Data Centers Revisited: Assessment of the Energy Impact of Retrofits and Technology Trends in a High-Density Computing Facility

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Abstract: As information and communications technology matures, the nature of the infrastructure that supports it evolves and specializes. While the telephone infrastructure had been built as a network with central offices acting as hubs, the information and communications technology maintains a similar structure, but instead, has hubs of specialized Internet data centers which house the routers and servers. This paper updates one of the first studies to document the electricity consumption and power distribution within an Internet data center. For this study, electricity billing data, metering data, and facility floor space allocation data were used to calculate computer room, total computer room, and building power densities for July 2002. The results of this 2002 study indicate that although the data center had expanded its operations by roughly 33% from the previous year and increased the electricity demand associated with the computer equipment by 55%, the total computer room power density (which includes cooling and auxiliary equipment) remained the same as the previous year at 355 W/m^2. The facility's efforts to improve energy efficiency offset the energy demand from an increased, electrically active, computer room area. The energy-efficiency measures included better optimization of power distribution units, power management modules, computer room air-conditioning units, alterations to operating conditions, facilitywide reductions in lighting, and improved facility controls. A key recommendation is to expand this research to address the need to develop metrics to capture the energy efficiency of the data network throughput.

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Introduction

As information and communications technology (ICT) matures, the nature of the infrastructure that supports it evolves and specializes. While the telephone infrastructure had been built as a network with central offices acting as hubs, ICT maintains a similar structure, but instead, has hubs of specialized Internet data centers which house the routers and servers. Originally, Internet servers were located within office buildings in a decentralized fashion. In response to the need for reliable power as well as air-conditioning requirements, Internet data centers (IDC) were constructed to centralize this computing function and to house the function in specialized facilities. It should be noted that the data center configurations vary greatly and that there may be no typical data center (Beck 2000). IDCs can vary from dedicated IDCs, in which the operation is run by one company, to Web-hosting facilities, in which tenants can house their servers in rented, conditioned space, ''server farms,'' or ''server hotels.'' During the planning of such facilities, the estimates of their power draw assumed power densities that were never realized during operation. But as the IDCs were built in communities, government organizations, nongovernmental organizations, and power companies raised concerns regarding the potential electricity consumption of IDCs (Mills 1999; Peyton 2000).

Actual data regarding the number of IDCs, their size, energy consumption, and data processing capacities are usually not publicly available because much of the information is considered proprietary by those who operate such facilities. Early estimates of power requirements had been inflated due to the lack of facility-specific data and assumptions of capacity, redundancy, and exponential growth and ranged from 1076–2150 W/m^2 (Tschudi 2003a). Certain centers such as those planned by NEC in Tokyo have used the 1076 W/m^2 range in their early planning (Tanaka 2002). Early reports of expansive IDC growth have been subdued due to the economic slowdown, and estimates of exponential increases in electricity demand from such facilities have been refuted by baseline electricity consumption studies conducted by researchers from the University of California at Berkeley (Mitchell-Jackson et al. 2002, 2003), Lawrence Berkeley National Laboratories (LBNL), California Energy Commission (CEC), and the New York State Energy Research and Development Authority (NYSERDA) (LBNL 2003). A 2002 estimate of the extent of the IDC facility power draw was 550 MW (or 0.12% of the grid) for 900,000 m^3 (Mitchell-Jackson 2001).

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IDCs continue to undergo significant alterations over short periods of time, reflecting the ongoing restructuring and technological growth of the industry. Improvements to design and operations of the IDCs are evident in the dynamic and continual changes to these facilities. Prior to 2001, few estimates of IDC electricity had been supported by actual metering and consumption data; thus the Mitchell-Jackson data center study (Mitchell-Jackson 2001) was important because it was among the first studies for which actual usage data from metered and computer room readings were available to calculate the power density for the computer rooms. The study contains a careful lexicon to define affected floor space and energy usage for data centers. As the first of its kind, the 2001 study was the basis of many of the baseline projects that followed in 2002 and 2003. Among the key findings, and the one that is more widely quoted, was the calculation of computer room power density of 355 W/m^2, which was significantly less than 1076 W/m^2 (Mitchell-Jackson 2001). This study used many of the definitions that were developed by the Uptime Institute (Uptime 2000).

