The Direct Energy Demand of Internet Data Flows

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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. Because of 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

Although 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 (i.e., 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

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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, 16), "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." 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, refer to 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 to achieve worldwide strong dematerialization, thus fulfilling a necessary condition of sustainable development.

In recent years, ICT has been increasingly credited as a 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 (e.g., design, production, use, and end-of-life treatment) with respect to material and energy efficiency and to replace some goods by services. Mattern and colleagues (2010, 2) 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 (GHGs) alone, ICT is credited with a potential to induce global reductions between 1 gigaton (Gt) of carbon-dioxide 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 GHG 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, 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. Though some studies include the terminal equipment (e.g., personal computers and servers) within the system boundaries (Koomey et al. 2004; Taylor and Koomey 2008; Weber et al. 2010), others do not (Baliga et al. 2007, 2008, 2009; Hinton et al. 2011; Kilper et al. 2011). Most studies include the overhead for cooling and power distribution, but Lanzisera and colleagues (2012) do not. Because of 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 on the energy consumption induced by network traffic. However, these studies either do not take it into consideration (Verdantix 2011; Google 2011), do not 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.

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 14 and 16, 2009, simultaneously in Davos, Switzerland and Nagoya, Japan. Both events could be attended at both sites. This organization mode was chosen to reduce the GHG emissions caused by the travel of attendees to the conferences, in particular, by intercontinental flights. The energy consumed by the travel of the attendees and their satisfaction with the virtual combination

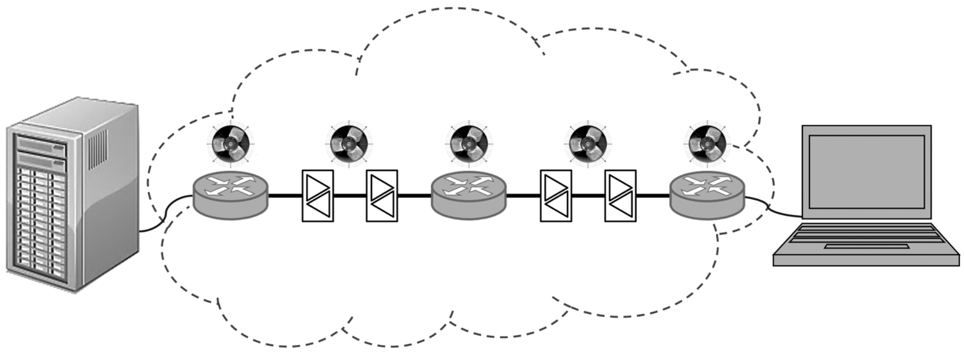

Figure 1 System boundaries underlying our study. We consider the consumption of Internet nodes (i.e., routers including line cards and optical plug-ins) as well as the consumption along transmission lines (i.e., of the optical amplifiers). We also consider the cooling of nodes and amplifiers. We exclude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

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 megabits 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, and the Pacific, as shown in figure 2.

On this longer route, because of 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 kilometers per second, or two thirds the speed of light (Azadeh 2009), the signal propagation delay inside the 27,117 kilometers (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 of switching time for all the 25 nodes along the route. Nevertheless, as a result of 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—allowed the very analysis presented in this article.

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 by 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 transcontinental hops within the United States 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 and optical fiber amplifiers), maximum load capacity, and 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

