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The Direct Energy Demand of Internet Data Flows

Vlad C. Coroama, Lorenz M. Hilty, Ernst Heiri, Frank M. Horn*

* Address correspondence to: Vlad C. Coroama, IST, Instituto Superior Técnico, Univ Tecn Lisboa, Avenida Rovisco Pais, 1049-001 Lisboa, Portugal. Email: vcoroama@gmail.com

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Summary: The direct energy demand of Internet data flows can be assessed using a variety of methodological approaches (top-down, bottom-up or hybrid/model-based) and different definitions of system boundaries. Due to this diversity, results reported in the literature differ by up to two orders of magnitude, and are difficult to compare. We present a first assessment that uses a pure bottom-up approach and a system boundary that includes only transmission equipment. The assessment is based on the case study of a 40 megabit per second videoconferencing transmission between Switzerland and Japan, yielding a consumption of 0.2 kilowatt hours per transmitted gigabyte for 2009; a result that supports the lowest of the existing estimates. We discuss the practical implications of our findings.

Introduction

While in the past the debate revolved more around the negative environmental and energy impacts of information and communication technology (ICT) and the Internet in particular (Masanet and Matthews 2010), these technologies are increasingly credited as enablers of dematerialization of production and consumption and therefore of sustainable development. Assertions to this enabling effect come from academia (Laitner and Ehrhardt-Martinez 2009; Laitner 2010; Mattern et al. 2010; Hilty and Ruddy 2010), but also from organizations as diverse as ICT industry associations (GeSI 2008), the European Commission (2008), and the World Wildlife Fund (Pamlin and Pahlman 2008). Despite the increasing importance of ICT and the ubiquity of the Internet, however, several basic questions about their environmental impact are still unanswered or controversial. One of these questions is: Which amount of electrical energy is consumed for sending a given quantity of data over the Internet?

Existing analyses of the direct energy consumption of the Internet are based on a variety of methodologies and on different system boundaries (i.e. they are using different definitions of what belongs to “the Internet” as a distributed power-consuming system). This article presents a novel approach to the assessment of Internet energy demand, which is based on almost pure bottom-up analysis and a definition of system boundaries ensuring that only devices needed for data transmission are included in the calculation. This approach is applied to the case study of a three-day Internet video transmission between Switzerland and Japan.

We argue that this case study represents a setup that is less energy efficient than the usual setup for transmitting data over the Internet. We therefore claim that the energy intensity (energy consumed per amount of data transmitted) we calculated from the case study represents a pessimistic estimate (an estimate that is, if anything, higher than actual) for the energy intensity of the average Internet transmission. Although we cannot exclude that some data in some situations may be transmitted with higher energy intensity, there is strong evidence that the average value of the energy intensities of all Internet transmissions is below our result. If our claim is correct, several yet unanswered or controversial questions can be addressed. In particular, the balance between the amount of energy saved by avoiding the transport of physical mass and the energy needed for transferring data instead can be reconsidered. This may be relevant for many practical cases of dematerialization, including e-books replacing printed books, movie downloads replacing DVDs, or virtual meetings substituting physical travel. To avoid misinterpretations, we would like to point out that our study excludes wireless or mobile Internet access, which would certainly deserve separate treatment.

Information and Communication Technology and Its Effect on Dematerialization

Dematerialization, a concept introduced in the late 1980s (Herman et al. 1990), describes a reduction of the material and energy intensity of economic processes. According to Cleveland and Ruth (1999), "dematerialization refers to the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output". The *intensity of use* (IU), which for an economic process denotes the ratio of materials or energy used to the value added, is often used as a measure for dematerialization – a decline in the IU implying dematerialization. De Bruyn and Opschoor (1997), however, call the (per-unit) decrease of the IU as "weak dematerialization," and distinguish it from "strong dematerialization," which denotes an absolute decline in (total) material or energy usage.

In the context of population growth and increasing wealth, it has been suggested that a weak dematerialization factor of four (von Weizsäcker et al. 1995) to ten (Schmidt-Bleek 1993) would be needed across the economy in order to achieve worldwide strong dematerialization, thus fulfilling a necessary condition of sustainable development.

In recent years, ICT has been increasingly credited as key contributor for the achievement of high levels of dematerialization in numerous sectors of the economy. Hilty (2008) claims that ICT has the potential to optimize all phases of a product life cycle (design, production, use, end-of-life treatment) with respect to material and energy efficiency and to replace some goods by services. Mattern and colleagues (2010) notice "strong evidence to suggest that ICT is an important driver for improving energy productivity." Laitner and Ehrhardt-Martinez (2009) estimate that for every kilowatt hour (kWh) used by ICT equipment today, there are tenfold energy savings induced through productivity gains and efficiency improvements. With respect to greenhouse gases alone, ICT is credited with a potential to induce global reductions between 1 gigaton (Gt) of carbon dioxide (CO_2) equivalents today (Pamlin and Pahlman 2008) and up to 7.8 Gt in 2020 (GeSI 2008). A comparison of studies assessing the effects of ICT on greenhouse gas emissions is provided by Erdmann and Hilty (2010).

Obviously, all these claims must take into account the energy intensity of the ICT infrastructure needed for storing, processing and transmitting data, which includes the Internet.

Related Work

Several previous studies have explored the electricity intensity of Internet data transfers (Koomey et al. 2004; Baliga et al. 2007; Taylor and Koomey 2008; Baliga et al. 2008; Baliga et al. 2009; Weber et al. 2010; Hinton et al. 2011; Kilper et al. 2011; Lanzisera et al. 2012). Comparing their estimates is difficult because of inconsistent boundaries, data uncertainties, and different methodologies used. Some of these studies are based on estimates of regional or worldwide Internet energy consumption combined with estimates of Internet traffic to compute the energy consumed per amount of data. Other studies model the network components needed to provide the Internet traffic for a given amount of subscribers. The distinction with the largest influence on the result, however, is the definition of system boundaries. While some studies include the terminal equipment (e.g., personal computers, servers) within the system boundaries (Koomey et al. 2004; Taylor and Koomey 2008; Weber et al. 2010), others do not (Baliga et al. 2007; Baliga et al. 2008; Baliga et al. 2009; Hinton et al. 2011; Kilper et al. 2011). Most studies include the overhead for cooling and power distribution, (Lanzisera et al. 2012) does not. Due to these differences, we do not undertake a comparison here. Instead, we focus on a case study where the underlying data are particularly well characterized and the system boundaries clear and consistent.

