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Abstract

The direct electricity used by data centers has become an important issue in recent years as demands for new Internet services (such as search, music downloads, video-on-demand, social networking, and telephony) have become more widespread. This study estimates historical electricity used by data centers worldwide and regionally on the basis of more detailed data than were available for previous assessments, including electricity used by servers, data center communications, and storage equipment.

Aggregate electricity use for data centers doubled worldwide from 2000 to 2005. Three quarters of this growth was the result of growth in the number of the least expensive (volume) servers. Data center communications and storage equipment each contributed about 10% of the growth. Total electricity use grew at an average annual rate of 16.7% per year, with the Asia Pacific region (without Japan) being the only major world region with growth significantly exceeding that average.

Direct electricity used by information technology equipment in data centers represented about 0.5% of total world electricity consumption in 2005. When electricity for cooling and power distribution is included, that figure is about 1%. Worldwide data center power demand in 2005 was equivalent (in capacity terms) to about seventeen 1000 MW power plants.

Keywords: data center, server farm, data center electricity use, information technology, computers, electricity demand growth

1. Introduction

Electricity used by information technology (IT) equipment has been a subject of intense interest since the first ENERGY STAR specification for personal computers was released in the early 1990s (Johnson and Zoi 1992). The first detailed measurements of personal computer electricity use were published in the late 1980s (Harris *et al* 1988) followed by estimates of total electricity used by office equipment (Koomey *et al* 1996, Norford *et al* 1990, Piette *et al* 1991) and assessments of potential efficiency improvements in that equipment (Koomey *et al* 1996, Ledbetter and Smith 1993, Lovins and Heede 1990).

As the 1990s came to a close, it was becoming clear that a new class of IT equipment was increasing in importance. Computer servers, and the data center facilities in which they were located, were becoming more numerous and more electricity intensive. The first major efforts to understand server electricity use more deeply were spurred by a controversy over the total electricity used by IT equipment in which dubious claims were made about the contribution of such equipment to total electricity use in the US (Huber and Mills 1999, Mills 1999). These claims were subsequently refuted (Baer *et al* 2002, Brown and Koomey 2003, Kawamoto *et al* 2002, Koomey 2008, Koomey *et al* 1999, 2002, 2004, Roth *et al* 2002) but out of the controversy grew the first peer-reviewed measurements of data center electricity use (Blazek *et al* 2004, Mitchell-Jackson *et al* 2002, 2003). Later studies built upon that earlier work to create detailed measurements of data center electricity use in multiple facilities (Greenberg *et al* 2006, Tschudi *et al* 2003, 2004, 2006).

Recent growth in the Internet industry has led the popular press to report on increasing electricity use by data centers (Delaney and Smith 2006, Markoff and Hansell 2006), but

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these reports are anecdotal and may not reflect aggregate trends. Reports of large demand growth have also prompted interest from the policy community in promoting higher efficiency in these facilities (Loper and Parr 2007, US EPA 2007). The purpose of this paper is to accurately characterize electricity used by data centers in a peer-reviewed publication so that public debate can proceed based on accurate data instead of the speculation and hearsay that so often runs rampant in discussions of such topics (Koomey 2003, 2008, Koomey *et al* 2002).

This study only assesses the direct electricity used by data centers. It does not attempt to estimate the effect of structural changes in the economy enabled by increased use of information technology, which in many cases can be substantial.

2. Previous work

Several peer-reviewed estimates of electricity used by servers and data centers were completed around the year 2000 (Kawamoto *et al* 2001, Mitchell-Jackson *et al* 2002, Roth *et al* 2002). The most detailed and comprehensive of these was that by Roth *et al* (2002), which used aggregate installed base data from IDC (http://www.idc.com) by server class and measured power consumption for a representative server in each class. The study also assessed the electricity used by data storage (tape and hard disk drive) systems and network equipment. It did not include infrastructure energy as defined in this paper except in a qualitative way.

Unfortunately, little recent peer-reviewed work has been completed in this area. One exception was an extension of the Roth *et al* analysis to 2004 completed by Ton and Fortenbery (2005) as part of their work on server power supplies. This work used the same analytical structure as Roth *et al* but updated the installed base and power use per unit estimates to reflect more recent data.