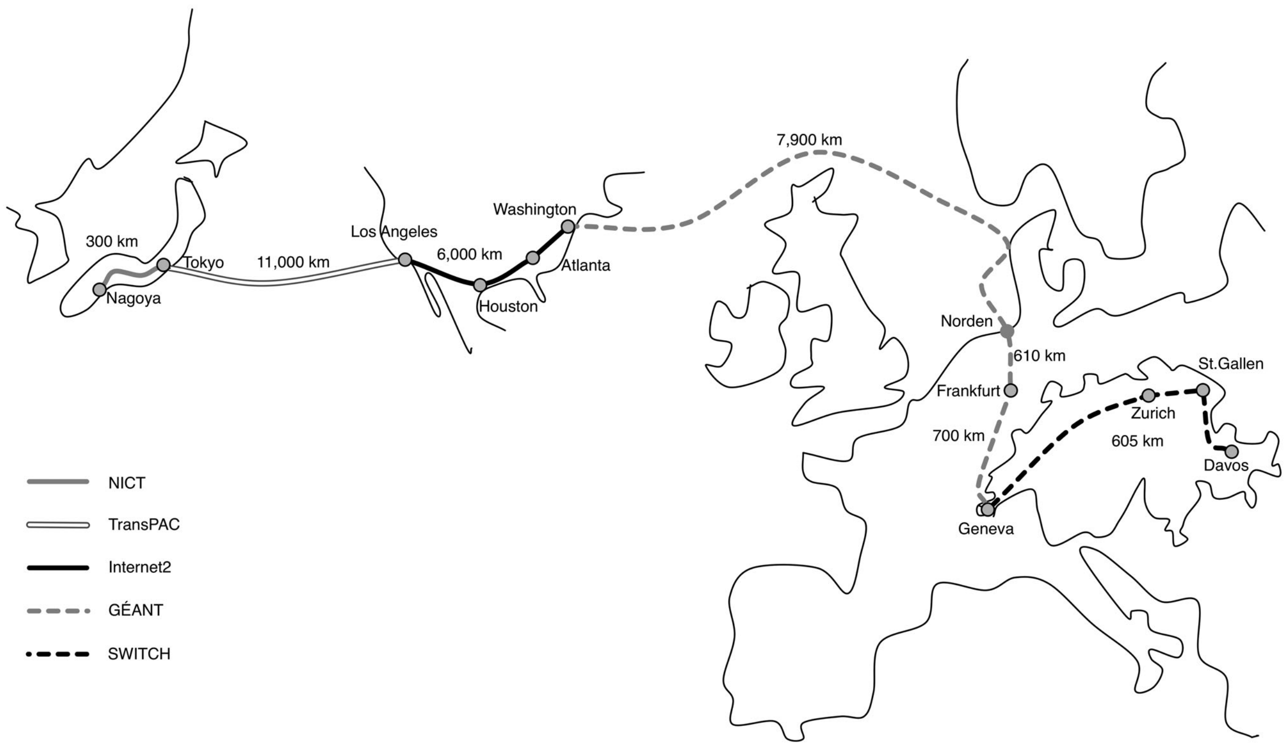

Figure 2 Network path used between Davos, Switzerland and Nagoya, Japan with an overall length of 27,117 kilometers. The map is not to scale.

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 a 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 (i.e., focusing on marginal, instead of average, effects) would as well have produced a much lower value, because 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 second-to-last column shows the allocated power consumption along the chosen path, the sum of which is presented in the last column and 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. Nonunderlined entries were measured directly either by the investigators or by partners from the worldwide research and commercial networks. In total, the 40 Mbit/s (20 Mbit/s in each direction) of the four simultaneous video sessions of the conference required 1,794 watts (W) of power along the Internet, out of which 1,358 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 Web site present the data sources and assumptions in detail.

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, and so on) 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. Though older data centers might still have PUEs of 2.5 or higher, today's best practice is as low as 1.1 to 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 is currently in the 1.8 to 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 3,588 W for the 40 Mbit/s (or 89.7 watts per megabit per second [W/Mbit/s]). Given that a gigabyte (GB) consists of 8,000 megabits, the transmission of 1 GB at the flow

Table 1 Traffic and power consumption data for the Internet nodes and the connecting links that were passed by the conference's data traffic