Some newer industry studies on the energy consumption of cloud computing could be expected to provide insight in the energy consumption induced by network traffic. However, these studies either don't take it into consideration (Verdantix 2011; Google 2011), don't devise it separately from the data center's energy consumption (Accenture

2010; WSP Environmental 2011), or they consider it only as a fixed percentage on top of the server's consumption (Google 2012).

Methodology

Our own study is based on a bottom-up approach, first applied in the case study described below. The system boundary includes only transmission equipment and excludes the terminal devices, as shown in figure 1.

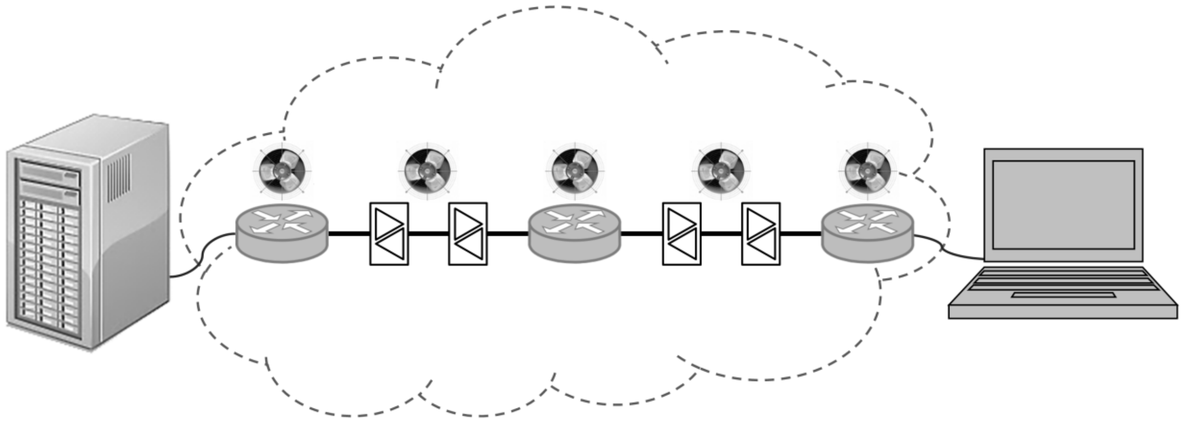

Figure 1. System boundaries underlying our study. We consider the consumption of Internet nodes (i.e., routers including line cards and optical plug-ins) as well as the consumption along transmission lines (i.e., of the optical amplifiers). We also consider the cooling of nodes and amplifiers. We exclude the terminal devices.

Case Study: The 2009 Congress on Resource Efficiency and Resource Management and the World Resources Forum

The case study was a conference consisting of two back-to-back events, the 8th Congress on Resource Efficiency and Resource Management, R'09, and the first World Resources Forum (WRF). They took place between September 14th and 16th, 2009, simultaneously in Davos, Switzerland, and Nagoya, Japan. Both events could be attended at both sites. This organization mode was chosen in order to reduce the greenhouse-gas emissions caused by the travel of attendees to the conferences, in particular by inter-continental flights. The energy consumed by the travel of the attendees and their satisfaction with the virtual combination of the two sites have been assessed and published elsewhere (Coroama et al. 2012).

This conference mode required several high-quality video- and audio-links between the two sites for the four hours per day of simultaneous and interactive events shared among sites. Four parallel Cisco "TelePresence" sessions were in use, together causing a traffic volume of 20 megabit per second (Mbit/s) in each direction.

Signal Path

The real-time nature of the application required a considerable amount of cross-site interaction, such as intercontinental question and answer sessions (Coroama et al. 2012). This imposed a strict upper limit on the delay of the signal. For audio-video applications, the maximum one-way delay that still allows seamless interaction is 150 milliseconds (ms) (ITU-T 1998). The geographically shorter East-bound route (as seen from Switzerland) over continental Europe and Asia comprised the risk of network congestion which would have reduced the quality of the transmission. We had thus to opt for the geographically longer path crossing the Atlantic, continental United States (US), and the Pacific, as shown in figure 2.

On this longer route, due to the given opportunity to access the international research networks, we could guarantee the absence of any delays other than the inherent delay of the signal transmission. As data travels through optic fibers at 200,000 km/s, or two thirds the speed of light (Azadeh 2009), the signal propagation delay inside the 27,117 km of optical fibers is 135.58 ms. The delay caused by packet switching along the route was negligible – the typical time of 20 microseconds (µs) (EANTC 2005) implies less than 1 ms switching time for all the 25 nodes along the route. Nevertheless, due to the length of the fibers, the overall delay was already very close to the targeted limit of 150 ms. The detailed network monitoring we needed to ensure no additional delays – highly unusual and out of reach for most users and organizations – proved as a stroke of luck, as it allowed the very analysis presented in this article.