Recognizing the dynamic changes to data centers, the writers of this paper proposed a follow-up study that used Mitchell-Jackson's April 2001 study as a baseline. This study, conducted during the summer of 2002, demonstrates early operational and electricity consumption trends of a selected data center, which is a Web-hosting facility with multiple tenants. This 2002 study used and partly refined the methodology used in the previous study to update the electricity consumption at one facility (Mitchell-Jackson 2001).

Since 2002, a team from the Lawrence Berkeley National Laboratory, sponsored by the CEC and NYSERDA, has conducted an exhaustive benchmark study of 11 data centers. Their report (LBNL 2003) highlighted opportunities for improved IDC design and facility operation. As a follow-up to these studies, the Rocky Mountain Institute held an Integrated Design Charrette during February 2003 entitled Design Recommendations for High Performance Data Centers (RMI 2003). While these activities were conducted in parallel, many of the design recommendations had been implemented by the subject data center facility during 2001. These reports and associated Web sites are rich in explanatory and comparative information and to the extent that they are consistent will be discussed in this paper.

Purpose of Study

Since the building infrastructure and equipment configurations of data centers vary regarding requirements and specifications, the data center that was the subject of this study was chosen for consistency with the 2001 project. Due to the market changes and technical improvements, data centers are subject to iterative facility alterations and improvements. Since the 2001 study, the subject data center had undergone significant facility renovations associated with build-out of new computer rooms and a concerted effort to conserve electricity at the facility. The purpose of this study was to document the changes to one data center and to provide a comparison between the energy-consumption patterns from 2001 and 2002 in order to determine the effects of the facility expansion and energy conservation on energy-consumption patterns.

Methodology and Definitions

This paper presents an update of the facility baseline study presented in J. Mitchell-Jackson's 2001 thesis and subsequent articles (Mitchell-Jackson 2001; Mitchell-Jackson et al. 2002, 2003). For this update study, the methodology and format of the previous study was carefully followed and partially refined. The energy indicators, equipment inventory, and electricity consumption were recorded for the same facility in 2002. Noting the lack of standardized definitions resulted in misinterpretation and overestimation in early estimates of data centers, this report uses the same power density terms used in the 2001 study (Mitchell-Jackson 2001) (Table 1).

Table 1. Key Definitions for Power Density in Data Centers

Term	Definition
Computer power density (W/m^2)	Power drawn by the computer equipment (in watts) divided by thecomputer room floor area (in square meters). Computer equipment includes routers, servers, and other computer equipment located within racks or cabinets.
Total computer room density (W/m^2)	Power drawn by the computer equipment (computer power density) and all of the supporting equipment such as power distribution units, UPSs, HVAC, and lights (in watts) divided by the computer room floor area (in square meters).
Total building power density (W/m^2)	Total power drawn by the building (in watts) divided by the total floor area of the building (in square meters).

Note: UPS=uninterruptible power supply; and HVAC=heating, ventilation, and air conditioning.

The building's electricity consumption patterns for 2002 were identified by reviewing the electricity bills over a 12 month period. Floor space utilization was compared with the April 2001 study, and equipment was inventoried in areas common to both studies and the facility's expansion. Although the annual bills were reviewed, only the consumption during the month in which the inventory took place was used in the calculations. The definitions that were used in this study assumed a uniform daily load that may not be representative of the actual daily and seasonal fluctuations associated with peak power usage and air-conditioning.

The computer power density and total computer room power density were calculated based on an energy audit of the data center of the following building aspects:

1. power distribution units (PDU) and power management modules (PMM),
2. Power losses due to auxiliary equipment,
3. Computer room lighting,
4. Central plant, and
5. Computer room air-conditioning (CRAC) units.

Results

The power density calculations for each part of the building are listed in Table 2. By multiplying the power density for each area by the applicable floor space allocation, the approximate facility draw was approximately 1.6 MW of power in July 2002. This draw corresponds to that recorded on the utility bill for that month. The total computer room power density remained the same as the previous year at 355 W/m^2, even with the 55% increase in computer equipment load. Table 3 contains the breakdown of power consumption by function and source.