A 2007 report (Koomey 2007b) improved on the Roth *et al* analysis for servers by using the latest IDC estimates of the installed base of servers in each class (Cohen and Josselyn 2007), which are calculated using IDC's detailed stock accounting model, not available to Roth. In addition, this analysis relied on a much more detailed assessment of per server power use than did Roth. Finally, the detailed IDC data also allowed calculation of server electricity use by major world region as described in a follow-up report (Koomey 2007a).

The US Environmental Protection Agency's (EPA's) report to the US Congress on data center electricity use (US EPA 2007) built on the results for energy used by servers in the US from Koomey (2007a, 2007b). It also added estimates for electricity used by data center communications (i.e. networking) and storage equipment, projected US electricity use for all components of data centers to 2012, and estimated the energy savings achievable over that period through data center energy efficiency improvements.

3. Data and methods

There are many different ways to define what constitutes a data center. For this analysis I follow IDC (Bailey *et al* 2007) and US EPA (2007) by including as data centers any space whose main function is to house servers, including data closets and server rooms. This definition does not include the parts of telecommunications central offices whose primary purpose is to house telephone switches, routers, and other large-scale network equipment (the parts of those facilities devoted to housing standard servers for voice over Internet protocol applications would be included in my definition).

The analysis for this article begins with the estimates of total server electricity use for the US and the world from Koomey (2007b). That study estimated total electricity use as the product of the number of servers and the electricity used per server. The installed base of servers, broken out into volume, mid-range, and high-end servers, was taken from IDC. That source only reported installed base estimates for the US and the world, so IDC's regional *shipments* for servers were used to estimate installed base by major world region as per Koomey (2007a).

Typical power use per server was derived from a detailed analysis of the most popular server models reported by IDC, as detailed in Koomey (2007b). That analysis estimated the actual electricity used by the six most popular models in the installed base for each major class of server (volume, mid-range, and high end) for the US and the world. Power use was based on manufacturer data, measurements, or engineering estimates of servers typically configured and operated. Power use per server for non-US regions was inferred from the world and US installed base and power use per server numbers.

Table 1 compiles the installed base and power use per server by major world region and server type, from Koomey (2007a). Table 2 uses those data to calculate electricity used by servers, then adds data center communications (internal networking), storage, and infrastructure electricity use. I derived electricity used by data center communications and storage equipment in 2000 and 2005 from the US data in EPA 2007, and expressed that electricity use as a fraction of total US server electricity use for 2000 and 2005, respectively. I then multiplied those fractions by total server electricity use in each region in each year, an approach that assumes that there are no regional differences in electricity used by data center communications and storage equipment. That approximation is the best one possible in the absence of better data.

Infrastructure energy use includes that used for cooling and air handling as well as that lost in power distribution. This component is characterized by what the Uptime Institute calls the Site Infrastructure Energy Overhead Multiplier (SI-EOM), also known by the somewhat less intuitive term Power Utilization Effectiveness (PUE) (Stanley *et al* 2007). This concept characterizes the ratio of total data center loads to information technology (IT) loads. The data compiled and documented in Greenberg *et al* (2006) and Belady and Malone (2007) show that typical SI-EOM's are roughly 2.0, although in practice they can range widely (from 1.2 to over 4.0). I assumed an average SI-EOM of 2.0, which implies that for

Table 1. Installed base and server power per unit in 2000 and 2005 by major world regions.

