9	1.0	50 GJ	45×10^6 GJ	50×10^6 GJ	3 years
Wi-Fi/LAN	100×10^6	0.75	1.0	1 GJ	75×10^6 GJ	100×10^6 GJ	3 years
Cell Towers	5×10^6	0.1	0.5	100 GJ	50×10^6 GJ	250×10^6 GJ	10 years
Telecom Switches	0.075×10^6	0	0.25	1000 GJ	0 GJ	19×10^6 GJ	10 years
Fiber Optics	$1,500 \times 10^6$ km	0.5	0.9	10 GJ	$7,500 \times 10^6$ GJ	$13,500 \times 10^6$ GJ	10 years
Copper	$3,500 \times 10^6$ km	0.1	0.5	10 GJ	$3,500 \times 10^6$ GJ	$17,500 \times 10^6$ GJ	30 years

Table 1: Census estimate of Internet devices and infrastructure, embodied energy (emergy), and replacement timespan.

servers, as they are often targets for energy-efficiency; a typical server has an emergy of about 5 GJ [8]. Given the newness of smartphones, the research literature has yet to catch up and perform a detailed emergy calculation; WattzOn estimates that a typical smartphone such as an iPhone or Droid has an emergy of about 1 GJ [34].

It is more difficult to find data for the emergy of routers and other infrastructure devices, as these are less common and thus less studied. We guesstimate a router's emergy to be 50 GJ. Using a recent study on decreasing the energy and emergy of network switches, we estimate that a small network switch or WiFi device has an emergy of about 1 GJ [22]. Surprisingly, a recent study considered the emergy of a conventional cell base station, which, when added to the emergy due to installation we estimate to be about 100 GJ [14]. We have little data on the emergy of telecom switches; we estimate them to be about 1 TJ. Finally, we find that the emergy of fiber optics and copper are quite similar on a per km basis, and once installation is included we estimate this to be about 10 GJ/km [32].

2.4 Power consumption

Emergy is half the story. The other half is more conventional: wall-socket electricity usage. In Table 2, since values for power consumption are more commonplace, we use conventional estimates rather than using specific studies for these values. However, in the case of smartphones (1 W) [6], routers (4 kW) [16], telecom switches (50 kW) [2], and cell towers (3 kW) [14], we use specific estimates. We estimate device duty cycles crudely, by assuming that end-user devices are used half the time and all others are always on and include 50% cooling overhead for the cloud and telecom and 25% cooling overhead for other servers.

We now have the values required to get a holistic picture of the power consumption of the Internet. However, emergy expressed in joules ignores the time dimension, so it inherently conflates energy expenditures that occur frequently with those that occur infrequently, which would hide some costs while magnifying others. Instead, we can express the quantity as embodied power, which we calculate by dividing emergy by the expected timespan in which a device gets replaced—that is, Total power (embodied) in Table 2 equals Total emergy / Replacement timespan from Table 1. As a simple example, a device that takes 1 GJ to make and is replaced every year has an embodied power of 31 W.

We sum embodied power and wall-socket power together in Table 2 to yield lower (min) and upper (max) bounds on the total power consumption of the Internet and its components, which is between 170–307 GW.

3. REFINING THE MODEL

Although our model is crude, it provides an estimate of the Internet's energy use that we can build upon. As we discussed earlier, building a highly-accurate model is difficult due to a lack of published data and the Internet's complexity. Nevertheless, next we consider a number of additional factors that could be modeled to improve accuracy. Many of the following categories of energy use are less concrete than the ones we have considered so far, so it is unclear how to include them quantitatively though we believe that they are important and hope that a future study can include them.

3.1 The Electric Grid

All networked systems depend upon the electric grid.[4] The grid has a huge already-built infrastructure, and thus large emergy. In addition, electric power production has numerous energy losses—from the extraction of fossil fuels to the transmission of electricity—that we could include. Because the Internet uses 84–143 GW of wall-socket power—3.6–6.2% of the 2.3 TW of electricity produced worldwide—we could imagine computing the emergy of the electric grid and then using 3.6–6.2% as the weight for that value to compute its contribution to the Internet [1]. However, it is unclear how much of that grid existed before the Internet's development and thus we again arrive at an ontological question about the Internet's constituent components.

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[4] Even off-grid systems depend upon their power generation and transmission infrastructure.