Table 2. Breakdown of Power Density (W/m^2)

Area breakdown	Floor area (m^2)	Direct use power densities (W/m^2) Computers or prior use	Lights	Other	Supporting equipment power densities (W/m^2) Auxiliary equipment	Central fans chiller plant units	CRAC AHUs	Power density (W/m^2)
Computer rooms	3494	194	5.9	0.0	40.9	59	49	355
Prior use	1171	215	NA	NA	NA	51	NA	269
Equipment rooms	2888	0.0	3.8	0.0	0.0	1.1	1.1	108
Office space	1329	1.1	9.7	3.2	0.0	3.2	3.3	21.6
Other floor area	2665	0.0	5.4	1.1	0.0	1.1	1.1	10.8
Total building	11,647	8.0	5.4	1.1	11.8	2.4	15	140

Note: CRAC=computer room air conditioning; AHU=air handling unit; and NA=not applicable.

Discussion of Data

Floor Space Use Comparison

The survey of floor space allocation was a key task for the equipment inventory. Fig. 1 shows the percentage allocation of floor space by function. At the facility, additional computer room floor area had been opened for customers since the time of Mitchell-Jackson's report (July 2001). The previous computer room total floor area was approximately 2556 m^2. An additional 1766 m^2 was designated as future computer room but not yet built-out or occupied. As of the summer of 2002, about 939 m^2 of the area previously designated as the future computer room was occupied by customers. The basement, office areas, and all other areas remained unchanged since 2001 (Mitchell-Jackson 2001). To be consistent with the previous study, general building areas such as restrooms, hallways, and lobbies were included in the other area category.

For both the 2001 and 2002 studies, the prior-use area, which is the area of operations prior to the IDC, remained the same as before the IDC was constructed, and represented approximately 10% of the total facility floor space. The prior use area contained telephone equipment. As the power loads from this part of the building do not represent new power requirements due to growth of the Internet, or the additional data center space, they are excluded from the computer room power loadings. However, the allocation of the chiller loads reflect historic use.

Computer Area Equipment Inventory

The calculation of the power density for the computer room area was determined in both studies by determining the occupancy rate for each room, making an inventory of the equipment used (servers, routers located within cabinets or racks, and associated computer equipment), and reading output panels for PDUs and PMMs. The 2002 study verified and updated the equipment inventory that was used in 2001 and included the equipment in the newly built areas as well as equipment that had been in cages that were not available for inventory for the 2001 study. The utilization of the racks in the older part of the data center had not changed significantly since the time of the April 2001 audit, which was approximately 36% of rack capacity. During the 2002 audit, approximately 50–60% of the total capacity of the enclosed racks was occupied by network equipment. As a result of this extension of the data center, the computer power density has increased by about 14%. Fig. 2 shows the power allocation for specified areas within the IDC.

Power Distribution Units and Power Management Modules

The equipment in the computer rooms draws power from the PDUs and PMMs, the load on which is rotated between active and redundant PDUs and PMMs. To determine the power used in the computer equipment, the output voltage was recorded from the PDUs and PMMs. To determine the input voltage from the output, a 5% loss was assumed based on manufacturers' data due to the transformer and other internal components. The apparent power (in kVA) was obtained by multiplying the average of the output voltage by the sum of the currents in amperes. The apparent power was then converted to actual power using a power factor of 0.97. These conversion assumptions and methods were identical to those contained in the 2001 study. In 2002, the total computer load was 669 kW, a 55% increase from the 2001 study.

Lighting

In the 2001 report, the power density of the computer room lighting was estimated to be 11.8 m^2 (Mitchell-Jackson 2001). Facility engineers reported that nearly half of the lighting from the data center had been removed, and the remaining lights were switched off when not in use. Inspections verified these energy-conservation measures. The resultant estimated power density

Table 3. Distribution of Power Consumption

Area breakdown	Direct use power (kW) Computer equipment or prior use	Lights	Other	Supporting equipment power (kW) Auxiliary equipment	Central fans chiller plant units	CRAC AHUs	Total power (kW)
Computer rooms	669	20	0	138	202	169	1,197
Prior use	252	NA	NA	NA	62	NA	314
Equipment rooms	0	11	0	0	3	2	16
Office space	2	13	4	0	5	4	27
Other floor area	0	15	3	0	4	4	26
Total facility	923	59	7	138	275	178	1,580

Note: CRAC=computer room air conditioning; AHU=air handling unit; and NA=not applicable.