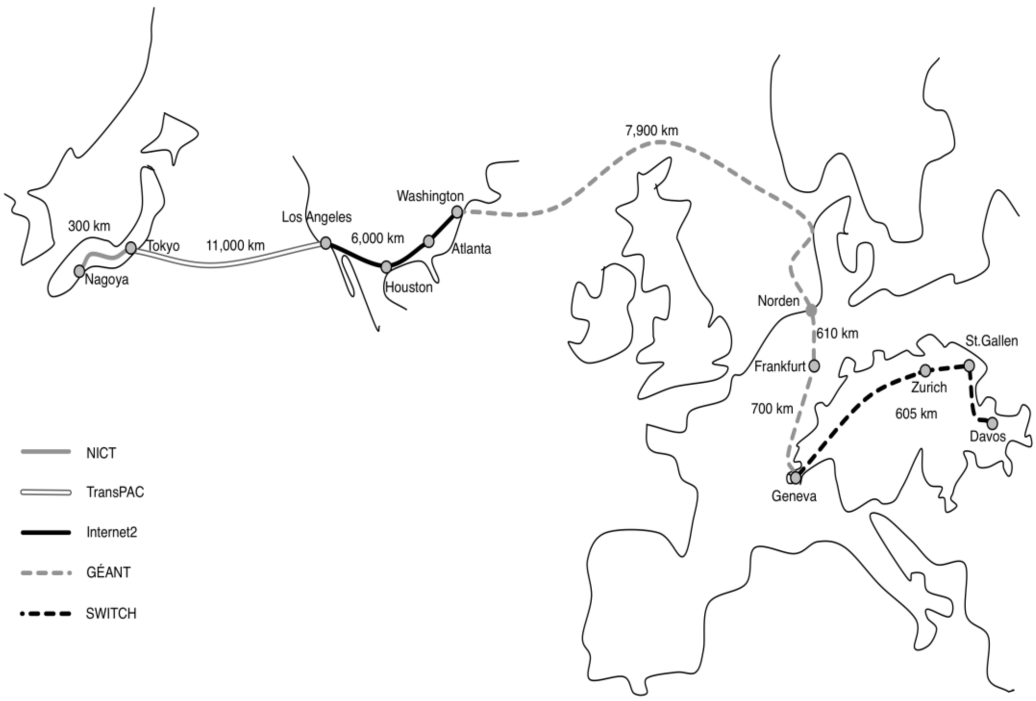

Figure 2. Network path used between Davos, Switzerland and Nagoya, Japan with an overall length of 27,117 kilometers. The map is not to scale.

In detail, the setup was as follows: The TelePresence systems inside the Davos Congress Center were connected by fast Ethernet copper cables to two routers located inside the building (the second router was included for redundancy). The signal was then sent via optical fibers to the Swiss Institute for Snow and Avalanche research, located 4.5 km away, where it entered the Swiss research network, governed by SWITCH, one of the conference's official technology partners. After seven hops within the SWITCH network (a "hop" represents the distance between two Internet routers; a signal passing n routers has to do n-1 hops), the signal passed two hops within the European research network GÉANT, the second of which was across the Atlantic to Washington, DC. After three trans-continental hops within the US and the following trans-Pacific cable, the signal passed four nodes of the Japanese academic network "NICT" to finally arrive at Nagoya University.

From Davos up to Atlanta, i.e. for nearly half of the route both in terms of distance and of number of hops, we have accurate data about the equipment used in the Internet nodes. We analyzed electricity consumption, maximum throughput, as well as average loads of the nodes passed by the conference transmission. The consumption of each Internet node comprises the consumption of the router including line cards and optical plug-ins. Correspondingly, for the long-haul links between these nodes, we collected data on the power consumption of the optical devices involved (e.g., wavelength division multiplexers, optical fiber amplifiers), the maximum load capacity, and the respective loads during our transmission.

Allocating Consumption to the Conference Traffic

For each Internet node and link along the way, a percentage of its electricity consumption must be allocated to our transmission. We apply a simple allocation rule from attributional life cycle assessment (attributional LCA) methodology, distributing the energy according to the relative traffic volumes. This means that the percentage of energy attributed to our traffic corresponds to the share of this traffic within the average overall traffic in the respective node or link. This is a very conservative assumption, intended to result in an estimate of energy usage that is, if anything, high: as any designer of computer networks will testify, the Internet nodes and links are configured according to their peak load during a 24 hour cycle; had we related our traffic to the peak traffic, a smaller percentage would have resulted and thus a lower consumption would have been allocated. Using as reference the capacities of the links and nodes (the maximum possible traffic) would have yielded an even lower value. Applying a consequential instead of an attributional LCA approach (focusing on marginal instead of average effects) would as well have produced a much lower value, as everything along the route except the poorly utilized Davos routers would have become negligible. The allocation scheme we chose is thus the most pessimistic one in terms of energy consumption caused by the conference's data traffic.

Results

Table 1 shows the consumption data and its allocation to the traffic caused in our experiment. The last column shows the allocated power consumption along the taken path, the sum of which is depicted in figure 3. The underlined entries in table 1 are our estimates based on data from the known parts of the route as well as from experience in designing and developing international networks. Non-underlined entries were measured directly either by the authors or by partners from the worldwide research and commercial networks. In total, the 40 Mbit/s (20 Mbit/s in each direction) of the 4 simultaneous video sessions of the conference required 1794 W of power along the Internet, out of which 1358 W were consumed in Internet routers and switches, and 436 W were consumed along the transmission lines (the consumption of the terminal equipment being excluded). Tables S1 and S2 of the supporting information available on the Journal's website present the data sources and assumptions in detail.

Table 1. Traffic and power consumption data for the Internet nodes and the connecting links that were passed by the conference's data traffic. By relating the conference's traffic to the overall traffic of a node or link, the power consumption attributable to the case study is calculated. Underlined data are own assumptions, the other data are either direct measurements or measurements of our partners.