Installed base	Units	Volume	Mid-range	High-end	Total/avg
2000					
US	Thousands	4 927	663	23	5 613
Western Europe	Thousands	3 332	447	15	3 794
Japan	Thousands	1 140	250	15	1 405
Asia Pacific (ex. Japan)	Thousands	1 416	132	4	1 552
Rest of World	Thousands	1 425	317	8	1 750
Total	Thousands	12 240	1808	66	14 114
2005					
US	Thousands	9 897	387	22	10 306
Western Europe	Thousands	6 985	356	15	7 355
Japan	Thousands	2 361	185	12	2 558
Asia Pacific (ex. Japan)	Thousands	3 553	137	4	3 694
Rest of World	Thousands	3 162	199	7	3 368
Total	Thousands	25 959	1264	59	27 282
Average power used per server	Units	Volume	Mid-range	High-end	Total/avg
2000					
US	Watts/server	186	424	5534	236
Western Europe	Watts/server	181	422	4517	227
Japan	Watts/server	181	422	4517	271
Asia Pacific (ex. Japan)	Watts/server	181	422	4517	212
Rest of World	Watts/server	181	422	4517	246
Total	Watts/server	183	423	4874	236
2005					
US	Watts/server	219	625	7651	250
Western Europe	Watts/server	224	598	8378	258
Japan	Watts/server	224	598	8378	289
Asia Pacific (ex. Japan)	Watts/server	224	598	8378	247
Rest of World	Watts/server	224	598	8378	263
Total	Watts/server	222	607	8106	257

Note: (1) Installed base for US and World taken from Koomey (2007b). Non-US installed base by region was not available from IDC, so it was approximated using IDC shipments data by region and multipliers characterizing the relationship between installed base and shipments for all non-US regions in the aggregate (Koomey 2007a). This approach assumes that installed base for each non-US region grows in the same manner as does the sum of those regions. (2) Average power used per server for US and World taken from Koomey (2007b). Non-US average power per server calculated for non-US regions using the differences between US and World installed base and direct electricity consumption from Koomey (2007b).

every kWh of IT electricity use there is another kWh of infrastructure electricity use.

4. Results

I explore different dimensions of the results below, beginning by summarizing total electricity use for data centers and then analyzing the changes over time from 2000 to 2005.

4.1. Electricity used by data centers worldwide

Worldwide electricity used by data centers doubled from 2000 to 2005, as shown in figure 1, representing an aggregate annual growth rate of 16.7% per year for the world. About 80% of this growth is attributable to growth in electricity used by servers (almost entirely volume servers), with ten per cent of growth in electricity use associated with data center communications and about the same percentage for storage equipment. The overall increase in server electricity use is driven almost entirely by the increase in the number of volume servers, with a small component associated with increases in the server power used per unit.

4.2. Regional results

Figure 2 shows that electricity used by data centers in the US and Europe comprise about two thirds of the total, with Japan, Asia Pacific (excluding Japan), and the rest of the world each falling at between 10 and 15% of the total. Europe alone accounts for more than one quarter of the world's data center electricity. In 2005, Asia Pacific (excluding Japan) jumped from about 10% of the total to over 13%, reflecting the significant economic growth during that period in China, India, and other Asian economies.

Figure 3 summarizes the annual percentage growth rates in data center electricity use by region from 2000 to 2005. Data center electricity use in the Asia Pacific region (excluding Japan) grew at a 23% annual rate, as compared to a world

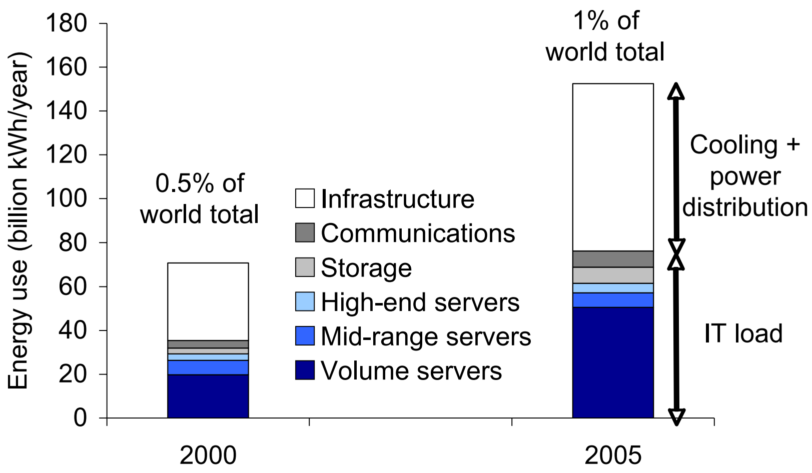

Figure 1. Total electricity use for data centers in the US and the world in 2000 and 2005, including cooling and auxiliary equipment. Total world electricity consumption was 13 238 billion kWh in 2000 and 15 747 billion kWh in 2005, according to the data in table 6.2 of the US Energy Information Administration's *International Energy Outlook*, downloadable at http://www.eia.doe.gov/iea/elec.html. Data center communications electricity use includes only that for networking equipment internal to data centers—it does not include the electricity use of the networks connecting data centers to the Internet as a whole or to the other parts of that broader network.