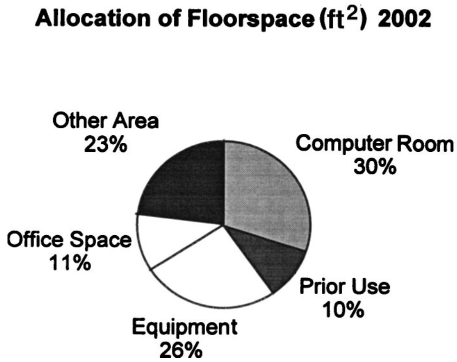

Fig. 1. Allocation of floor space by building use

was reduced to 5.9 W/m^2 for the power needs of lighting in the computer rooms. This accounted for a total of 20 kW for the computer rooms' lighting.

These lighting reductions were extended to all other areas in the data center as well. The 2002 lighting densities were then reduced to one-half that of the 2001 study (based on floor plans and estimations of lighting densities for equipment and mechanical rooms) for mechanical and equipment room and other floor areas. The resultant power densities in 2002 were 9.7 W/m^2 over 1329 m^2 of office space, 3.8 W/m^2 over 2988 m^2 of equipment room, and 5.4 W/m^2 over 2767 m^2 of other floor area. Hence the total load from lighting was approximately 59 kW in 2002, a reduction of 50% relative to 2001.

Central Plant

The central plant contains the chiller, cooling tower, and pumps that are needed to cool the entire facility. The centrifugal, closed-loop, chilled-water chiller had a variable speed drive which allowed greater control for the facility. Like the 2001 study, the total heat load for the facility was recorded from the monitor on the chiller for 2002. The monitor displayed the input power of the chiller and the percentage capacity at which it was running. The reading from July 3, 2002, indicated that the chiller was operating at 51% of capacity and the power input was 163 kW.

While the 30 horsepower cooling tower had not been altered since the 2001 study, its efficiency had changed in July 2002 because the engineers reported that it was running at 100% capacity in the summer, hence consuming approximately 22 kW (note that in winter when the 2001 study was conducted, the motor would consume less power and hence would operate at a lower capacity). The engineers at the data center said the facility always had two pumps that required a total of 90 kW. The central plant total power requirement was 275 kW for July 2002.

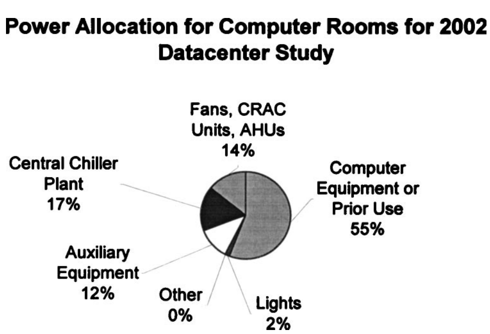

Fig. 2. Power allocation for computer rooms for 2002

Computer Room Air-Conditioning Units

CRAC units are required to transfer heat from the room air to the chilled water loop as well as dehumidify the room air as needed. During 2002, there were 26 CRAC units for the entire data center, of which 17 are on-line at any one time. There is at least one CRAC unit down for routine maintenance at the facility each month.

These CRAC units are heat exchangers, which have humidification/dehumidification and reheat systems. The CRAC units automatically control the humidity level, which is maintained at 40 to 45%. All the CRAC units have humidifying/dehumidifying and reheating capabilities. The fans within the units run at full capacity and are assumed to have an efficiency of about 75% (S. Greenberg, personal communications, 2002). The fans could not be directly observed because they were encased within the CRAC unit. The motors within the CRAC units have efficiencies between 84 and 91%.

During the period between the two studies, facility personnel had removed five of the 18 CRAC units from the existing data center in order to reduce the power draw from these units and redeployed four of them for the expansion. By 2002, the facility had 17 CRAC units in operation at any one time.

The CRAC units that are not required have been turned off, and the temperature had been raised whenever possible. The 17 CRAC units that were online for the entire data center in 2002 required approximately 143 kW. To account for the package air-handling units for the office space and additional fans throughout the building, 35 kW were added to the 2001 calculations. In total, the CRAC units, fans and air-conditioning units required about 178 kW in 2002 (Mitchell-Jackson 2001).

The changes to the CRAC efficiency are related to the changes in equipment configuration. Because the facility engineers installed additional temperature sensors throughout the computer room, they were able to pinpoint hot spots and recommend that the clients reconfigure their equipment to minimize heat buildup. The maximum temperature within the data center was increased by 4°F. Although customers who had been accustomed to having their computer equipment in colder environments noticed the increased temperatures in the IDC, no outages or equipment troubles were reported as a result of this temperature increase.