Router in		Router-electrical power [W]	Router-capacity [Gbit/s]	Router load [%]	Router load [Gbit/s]	Router power [W]	Cumulated power [W]
Link between	Fiber Span [km]	Link equipment power [W]	Link-capacity* [Gbit/s]	Link load [%]	Link load* [Gbit/s]	Link power [W]	Cumulated power [W]
Davos		200	32	0.1%	0.04	200	200
	0	0	1	nr	nr		200
Davos		200	32	0.1%	0.04	200	400
	5	0	1	nr	nr		400
Davos		250	4	2.8%	0.11	91	491
	81	0	1	nr	nr		491
Buchs		250	7	2.1%	0.15	67	558
	74	0	1	nr	nr		558
St.Gallen		250	4	5.3%	0.21	48	605
	5	0	1	nr	nr		605
St.Gallen		1000	4	7.0%	0.28	143	748
	130	0	1	nr	nr		748
Zürich		1000	60	1.8%	1.1	36	784
	310	1600	20	2.2%	0.44	73	857
Geneva, CERN		1000	77	2.6%	2	20	877
	0	0	10	nr	nr		877
Geneva, CERN		1000	50	9.6%	4.8	8	885
	0	0	10	nr	nr		885
Geneva, CERN		4000	77	27.3%	21	8	893
	700	4200	210	20.0%	42	2	895
Frankfurt		4000	155	20.0%	31	5	900
	610	68300	800	75.0%	600	2	903
Norden		0	no router				903
	7900	322100	830	80.0%	664	10	912
Washington		810	50	24.0%	12	3	915
	1100	7800	20	37.5%	7.5	21	936
Atlanta		810	50	20.0%	10	3	939

	2200	15400	10	25.0%	2.5	123	1062
Houston		810	50	20.0%	10	3	1065
	2700	19700	20	20.0%	4	99	1164
Los Angeles		810	50	20.0%	10	3	1167
	0	0	10	nr	nr		1167
Los Angeles		810	50	20.0%	10	3	1170
	11,000	450,000	830	70.0%	581	15	1186
Tokyo		1,000	50	20.0%	10	4	1190
	0	0	10	nr	nr		1190
Tokyo		250	20	20.0%	4	3	1192
	2	***0***	10	nr	nr		1192
Tokyo		250	20	5.0%	1	10	1202
	300	3,200	10	7.0%	0.7	91	1294
Nagoya		200	20	2.0%	0.4	20	1314
	0	0	10	nr	nr		1314
Nagoya		200	20	1.0%	0.2	40	1354
	0	0	1	nr	nr		1354
Nagoya		200	10	2.0%	0.2	40	1394
	0	0	1	nr	nr		1394
Nagoya		200	5	0.8%	0.04	200	1594
	0	0	1	nr	nr		1594
Nagoya		200	5	0.8%	0.04	200	1794

Notes: km = kilometer, W = Watts, Gbit/s = gigabits per second. nr = not relevant. Short links with zero power consumption consist of optical transceivers plugged into the routers; their power consumption is included in the routers' consumption. As there is no power to distribute, their load is also not relevant.

* Unlike routers, the capacity ratings and average traffic loads of links traditionally denote one-way traffic values, which are assumed to be symmetric. For example, a link load of 440 Mbit/s in this table indicates a load of 440 Mbit/s in each direction at once. Thus, while for nodes we relate the conference's overall 40 Mbit/s traffic (20 Mbit/s in each direction), for links we relate only the 20 Mbit/s one-way conference traffic.

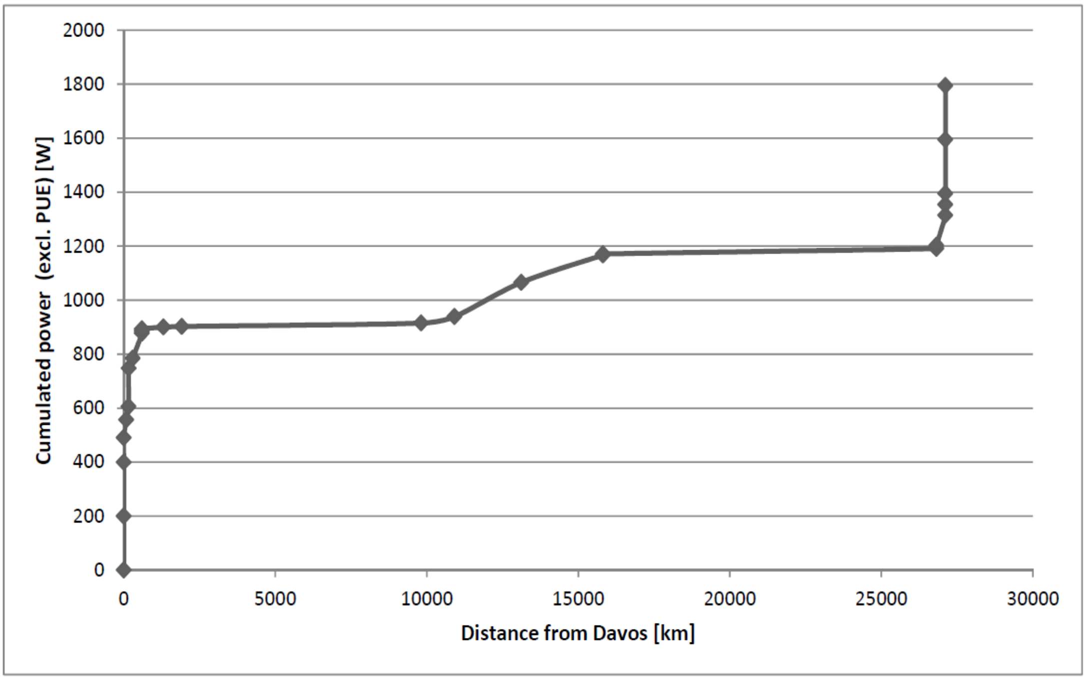

Figure 3. Cumulated power demand along the way from Davos to Nagoya. The power demand of local network components, albeit relatively small, must be allocated to a relevant extent to the case study's traffic. These local components therefore clearly dominate the overall power consumption of the transmission. The large core Internet nodes and the transoceanic "data highways", while utilizing a relatively large amount of power, typically have a switching/transporting capacity in the order of hundreds of gigabits per second (GBit/s), or even terabits per second (TBit/s). Their contribution to the overall demand amounts to less than 1 Watt per megabit per second (1 W/Mbit/s) in our case study. By contrast, the power demand of the North-American transcontinental links does contribute significantly to the overall consumption, due to their relatively low bandwidths. Note: PUE=power usage effectiveness, km=kilometer.