Category	Wall-socket power	Wall-socket duty cycle	Total power (min)		Total power (max)	
			Wall-socket	Embodied	Wall-socket	Embodied
Desktops	150 W	0.5	28.1 GW	22.3 GW	53.4 GW	42.3 GW
Laptops	40 W	0.5	11.3 GW	26.7 GW	15.0 GW	35.6 GW
Cloud	450 W	1.0	18.0 GW	2.1 GW	22.5 GW	2.6 GW
Smartphones	1 W	0.5	0.13 GW	4.0 GW	0.45 GW	14.3 GW
Servers	375 W	1.0	18.8 GW	2.6 GW	35.6 GW	5.0 GW
Routers	5 kW	1.0	4.5 GW	0.48 GW	5.0 GW	0.53 GW
Wi-Fi/LAN	20 W	1.0	1.5 GW	0.80 GW	2.0 GW	1.1 GW
Cell Towers	3 kW	1.0	1.5 GW	0.16 GW	7.5 GW	0.80 GW
Telecom Switches	75 kW	1.0	0 GW	0 GW	1.4 GW	0.06 GW
Fiber Optics	0 W	0	0 GW	23.8 GW	0 GW	42.8 GW
Copper	0 W	0	0 GW	3.7 GW	0 GW	18.5 GW
Total for Internet			84 GW	87 GW	143 GW	164 GW
			170 GW		**307 GW**	

Table 2: Wall-socket power and embodied power estimates for Internet devices and infrastructure. Embodied power is embodied energy divided by timespan (from Table 1). The total of wall-socket and embodied power for the Internet is given in the last row (with min and max bounds). Values are rounded.

3.2 Operational maintenance and Disposal

A more natural target is the energy for Internet maintenance. Beyond device replacement, there is significant energy investment in other maintenance, such as digging trenches to replace cables, maintaining cell towers and wireless base stations, and sending technicians to diagnose network outages. Also, there is a substantial energy cost in disposing of old components, though we must also factor in recycling because it can decrease energy waste.

3.3 Software

Without software, the network would not be useful. However, software's emergy is complicated by the overwhelmingly-human nature of its creation. Most of its emergy is likely not due to the physical media on which it is distributed (whose amount is decreasing these days) but rather the energy used by the programmers and software companies themselves in the production of the software. This includes the energy used by the software companies in their facilities and the human energy of the programmers.[5]

3.4 Replacement

Not all components are the same age, and some older fabrication technologies are more energy intensive. In addition, because the number of devices produced each year has grown, and old devices stop working or are decommissioned, we may need to determine the distribution of old and new devices for each device/infrastructure category.

3.5 Substitutability

Beyond simply considering omitted values, there are more fundamental issues in energy production and use that we have thus far ignored. Specifically, we ignored the substitutability of energy sources when computing the embodied power of the Internet. For example, a gallon of oil that is used to make the components in a router cannot be substituted with an equivalent amount of energy supplied by a wind turbine, and this is a fundamental issue that we must face squarely given the energy challenges we face.

4. CONSEQUENCES

Thus far we have calculated the energy and emergy of the Internet. However, this data has many interpretations. Because our goal is to understand the Internet's energy use from a holistic perspective, what impact would energy-efficient networking have on global energy use?

4.1 The Big Picture

The Internet's energy use is small compared with the 16 TW consumed globally [5]. In contrast, transportation uses 61% of global oil production [1]. Rather than focusing on saving energy for the Internet in isolation, could we achieve bigger savings in worldwide energy use by having the Internet offload some of the functionality of these other sectors?

More importantly, we should look at *why* there is an urgent need to decrease energy use. Industrialized nations are likely to face a pervasive oil bottleneck this decade that will force major changes [28]. On a similar timescale and a more global basis, climate change demands the rapid phasing-out of fossil fuels. If the Internet is to be part of the solution rather than part of the problem, our approaches to energy-efficiency must target these challenges head on.

4.2 Lessons

Our takeaway lessons are not deep or novel; they are however grounded in the data.

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[5] To further complicate matters, we might need to consider, for example, the emergy difference between industrial-meat heavy North American diets and their Asian counterparts.

4.2.1 *Target end-user devices*

Desktops and laptops actually comprise the largest fraction (roughly half) of the Internet's total power consumption, due in large part to their emergy. We should target these end-user devices instead of the servers and core of the Internet.

Our model suggests several potential approaches to decrease the energy and emergy footprint of end-user devices: (a) reduce the number of deployed devices, (b) reduce per-unit wall-socket electricity consumption, (c) reduce per-unit emergy, and (d) increase per-unit replacement timespan. Approach (a) is infeasible for research because it would require stripping users of their devices or curtailing manufacturing. Approach (b) falls within the purview of current green networking research, but because of the emergy-electricity tradeoff we urge researchers to rethink whether manufacturing new energy-efficient devices (with high emergy) should be the default response—should we instead use existing devices more efficiently? Approach (c) is feasible if we are willing to shift to a more cloud-based model of personal computing, where end devices are ultra-low power terminals for accessing remote resources, but this approach could impose an added energy cost on cloud/server infrastructure and would have to be studied. We examine approach (d) next as it applies to all Internet hardware (not just end-user devices).

Approaches (a) and (d) do not require investing in new technologies (and are thus easier to implement), but they require impeding the production and consumption of devices, thereby affecting the financial viability of the computing industry. This potential tradeoff between the financial viability of industry vs. the energy viability of the Internet is one we leave the reader to ponder.