Router in		*Router electrical power (W)*	*Router capacity (Gbit/s)*	*Router load (%)*	*Router load (Gbit/s)*	*Router power of case study (W)*	*Cumulated power (W)*
Link between	*Fiber span (km)*	*Link equipment power (W)*	*Link capacity*[a] *(Gbit/s)*	*Link load (%)*	*Link load*[a] *(Gbit/s)*	*Link power for case study (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		1,000	4	7.0	0.28	143	748
	130	0	1	nr	nr		748
Zürich		1,000	60	1.8	1.1	36	784
	310	1,600	20	2.2	0.44	73	857
Geneva, CERN		1,000	77	2.6	2	20	877
	0	0	10	nr	nr		877
Geneva, CERN		1,000	50	9.6	4.8	8	885
	0	0	10	nr	nr		885
Geneva, CERN		4,000	77	27.3	21	8	893
	700	4,200	210	20.0	42	2	895
Frankfurt		4,000	155	20.0	31	5	900
	610	68,300	800	75.0	600	2	903
Norden		0	No router				903
	7,900	322,100	830	80.0	664	10	912
Washington		810	50	24.0	12	3	915
	1,100	7,800	20	37.5	7.5	21	936
Atlanta		810	50	20.0	10	3	939
	2,200	15,400	10	25.0	2.5	123	1,062
Houston		810	50	20.0	10	3	1,065
	2,700	19,700	20	20.0	4	99	1,164
Los Angeles		810	50	20.0	10	3	1,167
	0	0	10	nr	nr		1,167
Los Angeles		810	50	20.0	10	3	1,170
	11,000	450,000	830	70.0	581	15	1,186
Tokyo		1,000	50	20.0	10	4	1,190
	0	0	10	nr	nr		1,190
Tokyo		250	20	20.0	4	3	1,192
	2	0	10	nr	nr		1,192
Tokyo		250	20	5.0	1	10	1,202
	300	3,200	10	7.0	0.7	91	1,294
Nagoya		200	20	2.0	0.4	20	1,314
	0	0	10	nr	nr		1,314
Nagoya		200	20	1.0	0.2	40	1,354
	0	0	1	nr	nr		1,354
Nagoya		200	10	2.0	0.2	40	1,394
	0	0	1	nr	nr		1,394
Nagoya		200	5	0.8	0.04	200	1,594
	0	0	1	nr	nr		1,594
Nagoya		200	5	0.8	0.04	200	1,794

Note: 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. Short links with zero power consumption consist of optical transceivers plugged into the routers; their power consumption is included in the routers' consumption. Because there is no power to distribute, their load is also not relevant.

[a]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 megabits per second (Mbit/s) in this table indicates a load of 440 Mbit/s in each direction at once. Thus, whereas for nodes we relate the conference's overall 40 Mbit/s of traffic (20 Mbit/s in each direction), for links we relate only the 20 Mbit/s of one-way conference traffic.

km = kilometer, W = Watts, Gbit/s = gigabits per second. nr = not relevant.

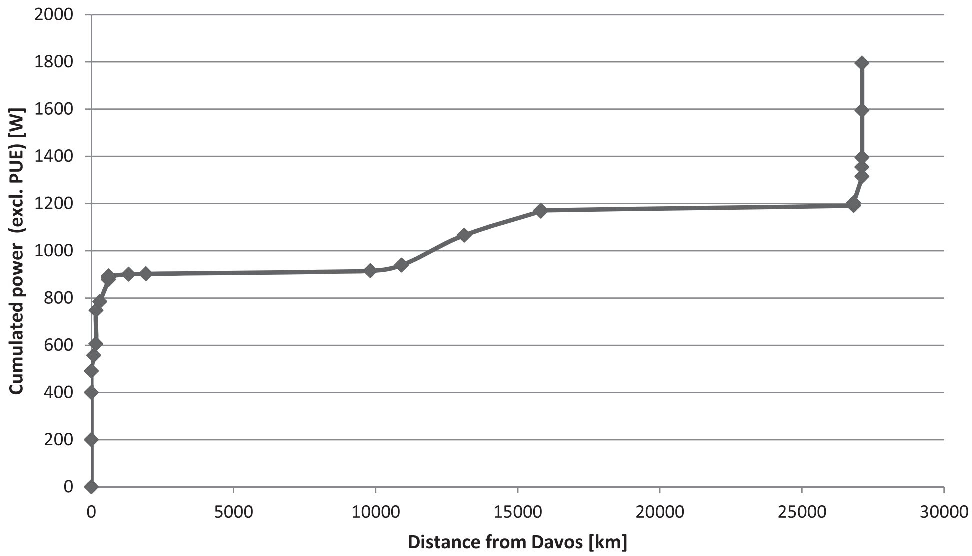

Figure 3 Cumulated power demand along the way from Davos to Nagoya. The power demand of local network components, albeit relatively small, must be allocated, to a relevant extent, to the case study's traffic. These local components therefore clearly dominate the overall power consumption of the transmission. The large core Internet nodes and the transoceanic "data highways," though 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 because of their relatively low bandwidths. PUE = power usage effectiveness; km = kilometer.

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 1 GB in our 2009 case study needs 717,600 Joules, 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 kilowatt-hours per gigabyte (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 because of underutilized 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 are rooted 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. Though, 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 intracountry data flows. Among the other 65.5%, 41% were intracontinental 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.