So far, we considered only the power consumption of the network equipment. For an analysis of direct energy demand, the so-called "power usage effectiveness" (PUE) has to be taken into account as well. The PUE is a measure for the efficiency of a room or building dedicated to the operation of devices such as Internet routers. It is computed as the facility's total power (including lightning, air conditioning, etc) divided by the power needed to run the ICT equipment only (Rawson et al. 2008). The larger the PUE, the more power is "wasted" because it is not being used to process data. While older data centers might still have PUEs of 2.5 or higher, today's best practice is as low as 1.1-1.2, and in some cases even lower. Google's servers, for example, have an average PUE of 1.13 (Google 2012). According to industry surveys, the average PUE nowadays is in the 1.8-1.89 range, with decreasing tendency (Stansberry and Kudritzki 2012).

Allowing for a conservative PUE of 2.0 all along the way doubles the power to 3588 W for the 40 Mbit/s (or 89.7 W/Mbit/s). Given that a gigabyte (GB) consists of 8,000 megabits, the transmission of one gigabyte at the flow rate of 40 Mbit/s requires 200 seconds. Changing the perspective from flows of data and energy to amounts of data and energy, the transmission of one Gigabyte in our 2009 case study needs 717,600 Joule, equal to 0.1993 kWh. This energy intensity estimate is at the low end of existing estimates. For convenience, we will use the rounded value 0.2 kWh/GB.

Discussion

There are arguments suggesting that our relatively low result (0.2 kWh/GB) even represents a pessimistic estimate for the average energy intensity of Internet data transmission in 2009 – and even more for today, given the decreasing trend in energy intensity. We can of course not exclude the possibility that, in specific situations, data transmission may require more than 0.2 kWh/GB due to under-utilized nodes or an unusually large number of hops. However, we claim that the global average for the transmission energy intensity must be smaller than 0.2 kWh/GB. Our arguments root both in the setup of the case study and in the conservative assumptions made.

The route under consideration comprises 27,117 km (more than half the Earth's circumference), traversing three continents and the planet's two largest oceans. While occasionally some Internet data flows might cover longer distances, the average is most certainly shorter. Even for a small country like Switzerland, for example, from the 708.2 petabytes (PB) total traffic in 2010, 244.3 PB or 34.5% were intra-country data flows. Among the other 65.5%, 41% were intra-continental flows (i.e., within Europe) and 46% traversing the Atlantic. Only 8.51% of the Swiss traffic was not exchanged with Europe or North America (Girardin 2011); a small part of which might have travelled a longer distance than in our case study.

While the physical length of the connection correlates to the power consumption along the cables, the consumption in the Internet nodes (routers, switches) correlates to the number of hops along the connection. Here, again, the path in our case study was exceptional with its 24 hops; about double the Internet's average, estimated to be 11.67 (Mühlbauer et al. 2010) or 12.6-13.5 (Mieghem 2006).

A closer look at the data reveals that the local energy consumption (i.e., the consumption close to the two ends) dominates the overall energy consumption (figure 3). This is in agreement with the studies of Baliga and colleagues (2007; 2009). For this local connectivity, however, we had a fundamentally inefficient setup, with a Cisco 6524 router working with 40 Mbit/s at only 0.12% of its 32 Gbit/s capacity (as there was no other event happening simultaneously in the Davos congress center). Its 200 W power consumption, which is independent of load, was thus allocated to this small traffic, implying a disproportionate consumption per amount of data. Furthermore, as a network failure would have been intolerable for our real-time application, we installed two identical routers for redundancy, allocating twice this consumption to the relatively small conference traffic – hardly a typical setting.

A pessimistic assumption was made when extrapolating the consumption to the second half of the journey, from Washington to Nagoya. We assumed symmetry and equally inefficiently deployed routers on the other side. However, because in Japan the conference took place on the university campus during working hours and the network was also loaded with regular data traffic of the university, we most likely allocated an oversized portion of the energy to the part of the traffic caused by the conference. Lastly, the PUE of 2.0 is conservatively chosen; while it represents a typical value for data centers in general, the typical value for Internet routers has been reported to be lower at 1.7 (Moth and Norris 2010).

Based on these considerations, we believe that 0.2 kWh/GB is indeed a pessimistically biased estimate for the average energy intensity of Internet data flows in 2009.

Conclusion and Outlook

We made the case that 0.2 kWh/GB is a pessimistically biased estimate for the average energy intensity of transmitting data through the Internet in 2009. This result is certainly true for videoconferencing between two organizations with fast data connections. There are strong arguments suggesting that the result might be true also for different sorts of data exchange such as file download or web surfing, but further research is needed to substantiate this result.

The result has been calculated using a bottom-up approach which strictly excluded all terminal equipment. An advantage of our assessment method is that it produces information relevant for decision-making. Perennial issues such as the comparison of print media with virtual media can only be discussed rationally if the impact of data transmission is clearly separated from the impact of the use of the terminal devices. For each LCA study involving an Internet application, it is now possible to use our result as a pessimistic estimate for the average energy intensity of transmitting the data volume related to the given functional unit and then adding the part of the energy consumption of the terminal devices that must be allocated to the task of producing the functional unit. (We are aware that for an LCA study, issues other than direct use-phase energy consumption would be included as well, such as the production of the devices and the generation of electricity; however, all those issues remain untouched by our study.)

Based on our result, transmitting an e-book with the size of 1 MB would cost no more than 0.2 Wh of energy on the average (the amount of energy needed to light a 60W bulb for twelve seconds). Reading this book would require some hours of (almost) exclusive use of a desktop, laptop or tablet computer or of a dedicated e-book reading device, all with significantly different power consumption. In some cases, the owner of the e-book may also use an inkjet or laser printer to create a hardcopy of the book. All these cases should be treated separately, as their results can differ by orders of magnitude. As another dematerialized substitute of a printed book, also an audio file could be transmitted, causing an energy consumption of 0.1 kWh if we assume a file size of 500 MB. The book could then be consumed (i.e. listened to) by a variety of terminal devices, from a desktop PC to an mp3 player, again each with significantly different power consumption.