4.2.2 *Reuse existing hardware*

Embodied power comprises 53% of the Internet's total power use. One way to reduce embodied power is to reduce the emergy of new devices—this path is challenging because it could require refining existing manufacturing processes or introducing new processes. But because the lifespan of Internet hardware is the denominator in calculating embodied power, could we derive more immediate benefit by increasing the replacement timespan of existing devices instead? Doubling the replacement timespan for all components in our model reduces the Internet's embodied power by 43–82 GW. Such a simple action begets significant savings.

Reusing existing hardware has benefits beyond embodied power. The perpetual cycle of device production and consumption yields substantial waste. This waste represents lost energy: throwing away a smartphone after two years of a four year lifespan wastes about 500 MJ of (amortized) emergy. This waste also has adverse health and environmental impacts that are well-documented [11].

4.2.3 *Use networking to reduce societal energy use*

As one of the only global human artifacts, the Internet is uniquely suited to help meet many societal needs at potentially lower energy cost. Although there are many ways the Internet could save society energy, one approach with immediate benefits is replacing a fraction of transportation by virtualizing the physical, thereby decreasing oil consumption. The most common example of this is video conferencing vs. business travel; other similar examples include video and music streaming vs. physical delivery and coworking vs. centralized offices. While these alternatives are typically applications and thus are not within the purview of networking researchers, they rely upon the network to provide appropriate levels and types of service (such as high bandwidth and low jitter for high-quality video conferencing).

Here we consider one concrete and one speculative example of how the Internet can help decrease societal energy use. First, suppose we replace some fraction of business air travel worldwide with teleconferencing.[6] Each year there are 1.8 billion air passenger (one-way) trips [15]; suppose 25% of those trips are eligible for elimination and are replaced with video conferencing. This yields 400 million passenger trips eliminated yearly, each of which uses roughly 20 GJ [21], saving 285 GW total. Thus, by replacing one in four plane trips with videoconferencing, we save about as much power as the entire Internet, and in particular we save a lot of oil.

Of course, we should consider how an increase in videoconferencing traffic would increase the energy use of the Internet. We make a simplifying assumption that the network and transportation system are power proportional (which they most certainly are not). The amount of data transferred on the Internet in a year is about 144,000 PB [24], and given an estimated total Internet power consumption of about 307 GW (embodied power plus wall-socket), we estimate packet delivery energy to be about 0.06 J/byte. A high-definition Skype call requires 1.2 Mbps of bandwidth; assuming each call is one hour, the total bidirectional data sent is about 1 GB, which uses 65 MJ. Assuming each business trip includes 5 meetings that are each replaced by 5 one-hour videoconferencing calls, the replaced 200 million round-trips would increase the Internet's use by only 2.6 GW. Thus, it takes about 1/100 of the energy of air travel to video conference.

Second, a speculative example of how the Internet can help decrease societal energy use is 3D printing using local materials. That is, instead of transporting manufactured goods over long distances, 3D printing could make items with local raw inputs (ideally renewable materials). To make 3D printing viable and sustainable requires reducing the costs of manufacturing and deploying the printers, as well as harvesting the raw inputs, below that of the manufacturing and transportation they intend to replace. With this tradeoff in mind, is it better to have individually-owned 3D print-

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[6] This is a well-known example; however, to our knowledge no prior study has had the data on the Internet's energy consumption required to perform the calculation. In addition, the fact that this replacement would decrease oil consumption specifically makes it of particular importance to today's challenges.

ers, or is it better to deploy a smaller number of community-shared 3D printing centers? Moreover, the cost to 3D print more sophisticated items (such as electronics) may require importing exotic materials from across the globe, thereby rendering the printing of those items infeasible.

5. RELATED WORK

The study of emergy is not new; the field was pioneered decades ago by Odum [25, 26], but has been used only very recently to analyze computing.

We are not the first to attempt to calculate some aspects of the energy use of the Internet. In our community, Gupta and Singh were among the first to analyze the energy use of the Internet [12]. They found that networking devices within the United States use 0.07% of the national total—over an order of magnitude less than our estimate. This difference is largely due to their use of a limited data source that, in particular, excluded edge devices and emergy. Koomey *et al.* also performed their analysis on the electricity use of the Internet in the United States and found that it uses a slightly larger fraction: about 1% of the national total. However, their analysis again only applies to the U.S. and omits emergy and other energy costs [19]. Our numbers for data center electricity roughly match that of a 2007 EPA study [33].

More recently, two studies have considered the benefits of offloading services onto the Internet [4, 29]. Another study considered whether a data center approach is inherently more or less energy efficient than a peer-to-peer approach and found that it largely depends upon the paths used [23]. We hope our analysis will encourage more such studies in the future.

6. CONCLUSIONS

A medium-sized data center today has the emergy of the Great Pyramid of Giza and yet a fraction of its permanence [30]. The energy and emergy of the Internet is many hundreds of times larger still. Although the Internet is a small fraction in the scope of humanity's energy use today, it is both the case that society uses far too much energy (we can use the Internet to reduce this societal excess) *and* that the Internet should be more efficient (but we should choose our targets carefully).

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