Comparison between Data Center Studies

Facility personnel have made many changes in the data center between the time of the 2001 study and the current study. Most notable among these changes are additional computer room floor area of about 33% and the increased aggregate computer power load of about 55%. The application of energy-saving measures such as reducing the number of CRAC units operating at any time, disconnecting unnecessary lighting, and raising the temperature within the data center offset much of the draw and consequently balanced the power density for the computer room to 355 W/m^2.

The entire facility drew about 1,580 kW of power in July 2002, which is nearly identical to the draw of April 2001. The computer rooms, central power plants, fans, CRAC units, and its auxiliary equipment drew about 1,200 kW of power.

The total computer room power density remains about the same from Mitchell-Jackson's report, at 355 W/m^2, despite the in-

Table 4. Comparison between Power Densities of the Current and Prior Study

Term	Prior power density (W/m^2)	Current power density (W/m^2)
Computer power density	172	192
Total computer room power density	355	355
Building power density	118	140

crease in the aggregate computer power load because of significant energy-saving measures. Table 4 summarizes the key power densities for the 2002 study. Table 5 gives the differences between Mitchell-Jackson's study and the current study, and the ratio of the 2002 to the 2001 study. The computer power density was increased in the 2002 study with the extension of the data center with a rack occupancy of 50–60%, as compared with the 36% capacity of the older portion of the datacenter.

The facility personnel implemented comprehensive energy-saving measures throughout the facility. Between 2001 and 2002, the facility reduced the amount of lighting and the number of CRAC units used. Table 6 shows some of the energy-saving measures taken by the facility in 2002 and projected annual consumption savings due to these measures. The extent to which the optimization of PMM and PDS contributed to the energy conservation was difficult to ascertain, given the concurrent expansion of the computer rooms. However, in the absence of these conservation measures, the overall computer room power density would have no doubt been significantly greater, perhaps 25–30% greater, given the expansion of the computer room operations. Seasonal fluctuations were difficult to calculate for this facility because of the extent of renovations.

Table 6. Energy Saving Measures

Energy saving measure	Prior power used (kW)	Current power used (kW)	Power saved (kW)	Annual power saved (kWh)
Delamping/turning off unnecessary lighting	117	59	58	510,000
Turning off unnecessary computer room air conditioning	109	93	16	140,000

Conclusions and Recommendations

Even as IDCs increase their capacity and expand their operations, designers and engineers have learned lessons from previous configurations and facility operations. Clearly, the power density for these buildings is not as high as previous estimates would lead one to believe. While this study does not address issues of new design and siting, it demonstrates that improved building operation of existing facilities can produce significant savings, especially regarding lighting and CRAC operations. Even simple adjustments such as raising the temperature in the computer room, reducing unnecessary lighting, and implementing controls for the CRAC units can result in substantial reductions in electricity use. Early estimates of load demand growth had not considered efficiency measures to offset increased electricity demand from the expansion of operations. Another unexpected finding was that computer room power density (355 W/m^2) remained the same between 2001 and 2002. This consistency of the power density from year-to-year can also be attributed to balancing the growth of the facility with these energy-efficiency measures. It should be expected that improvements to equipment design, CRAC sizing, and power management configurations may reap additional efficiencies.

Table 5. Comparisons between the Current and Prior Study

Topic	Mitchell-Jackson	Current study	2002/2001
Computer room floor area (m^2)	2556	3312	1.33
Computer power load (kW)	432	669	1.55
Lighting (kW)	117	59	0.50
Central chiller plant (kW)	213	275	1.29
Fans, CRACs, AHUs, etc. (kW)	250	178	0.29
Total building lighting density (W/m^2)	10	5	0.5
Total building chiller plant density (W/m^2)	18	2.4	1.3
Total building fans/CRACs/AHUs density (W/m^2)	22	15	0.70
Computer power density (W/m^2)			
Power drawn by the computer equipment (in watts) divided by the computer room floor area (in square meters)	172	193	—
Total computer room density (W/m^2)			
Power drawn by the computer equipment and all of the supporting equipment such as PDUs, UPSs, HVAC, and lights (in watts) divided by the computer room floor area (in square meters)	355	355	—
Total building power density (W/m^2)			
Total power drawn by the building (in watts) divided by the total floor area of the building (in square meters)	118	140	—

Note: CRAC=computer room air conditioning; AHU=air handling unit; PDU=power distribution unit; UPS=uninterruptible power supply; and HVAC=heating, ventilation, and air conditioning.