In other cases of substitution, such as avoiding travel by videoconferencing, our result will in most cases make it possible to neglect the energy needed for Internet transmission on justifiable grounds, because the amount of energy consumption that can be avoided on the side of passenger transport is much higher. In our case study, for example, a single round-trip from Zurich to Tokyo was worth 9,880 kWh, while the pure data transmission energy consumed for the whole conference with hundreds of participants was only 43 kWh (3588 W for a daily 4 hours over 3 days) plus 108 kWh for the terminal equipment at both sites (four large plasma screens, four high definition cameras and four high definition projectors). The energy and greenhouse-gas balances of our case study were therefore completely dominated by avoided intercontinental flights versus rebound effects due to cheaper conference participation, the contribution of the ICT equipment being negligible (Coroama et al. 2012).

On the other hand, it is interesting to see that for an application that would fully utilize the download bandwidth provided by a 100 Mbit/s fiber optic connection (which is currently the fastest way for households in several countries to access the Internet), by extrapolation from our computed value of 89.7 W/Mbit/s, the Internet data transmission could theoretically cause a power demand of up to 8.97 kW, much more power than would usually be consumed by a private household. However, this interpretation of our result might only be valid under very unlikely conditions, because the largest share of the 0.2 kW/GB falls to local network components working far from capacity. Traffic-intensive applications would make these components work at a higher load, but not substantially increase their energy consumption, as the linear extrapolation would suggest.

In short, in situations of highly loaded local networking equipment, our estimate of the transmission energy intensity is certainly pessimistic. This means that the true value in such situations is much smaller (and is getting smaller as the Internet evolves). Using our result as a pessimistic estimate for the energy intensity of Internet data flows leads to valid conclusions as long as the resulting energy is small compared to other energy demands considered in a study. It is less useful when the energy used for data transmission becomes a dominant component of the environmental impacts that are assessed.

We would like to point out that our result is only valid for wired connections to the Internet. The trend to mobile Internet considerably changes the picture (Kilper et al. 2011). Simultaneous developments, however, such as the trends towards cloud computing and Internet protocol television (IPTV), are bound to keep wired Internet data flows – and the analysis of their energy intensity – highly relevant as well.

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About the Authors

Vlad Coroama is a research fellow at the IN+ Center of the Instituto Superior Técnico (IST), Technical University of Lisbon in Lisbon, Portugal; he was in charge of the former “Informatics and Sustainability” group of the Swiss Federal Laboratories for Materials Science and Technology (Empa) when the case study was completed. Lorenz Hilty is professor of Informatics and Sustainability in the Department of Informatics (IFI) at the University of Zurich in Zurich, Switzerland and head of the new “Informatics and Sustainability Research” (ISR) group shared between Empa and IFI. Ernst Heiri is a network engineer at SWITCH, the Swiss National Education and Research Network in Zurich. Frank Horn is a consultant in Zurich for IP-communications solutions at Cisco Systems. All authors were actively involved in the organization of the two-site conference case study for the WRF 2009.

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Summary

This supporting information presents the data sources and assumptions used to compute the energy intensity of transmitting data over the Internet in our case study, as reported in the main article. Tables S1 and S2 summarize this information. The subsequent text comments on the terminology used in the tables and explains how the assumptions were chosen such that the resulting energy intensity is rather over- than underestimated.

Table S1: Reported data and assumptions for the case study (columns 1-8); data sources and reasons for assumptions (columns 9-14, assumptions highlighted)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Router	-	Router-electrical power [W]	Router-capacity [Gbit/s]	Router load [%]	Router load [Gbit/s]	Router power for case study [W]	Cumulated power - case study [W]	Governing body	Router/Switch product type	-	Router/Switch electrical power	Router or Switch capacity	Router/Switch load
Link	Fiber Span [km]	Link equipment power [W]	Link-capacity [Gbit/s]	Link load [%]	Link load [Gbit/s]	Link power for case study [W]	Cumulated power - case study [W]	Governing body	-	Length of fiber span	Link equipment electrical power	Link Capacity	Link Load
Davos		200	32	0.1%	0.04	200	200	SWITCH	Cisco 6524		measured @ CS	owned	measured @ CS
	0	0	1	nr	nr		200	SWITCH		owned	optical transceivers only	owned	measured @ CS
Davos		200	32	0.1%	0.04	200	400	SWITCH	Cisco 6524		measured @ CS	owned	measured @ CS
	5	0	1	nr	nr		400	SWITCH		owned	optical transceivers only	owned	measured @ CS
Davos, SLF		250	4	2.8%	0.11	91	491	SWITCH	Cisco 6503-E		measured w/ identical config.	owned	measured @ CS
	81	0	1	nr	nr		491	SWITCH		owned	optical transceivers only	owned	measured @ CS
Buchs, NTB		250	7	2.1%	0.15	67	558	SWITCH	Cisco 6503-E		measured w/ identical config.	owned	measured @ CS
	74	0	1	nr	nr		558	SWITCH		owned	optical transceivers only	owned	measured @ CS
St.Gallen		250	4	5.3%	0.21	48	605	SWITCH	Cisco 6503-E		measured w/ identical config.	owned	measured @ CS
	5	0	1	nr	nr		605	SWITCH		owned	optical transceivers only	owned	measured @ CS
St.Gallen, Uni		1000	4	7.0%	0.28	143	748	SWITCH	Cisco 7603		measured w/ identical config.	owned	measured @ CS
	130	0	1	nr	nr		748	SWITCH		owned	optical transceivers only	owned	measured @ CS
Zürich, Uni		1000	60	1.8%	1.1	36	784	SWITCH	Cisco 7606		measured w/ similar config.	owned	measured @ CS
	310	1600	20	2.2%	0.44	73	857	SWITCH		owned	measured w/ similar config.	owned	measured @ CS
Geneva, CERN		1000	77	2.6%	2	20	877	SWITCH	Cisco 7606		measured w/ similar config.	owned	measured @ CS
	0	0	10	nr	nr		877	SWITCH		owned	optical transceivers only	owned	measured @ CS
Geneva, CERN		1000	50	9.6%	4.8	8	885	SWITCH	Cisco 7606		measured w/ similar config.	owned	measured @ CS
	0	0	10	nr	nr		885	SWITCH		owned	optical transceivers only	owned	measured @ CS
Geneva, CERN		4000	77	27.3%	21	8	893	GÉANT	Juniper T1600		provider	provider	measured @ CS
	700	4200	210	***20.0%***	42	2	895	GÉANT		provider	provider	provider	***low estimate***
Frankfurt		4000	155	***20.0%***	31	5	900	GÉANT	Juniper T1600		provider	provider	***low estimate***
	610	68300	800	75.0%	600	2	903	Provider X		provider	provider	provider	provider estimate
Norden		0	no router				903	Provider X			provider		
	7900	322100	830	80.0%	664	10	912	Provider X		provider	provider	provider	provider estimate
Washington		810	50	24.0%	12	3	915	Internet2	Juniper MX960		provider	provider	provider
	1100	7800	20	37.5%	7.5	21	936	Internet2		provider	provider	provider	provider estimate
Atlanta		810	***50***	***20.0%***	10	3	939	Internet2	Juniper MX960		provider	***similar to DC***	***lower than DC***
	2200	15400	10	25.0%	2.5	123	1062	Internet2		provider	provider	provider	provider estimate
Houston		810	***50***	***20.0%***	10	3	1065	Internet2	Juniper T640		provider	***similar to DC***	***lower than DC***