Table 2. Data center electricity consumption by major world region in 2000 and 2005.

	Servers								
	Volume ($BkWh\ yr^{-1}$)	Mid-range ($BkWh\ yr^{-1}$)	High-end ($BkWh\ yr^{-1}$)	Storage ($BkWh\ yr^{-1}$)	Communications ($BkWh\ yr^{-1}$)	Infrastructure ($BkWh\ yr^{-1}$)	Total/avg ($BkWh\ yr^{-1}$)	Power (GW)	*% of total*
2000									
US	8.0	2.5	1.1	1.1	1.4	14.1	28.2	3.2	*40%*
Western Europe	5.3	1.7	0.6	0.7	0.9	9.2	18.3	2.1	*26%*
Japan	1.8	0.9	0.6	0.3	0.4	4.0	8.1	0.9	*11%*
Asia Pacific (ex. Japan)	2.3	0.5	0.1	0.3	0.3	3.5	7.0	0.8	*10%*
Rest of World	2.3	1.2	0.3	0.4	0.4	4.6	9.2	1.0	*13%*
Total	19.7	6.7	2.8	2.8	3.4	35.4	70.8	8.1	*100%*
% of total	*28%*	*9%*	*4%*	*4%*	*5%*	*50%*	*100%*		
2005									
US	18.9	2.1	1.5	2.7	2.7	28.0	56.0	6.4	*37%*
Western Europe	13.7	1.9	1.1	2.0	2.0	20.7	41.3	4.7	*27%*
Japan	4.6	1.0	0.9	0.8	0.8	8.0	16.1	1.8	*11%*
Asia Pacific (ex. Japan)	7.0	0.7	0.3	1.0	1.0	9.9	19.9	2.3	*13%*
Rest of World	6.2	1.0	0.5	0.9	0.9	9.6	19.2	2.2	*13%*
Total	50.5	6.7	4.2	7.5	7.3	76.2	152.5	17.4	*100%*
% of total	*33%*	*4%*	*3%*	*5%*	*5%*	*50%*	*100%*		
Total 2005/2000	2.56	1.00	1.50	2.70	2.15	2.15	2.15	2.16	

Note: (1) Server electricity use taken from table 1, based on regional shipments and world/US installed base estimates from IDC and power use per server estimates from Koomey (2007b). Assumes 100% load factor, 8784 h $year^{-1}$ for 2000, 8760 h $year^{-1}$ for 2005.
(2) Communications electricity use (which includes only internal data center networking devices, not the broader Internet) for the US taken from US EPA 2007. Communications electricity use for other regions estimated by multiplying the ratio of US communications electricity use to US total server electricity use by total server electricity use in each region in 2000 and 2005. (3) Storage electricity use for US taken from US EPA 2007. Storage electricity use for other regions estimated by multiplying the ratio of US storage electricity use to US total server electricity use by total server electricity use in each region in 2000 and 2005. (4) Electricity consumed by infrastructure (cooling/auxiliary equipment) is equal to that of information technology equipment, based on typical industry practice (Koomey 2007b). This assumption implies an SI-EOM (PUE) of 2.0. (5) Ratio of 2005 to 2000 for total power is slightly different than for total energy because of the difference in the number of hours per year in 2000 and 2005 (2000 is a leap year, 2005 isn't).

average of 16.7% yr^{-1}, making this major region the only one with data center electricity use growing at a rate significantly greater than the world average. Europe also grew slightly faster than the world average over this period.