Although the physical length of the connection correlates to the power consumption along the cables, the consumption in the Internet nodes (i.e., routers and 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 to 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 gigabits per second capacity (because 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, because 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. Last, the PUE of 2.0 is conservatively chosen; though 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 megabyte (MB) would cost no more than 0.2 watt-hours of energy, on average (the amount of energy needed to light a 60-W bulb for 12 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, because their results can differ by orders of magnitude. As another dematerialized substitute of a printed book, an audio file could also 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, whereas the pure data transmission energy consumed for the whole conference with hundreds of participants was only 43 kWh (3,588 W for a daily four hours over three 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 GHG balances of our case study were therefore completely dominated by avoided intercontinental flights versus rebound effects resulting from 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 kilowatts, 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 kilowatts per gigabyte 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 if and when the energy computed for data transmission becomes a dominant component of the environmental impacts that are assessed, as the true consumption of the transmission might lie far below this pessimistic estimate.

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 toward 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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References

Accenture. 2010. Cloud computing and sustainability: The environmental benefits of moving to the cloud. www.accenture.com/us-en/Pages/insight-environmental-benefits-moving-cloud.aspx. Accessed 5 April 2012.

Azadeh, M. 2009. Fiber optics engineering. In *Optical networks*, edited by B. Mukherjee. New York: Springer.

Baliga, J., K. Hinton, and R. S. Tucker. 2007. Energy consumption of the internet. *Paper presented at Joint International Conferences on Optical Internet, and the 32nd Australian Conference on Optical Fibre Technology, COIN-ACOFT, 24–27 June*, Melbourne, Victoria, Australia.

Baliga, J., R. Ayre, W. V. Sorin, K. Hinton, and R. S. Tucker. 2008. Energy consumption in access networks. In *Optical Fiber Communication Conference and The National Fiber Optic Engineers Conference (OFC)*. San Diego, CA, USA: Optical Society of America.

Baliga, J., R. Ayre, K. Hinton, W. V. Sorin, and R. S. Tucker. 2009. Energy consumption in optical IP networks. *Journal of Lightwave Technology* 27(13): 2391–2403.

Cleveland, C. J. and M. Ruth. 1999. Indicators of dematerialization and the materials intensity of use. *Journal of Industrial Ecology* 2(3): 15–50.

Coroama, V. C., L. M. Hilty, and M. Birtel. 2012. Effects of internet-based multiple-site conferences on greenhouse gas emissions. *Telematics & Informatics* 29(4): 362–374.

de Bruyn, S. M. and J. B. Opschoor. 1997. Developments in the throughput-income relationship: Theoretical and empirical observations. *Ecological Economics* 20(3): 255–268.

EANTC (European Advanced Networking Test Center). 2005. *EANTC test report: Catalyst 6500 with Cisco IOS software modularity*. Berlin: European Advanced Networking Test Center.

Erdmann, L. and L. M. Hilty. 2010. Scenario analysis: Exploring the macroeconomic impacts of information and communication technologies on greenhouse gas emissions. *Journal of Industrial Ecology* 14(5): 826–843.

European Commission. 2008. *Addressing the challenge of energy efficiency through information and communication technologies*. Brussels: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

GeSI. 2008. SMART 2020: Enabling the low carbon economy in the information age. www.theclimategroup.org/what-we-do/ publications/smart2020-enabling-the-low-carbon-economy-in-the- information-age./ Accessed 20 October 2011.

Girardin, B. 2011. *Environmental impacts of information and communication flows in and out of Switzerland*. M.Sc. thesis, Geosciences and Environment, Université de Lausanne, Lausanne, Switzerland.

Google. 2011. Google's green computing: Efficiency at scale. www.google.com/de//green/pdfs/google-green-computing.pdf. Accessed 15 March 2012.

Google. 2012. Google apps: Energy efficiency in the cloud. www.google.com/green/pdf/google-apps.pdf. Accessed 24 September 2012.

Herman, R., S. A. Ardenaki, and J. H. Ausubel. 1990. Dematerialization. *Technological Forecasting and Social Change* 33(4): 333–348.

Hilty, L. M. 2008. *Information technology and sustainability: Essays on the relationship between information technology and sustainable development*. Norderstedt, Germany: Books on Demand.

Hilty, L. M. and T. Ruddy. 2010. Sustainable development and ICT interpreted in a natural science context: The resulting research questions for the social sciences. *Information, Communication & Society* 13(1): 7–22.