Table S2: Reported data and assumptions for the case study (columns 1-8); data sources and reasons for assumptions (columns 9-14) – continuation

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Router	-	Router-electrical power [W]	Router-capacity [Gbit/s]	Router load [%]	Router load [Gbit/s]	Router power for case study [W]	Cumulated power - case study [W]	Governing body	Router/Switch product type	-	Router/Switch electrical power	Router or Switch capacity	Router/Switch load
Link	Fiber Span [km]	Link equipment power [W]	Link-capacity [Gbit/s]	Link load [%]	Link load [Gbit/s]	Link power for case study [W]	Cumulated power - case study [W]	Governing body	-	Length of fiber span	Link equipment electrical power	Link Capacity	Link Load
	2700	19700	20	20.0%	4	99	1164	Internet2		provider	provider	provider	provider estimate
Los Angeles		810	***50***	***20.0%***	10	3	1167	Internet2	Juniper T640		provider	***similar to DC***	***lower than DC***
	0	***0***	***10***	nr	nr		1167			***inhouse link***	***optical transceivers only***	***nr***	nr
Los Angeles		810	***50***	***20.0%***	10	3	1170	Internet2	Juniper T320		provider	***similar to DC***	***lower than DC***
	11000	***450000***	***830***	***70.0%***	581	15	1186			***map-based estimation***	***extrapolation from transatlantic cable***	***same as transatlantic***	***lower than transatlantic***
Tokyo		***1000***	***50***	***20.0%***	10	4	1190	NICT	Juniper T640		***symmetric to Switzerland***	***typical value***	***low estimate***
	0	***0***	10	nr	nr		1190	NICT		provider	***optical transceivers only***	provider	nr
Tokyo		***250***	***20***	***20.0%***	4	3	1192	NICT	Hitachi GS4000 320E		***symmetric to Switzerland***	***typical value***	***low estimate***
	2	***0***	10	nr	nr		1192	NICT		provider	***optical transceivers only***	provider	nr
Tokyo		***250***	***20***	***5.0%***	1	10	1202	NICT	Hitachi GS4000 320E		***symmetric to Switzerland***	***typical value***	***low estimate***
	300	***3200***	10	7.0%	0.7	91	1294	NICT		provider	***typical value for such DWDM link***	provider	nr
Nagoya		***200***	***20***	***2.0%***	0.4	20	1314	NICT	Hitachi GS4000 160E		***symmetric to Switzerland***	***typical value***	***low estimate***
	0	***0***	10	nr	nr		1314	NICT		provider	***optical transceivers only***	provider	nr
Nagoya		***200***	***20***	***1.0%***	0.2	40	1354	NICT	Alaxala A3630S 24T		***symmetric to Switzerland***	***typical value***	***low estimate***
	0	***0***	1	nr	nr		1354	NICT		provider	***optical transceivers only***	provider	nr
Nagoya		***200***	***10***	***2.0%***	0.2	40	1394	NICT	Alaxala A3630S 24T		***symmetric to Switzerland***	***typical value***	***low estimate***
	0	***0***	1	nr	nr		1394	NICT		provider	***optical transceivers only***	provider	nr
Nagoya		***200***	***5***	***0.8%***	0.04	200	1594	NICT	Cisco 6513		***assumption: symmetric to Davos***	***typical value***	***symmetric to Davos***
	0	***0***	1	nr	nr		1594	NICT		provider	***optical transceivers only***	provider	nr
Nagoya		***200***	***5***	***0.8%***	0.04	200	1794	NICT	Cisco 6509		***assumption: symmetric to Davos***	***typical value***	***symmetric to Davos***

DATA SOURCES AND ASSUMPTIONS

The columns left of the bold line in tables S1 and S2 reflect the case study's energy and traffic data as presented in the main article. The data consists of measured values, estimates, and assumptions. Estimates and assumptions are boldfaced and emphasized.

The right parts of tables S1 and S2 show the sources of the data, and the reasoning behind the estimates and assumptions, respectively.

Governing body

Column 9 shows the organizations behind the respective Internet nodes or links. In Switzerland, it was the Swiss academic Internet provider, SWITCH, and in Japan the National Institute of Information and Communications Technology (NICT). For the rest of Europe, the case study used the GÉANT European research network, and for the transatlantic link the network of a commercial provider ("Provider X") collaborating with GÉANT, that prefers to remain unnamed. Finally, the transcontinental US link and the transpacific link were part of the "Internet2" network. Require

Router type

Column 10 shows the routers passed by the signal of the use case. Although their type is known, some of the cells corresponding to routers in column 12 are nevertheless estimates: A server's consumption does not only depend on its type but also on the so-called "line cards" or "plug-ins" that the router is configured with. The line cards are the router's interface to the optical transmission lines and their cumulated power consumption constitutes a relevant part of the router's overall consumption. Only by knowing the exact configuration of a router with line cards can its power consumption be exactly determined.