4.3. Forecasting future electricity use

The IDC worldwide forecast incorporates several trends that will affect electricity used by servers, including increasing demand for information technology services, the move to more

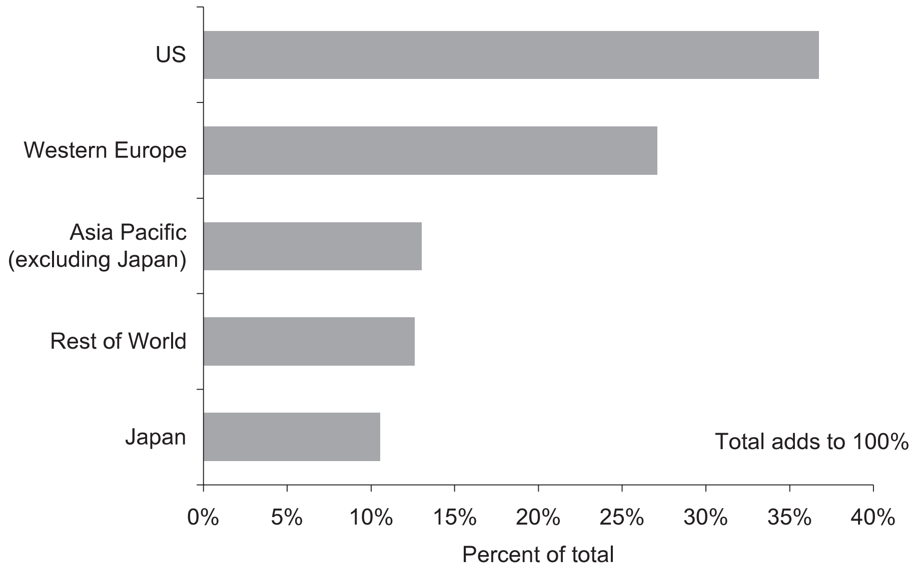

Figure 2. Regional distribution of electricity use for data centers in 2005.

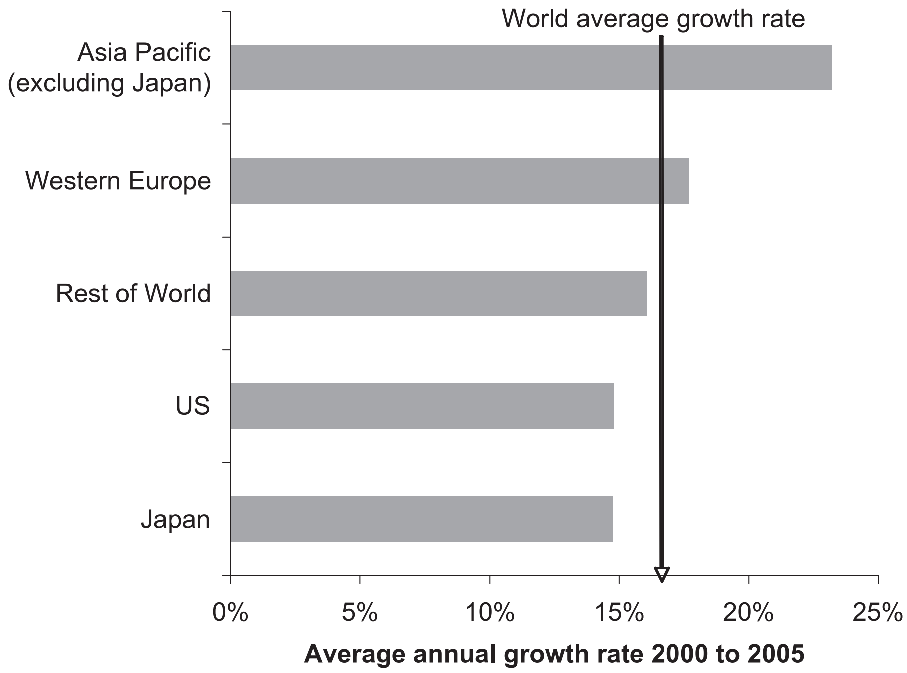

Figure 3. Average annual percentage growth rates in data center electricity use by major world region, 2000–2005.

use of blade servers (which will tend to decrease power use per server) and increases in server consolidation and virtualization (which will tend to reduce the number of physical servers that are needed). Assuming that the IDC forecast of worldwide server installed base is correct, that trends in electricity use per server continue to 2010 as they did from 2000 to 2005, and that the networking and storage electricity use figures continue to track server electricity use as assumed for the historical data, the total growth in data center electricity use would be 76%. This result implies that the average annual world growth rate in data center electricity use for 2005–2010 will be about 12% ($=1.76^{0.2} - 1$) compared to the 16.7% per year growth that prevailed from 2000 to 2005.