Hinton, K., J. Baliga, M. Feng, R. Ayre, and R. S. Tucker. 2011. Power consumption and energy efficiency in the internet. *IEEE Network* 25(2): 6–12.

ITU-T (Telecommunication Standardization Sector of ITU). 1998. P.911: Subjective audiovisual quality assessment methods for multimedia applications. In *P Series: Terminals and subjective and objective assessment methods*. Geneva: International Telecommunication Union.

Kilper, D. C., G. Atkinson, S. K. Korotky, S. Goyal, P. Vetter, D. Suvakovic, and O. Blume. 2011. Power trends in communication networks. *IEEE Journal of Selected Topics in Quantum Electronics* 17(2): 275–284.

Koomey, J., H. Chong, W. Loh, B. Nordman, and M. Blazek. 2004. Network electricity use associated with wireless personal digital assistants. *Journal of Infrastructure Systems* 10(3): 131–137.

Laitner, J. A. 2010. Semiconductors and information technologies: The power of productivity. *Journal of Industrial Ecology* 14(5): 692–695.

Laitner, J. A. and K. Ehrhardt-Martinez. 2009. Information and communication technologies: The power of productivity. *Environmental Quality Management* Part I: 18(2): 47–66; Part II: 18(3): 19–35.

Lanzisera, S., B. Nordman, and R. E. Brown. 2012. Data network equipment energy use and savings potential in buildings. *Energy Efficiency* 5(2): 149–162.

Masanet, E. and H. S. Matthews. 2010. Exploring environmental applications and benefits of information and communication technology. *Journal of Industrial Ecology* 14(5): 687–691.

Mattern, F., T. Staake, and M. Weiss. 2010. ICT for green—How computers can help us to conserve energy. In *Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking (e-Energy '10)*. Passau, Germany: ACM.

Mieghem, P. V. 2006. *Performance analysis of communications networks and systems*. Cambridge, UK: Cambridge University Press.

Moth, J. and M. Norris. 2010. *GÈANT3 carbon footprint*. Paper presented at Terena Networking Conference, 31 May–3 June, Vilnius, Lithuania.

Mühlbauer, W., S. Uhlig, A. Feldmann, O. Maennel, B. Quoitin, and B. Fu. 2010. Impact of routing parameters on route diversity and path inflation. *Computer Networks* 54(14): 2506–2518.

Pamlin, D. and S. Pahlman. 2008. Outline for the first global IT strategy for CO_2 reductions. http://assets.panda.org/downloads/global_strategy_for_the_1st_billion_tonnes_with_ict_by_wwf.pdf. Accessed 12 March 2010.

Rawson, A., J. Pfleuger, and T. Cader. 2008. *Green Grid Data Center power efficiency metrics: PUE and DCIE*. The Green Grid. www.thegreengrid.org/Global/Content/white-papers/The-Green-Grid-Data-Center-Power-Efficiency-Metrics-PUE-and-DCiE. Accessed 27 May 2013.

Schmidt-Bleek, F. 1993. MIPS. A universal ecological measure? *Fresenius Environmental Bulletin* 2(6): 306–311.

Stansberry, M. and J. Kudritzki. 2012. Uptime Institute 2012 data center industry survey. http://uptimeinstitute.com/2012-survey-results. Accessed 27 September 2012.

Taylor, C. and J. Koomey. 2008. Estimating energy use and greenhouse gas emissions of internet advertising. http://energy.lbl.gov/EA/emills/commentary/docs/carbonemissions.pdf. Accessed 17 June 2010.

Verdantix. 2011. Cloud computing—The IT solution for the 21st century. https://www.cdproject.net/Documents/Cloud-Computing -The-IT-Solution-for-the-21st-Century.pdf. Accessed 27 September 2012.

von Weizsäcker, E. U., A. B. Lovins, and L. H. Lovins. 1995. *Factor four: Doubling wealth, halving resource use*. London: Earthscan.

Weber, C. L., J. G. Koomey, and H. S. Matthews. 2010. The energy and climate change implications of different music delivery methods. *Journal of Industrial Ecology* 14(5): 754–769.

WSP Environmental. 2011. Salesforce.com and the environment: reducing carbon emissions in the cloud. www.salesforce.com/ assets/pdf/misc/WP_WSP_Salesforce_Environment.pdf. Accessed 5 April 2012.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: 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.