Length of link

Column 11 outlines the length of the individual links. The first hops (as seen from Davos), are governed by SWITCH and thus precise data was readily available. For the majority of the other links, the respective providers could inform us about the precise length of the fibers. Two estimates were made: i) that the link leading – within Los Angeles – from the transcontinental part of Internet2 to the transpacific fiber is an "***in-house link***", and thus of length zero, and ii) about the length of the transpacific fiber. The latter was measured with the Google maps distance tool ("***map-based estimation***") , assuming a direct connection from Los Angeles to Hawaii, a ring linking Hawaii's three main islands, and then a direct connection to Tokyo – resulting in a length of 11,000 km.

Power consumption

Column 12 deals with the power consumption of routers and links. Some of them were measured during the case study – in which case we write "**measured @ CS**". For some of the routers, we did not measure the power during the case study but at a later point using the same unchanged line card configuration. A router's power drain depends exclusively on its type and configuration, and not on other parameters such as traffic; this "**measurement w/ identical config.**" must thus provide results identical to the actual consumption during the case study. For some of the SWITCH routers, we cannot guarantee that between the case study and the moment of power measurement there was no change in their configuration; we thus write "**measured w/ similar config.**". As, however, the routers were the same and their configuration did only marginally change (or not at all), these results should be very close to the true valued during the case study as well. When the data was supplied by an external Internet provider (i.e., the provider mentioned in column 9), we indicate this as "**provider**".

As for the routers from Los Angeles on (and all the Japanese routers), we assume similar configurations and power consumptions and thus "**symmetry to Switzerland**", and – for the last two routers in Japan – "**symmetry to Davos**". As the routers are roughly of similar sizes to the ones in Switzerland, this seems to be a reasonable assumption.

The short fiber links listed in column 12 (typically below 80-100 km) do not need any signal repeaters/amplifiers. Other than the longer fiber links, such links consist of the two "**optical transceivers only**" at the two ends, and do not require any power supply. This is particularly the case for all in-house or campus links. Thus, irrespective of whether we know for a fact (from the governing provider) that the link consists of optical transceivers only, or it is our assumption based on the general knowledge that the link has to be in-house or campus, it is a rather safe assumption. Zero power consumption along the link also renders its actual load during the case study not relevant ("**nr**", both in column 14 and in columns 5 and 6): as the total is zero, the case study's share in the power consumption will be zero as well.

Transoceanic cables are always built according to one principle: a power cable runs along the DWDM ("dense wavelength division multiplexing") data fiber. Voltage and current are applied at the two ends of the power cable; the resulting power feeds the amplifiers that boost the signal every 80-100km. The required power is proportional to the cable's length. Our "**extrapolation from the transatlantic**" fiber is thus reliable estimate for the transpacific fiber. Finally, for the 300km link between Tokyo and Nagoya we were given data on its capacity and load, but not its power consumption; we assume a "**typical value for such DWDM link**" – of this length and capacity, that is.

Capacity

The routers and fibers within Switzerland were "**own**" equipment installed by SWITCH; data on their capacities were thus readily available. The capacities of several other routers and links were specified by their "**providers**". For the unknown routers in the US we assumed a "**similar capacity to [the known one in Washington] DC**". For the routers in Japan we assumed "**typical values**" for routers their type (that could be configured for much higher capacities, up to between 96 – 384 Gbit/s) when serving the links of known bandwidth. For the unknown capacity of the transpacific link, we assumed the "**same [capacity] as [the] transatlantic**" link.

Load

For the load of routers/switches and links during the case study, we used following data: the loads of all routers and fibers governed by SWITCH were measured directly during the case study, "**measured @ CS**". For the unknown link from Geneva to Frankfurt and the router in Frankfurt we assumed the loads to be lower than the loads of the surrounding fibers and routers, resulting in an "**low estimate**". We tried to set these values low enough to take only a negligible risk to overestimate the true loads.

Using a low estimate for the loads means to make a pessimistic assumption about the energy demand of the case study and thus its energy intensity, because: According to the allocation scheme we are using, the given power consumption in a router or along a link is divided evenly among the traffic processed by it. Assuming a lower total traffic makes the traffic of the case study relatively more expensive, i.e. it leads to the allocation of a larger share of the power consumed by the router or link.

For the five links Frankfurt-Norden, Norden-Washington DC, and the three transcontinental US links, the loads during the case study are unknown. The respective providers did, however, disclose the average loads they observed under similar conditions (same day of the week, same hours) as in column 5. We call these values “**provider estimates**”.

For the unknown loads of the three routers in Atlanta, Houston, and Los Angeles, we assume the values to be slightly “**lower than [the one known from Washington,] DC**” (20% instead of 24%). Similarly, for the transpacific hop we assume a somewhat “**lower load than the transatlantic**” link (70% instead of 80%). For the routers in Japan, we make “**low estimates**”, which are again rather pessimistic as compared to their European counterparts (e.g., Tokyo lower than Frankfurt or Geneva, Nagoya lower than St. Gallen). Finally, for the last two routers at the University of Nagoya, we pessimistically assume a load as poor as on the Davos side to create consumption “**symmetry to Davos**”. As mentioned in the article, it is almost certain that on Japanese side the loads were higher, because the conference took place within the University campus during normal working hours and therefore the routers were also serving regular university traffic and not only the traffic caused by the conference – as was the case in the Davos congress center. This pessimistic assumption contributes to the claim that our (relatively low) final result should be regarded as rather an overestimation than an underestimation of the energy intensity that will occur in an average situation of Internet data transfer.