5. Future work

5.1. Estimating typical power use per unit

Further analysis is needed to validate estimates of typical power for servers. The factors used in this analysis are based on measurements and recommendations from technical representatives of the major manufacturers, but measured data using a standardized protocol is the most accurate way to arrive at typical power use for servers in the field (ASHRAE 2004, Koomey *et al* 2006, SPEC 2007).

Power use per unit for data center communications and storage equipment is also needed. This analysis did not directly use such estimates, but future work should attempt to estimate power use for such equipment from the bottom up in as much detail as the data allow. US EPA (2007) made a first attempt at such analysis, but more detail is needed.

5.2. More accurate characterization of the installed base of equipment by region

IDC (Cohen and Josselyn 2007) gives installed base estimates for servers in the US and the world, and forecasts of server installed base that extend to 2012. The historical installed base numbers for different regions were not available for this analysis so they had to be estimated. To improve accuracy, future analysis should use the actual regional installed base data once they become available from IDC. Similarly, IDC estimates for the installed base of data center communications and storage equipment should be used in future analyses.

5.3. More accurate characterization of cooling and infrastructure efficiency

There are only two studies of which I am aware that give documented estimates of the SI-EOM (Belady and Malone 2007, Greenberg *et al* 2006). Ongoing data collection efforts by the Environmental Protection Agency and the US Department of Energy will remedy that lack, and when those data become available they should be incorporated into future analyses of total power use from data centers. SI-EOM data from different climates and regions will be of particular interest.

5.4. More detailed segmentation of the server markets

The aggregate segmentation of the server market used in this analysis masks some important variations in that market. Internet search is much different from web hosting, which is much different from application hosting, and is different still from high performance computing. In addition, variations in the physical characteristics of mid-range and high-end servers may interact in complex ways with equipment usage patterns and have a substantial impact on power use per unit. More detailed market segmentation may be helpful in disentangling some of these effects.

5.5. Opportunities for efficiency improvements

Previous work indicates substantial potential for improving the design and operation of IT equipment and data center infrastructure (Brill 2007a, Eubank *et al* 2004, Greenberg *et al* 2006, Tschudi *et al* 2004, 2006, US EPA 2007), but additional data collection, analysis, and policy changes are needed to realize those improvements in the real world. Many of the changes required to capture those potential savings are institutional in nature and involve addressing the misplaced incentives that pervade the industry. Current market structures and practices are aligned with minimization of first cost instead of reduction of total cost of ownership (Brill 2007a, 2007b, Koomey *et al* 2007) but that will change as new metrics are adopted and companies change design and purchasing practices to reflect the new emphasis on minimizing total costs.

6. Conclusions

The amount of electricity used by servers and other Internet infrastructure has become an important issue in recent years. This study estimates total electricity used by data centers in the world by combining IDC data on the installed base of servers with measured data and estimates of power used by the most popular servers as well as estimates of electricity used by data center communications and storage equipment. These estimates are based on more detailed data than previous assessments, and they should help policy makers and businesses attempting to make sense of recent trends in this industry.

Aggregate electricity use for data centers doubled worldwide over the period 2000–2005. Almost all of this growth was the result of growth in the number of volume servers, with only a small part of that growth being attributable to growth in the power use per unit. Total power used by information technology equipment in data centers represented about 0.5% of world electricity consumption in 2005.[2] When cooling and auxiliary infrastructure are included, that figure is about 1%. The total data center power demand in 2005 is equivalent (in capacity terms) to about seventeen 1000 MW power plants for the world.

This analysis splits electricity used by data centers outside the US into regions. The results reveal the predominance of the US and Europe in total data center electricity use as well as much greater than average annual growth rates in the Asia Pacific region (excluding Japan) over the 2000–2005 period.

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