Although the data for the 2002 study were collected prior to and independent of the RMI Charrette, these results uncanninily demonstrate the improvement possibilities for many of the RMI Charrette recommendations. Among the recommendations that are applicable to the findings of this study are eliminate heat sources (RMI Recommendation 1.3), improve power supplies (RMI Recommendation 1.6), conduct general low-no-cost optimization (RMI Recommendation 4.C.1), and CRAC optimization (RMI Recommendation 4.C.3) (RMI 2003). In addition, the results from the baseline study conducted in 2001 and those from the revisit in 2002 are consistent with other facilities that were part of the LBNL-CEC electricity consumption benchmarking study that was published in 2003 (LBNL 2003). The allocation of floor space varied among the various data centers, but the percentage of the computer equipment power draw (50–55% of the total computer room power density) was fairly consistent. This facility, with a total computer power density of 194 W/m^2, was higher than the average computer power density for the LBNL study (269 W/m^2), but lower than the LBNL projected average for full computer rooms of 425 W/m^2 (Tschudi et al. 2003b). For the Uptime Institute, the computer room densities ranged from a minimum of 86–108 W/m^2 to a maximum of 860–1080 W/m^2. The studied facility, with a computer room power density of 355 W/m^2 was slightly higher than the average studied by the Uptime Institute, which was 237–269 W/m^2 (Uptime 2000).

Furthermore, the writers of this study concur with many of the recommendations produced as part of the RMI Charrette and included in the data center roadmap (Tschudi et al. 2003b) and underscore the need to adopt a standard lexicon to describe power usage and functionality within data centers. The use of standard definitions would allow for comparisons between facilities as well as longitudinal studies that show the changes to consumption patterns over time.

In addition, the writers further recognize the limitations of using watts/square feet as a metric for comparison of functionality and power efficiency. For this case of an IDC (Web-hosting center), the comparisons of functionality were additionally complicated because the tenants do not share information regarding the amount of data flowing through their networks, their installed storage capacity, usage, etc. However imperfect a measure, the use of watts/square feet was considered used in this study as well as those conducted by LBNL, the Uptime Institute, and RMI in order to facilitate a measure for comparison between facilities.

The need for a functional unit that describes the throughput of the data network and its associated power consumption will become increasingly important as the function of data networks changes. Just as the function of the PC has rapidly increased over time, so have the functions of network servers. A functional unit that measures watts/square meters could not capture enhanced efficiency or increased functionality. Furthermore, such a metric could not adequately compare the energy usage of data networks with those of other information and communication technologies nor could it account for the convergence of such technologies. With the adoption of voice-over Internet protocol (VoIP), the function of the data network expands to include voice functions. However, the metric of watts/square meters could not adequately provide the basis for the functional comparison between a call on a data network and one on the switched telephone network. Conversely, as the switched telephone network is currently used to transmit a data message, a watt/network-minute may not adequately measure data transmission. Functional units such as MB/kWh and million instruction per second have been suggested, but their use would require some metering or measurement, sharing of proprietary measures, and conversion of existing metrics (such as those currently used for voice).

Similar debates regarding appropriate functional units have been raised in other related information technology studies—most vividly in the comparison of environmental impacts of wireless phone calls and calls on publicly operated telephone system lines. In that case, not only were the data required to calculate suchmetrics considered proprietary and business confidential, but a simple comparison was impossible because the systems were not independent of each other, and the functions were not entirely equivalent (Blazek et al. 1999).

Finally, energy-consumption studies of data centers should also be considered within the context of the uses of their function and service to society. The extent of the energy and environmental impacts of a data center should be evaluated to the extent that the use of ICT changes how people and companies consume other material and energy resources and to the extent that ICT may or may not replace other more energy/material intensive technologies. To address these compelling issues would require a project scope much larger than the one presented in this paper and would include comparisons between ICT and other technology systems. Furthermore, to fully answer these questions would require the assessment of the life-cycle impacts of comparative technological systems including the manufacturing, sale, and recycling of equipment. The barriers to completion of macroscale projects would be considerable, particularly regarding the availability of data and the comparability of function.

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