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Data center design and location: Consequences for electricity use and greenhouse-gas emissions

Arman Shehabi [a,b], Eric Masanet [b], Hillary Price [c], Arpad Horvath [a], William W Nazaroff [a,b,*]

[a] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, USA
[b] Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c] Rumsey Engineers, Oakland, CA 94607, USA

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ABSTRACT

The rapidly increasing electricity demand for data center operation has motivated efforts to better understand current data center energy use and to identify strategies that reduce the environmental impact of these buildings. This paper builds on previous data center energy modeling efforts by characterizing local climate and mechanical equipment differences among data centers and then evaluating their consequences for building energy use. Cities in the United States with significant data center activity are identified. Representative climate conditions for these cities are applied to data center energy models for several different prototypical space types. Results indicate that widespread, effective economizer use in data centers could reduce energy demand for data centers by about 20–25%, equivalent to an energy efficiency resource in the US of ~13–17 billion kWh per year. Almost half of the potential savings would result from better airflow management and proper control sequences. The total energy savings potential of economizers, although substantial, is constrained by their limited potential for use in server closets and server rooms, which together are estimated to account for about 30% of all data center energy demand. Incorporating economizer use into the mechanical systems of larger data centers would increase the variation in energy efficiency among geographic regions, indicating that as data center buildings become more energy efficient, their locations will have an increasing effect on overall energy demand. Differences among regions become even more important when accounting for greenhouse-gas emissions. Future data center development could consider site location, along with efficiency measures, to limit the environmental impact attributable to this increasingly prominent economic sector.

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1. Introduction

Increased reliance on the storage, transfer, and processing of digital information throughout all aspects of society has caused significant growth in data center energy use. These buildings house information technology (IT) equipment, such as computer servers, as well as storage and network devices. In the United States, data center energy use doubled between 2000 and 2006 to about 60 billion kWh annually and is expected to continue to rapidly increase [1–3]. While growth projections made before the current economic downturn may overestimate near-term growth in data center activity, a recent evaluation showed that significant growth continued at least through 2008 with data centers consuming ~70 billion kWh during that year [4]. That level of energy use corresponds to emissions of ~1.2×10^{13} g y^{-1} of fossil carbon (42 Mt/y of CO_2), based on the average carbon intensity of 160 gC/kWh for US electricity production [5].

Non-IT components in data centers—heating ventilation and air-conditioning (HVAC) equipment, uninterruptible power supplies (UPS), and building lighting—account for approximately half of data center electricity demand [6]. Total data center energy demand is often characterized with a simple metric, the power usage effectiveness (PUE) [7], which is defined as the ratio of the total data center building load to the data center IT equipment load. Based on industry consensus regarding data center practices, previous estimates have applied a PUE of 2.0 to represent current average data center energy efficiency, implying that IT and non-IT energy use are equal [1,2,4]. However, IT equipment operates in data centers of significantly different types and sizes, which could affect actual PUE values. Masanet et al. [4] apportioned estimates of national IT energy use among different data center space types

* Corresponding author. Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, USA. Tel.: +1 510 6421040.
E-mail address: nazaroff@ce.berkeley.edu (W.W. Nazaroff).

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based on International Data Corporation (IDC) data for 2005 US installed servers [1,8,9]. In that analysis, five space types were used to categorize the locations of IT energy use: server closets, server rooms, localized data centers, mid-tier data centers, and enterprise-class data centers. Table 1 shows that each space type represents a significant portion of total IT energy use in the United States.

Along with differences in data center space type, the location of an operating data center could affect the energy demand of non-IT equipment. HVAC systems are the dominant component of non-IT energy demand, owing to the large amount of heat generated by the IT equipment that must be removed from the interior space. HVAC energy use can be affected by local climate conditions, especially when incorporating economizers to cool the IT equipment by directly routing outside air into the data center during favorable weather conditions. Building location also affects greenhouse-gas emissions associated with data center operation, owing to regional differences in the mix of primary energy used for generating electricity.

This paper builds on previous data center modeling efforts by addressing climate and mechanical equipment differences among data center types and evaluating the consequences of these differences for energy use. Cities with significant data center activity are identified. The climate conditions of these cities are applied to data center energy models that have been tailored to represent different data center space types. The results of this analysis quantitatively demonstrate how building location and economizer use can influence energy demand and greenhouse-gas emissions. Aspects of data center operation are highlighted where the potential for improvement is large.

2. Methods

Energy use associated with data center operation in the United States is estimated using this equation:

$$E_{\text{total}} = \sum_{s,r} \mathrm{IT}_{s,r} \times \mathrm{PUE}_{s,r} \tag{1}$$

where E_{total} represents the energy required for all data center operations in the US and $\mathrm{IT}_{s,r}$ is the operational energy use associated with IT equipment for space type s in region r. Total data center building energy use is calculated as a function of the IT energy through the PUE metric, where $\mathrm{PUE}_{s,r}$ represents the estimated annual average energy use performance of the non-IT equipment associated with data center space type s in climate region r, expressed as the ratio of total energy use to IT energy use in a data center building.

For the purposes of this paper, the space type-specific IT equipment energy estimates presented in Table 1 are equally distributed into five representative US cities so as to explore the effect of climate differences on building operation among prominent data center locations. The five cities – San Francisco (CA), Seattle (WA), Chicago (IL), Dallas (TX), and Richmond (VA) – were selected after analysis of two data sets that are presented in the Supplementary Material section of this article, available on-line at the journal's website. First, commercial buildings with significant data center activity were identified from Commercial Building Energy Consumption Survey (CBECS) data [10]. Installed servers documented in that data set were disaggregated into census regions. Second, a list of US metropolitan areas with large concentrations of existing data centers previously compiled from US Department of Energy data [1] was used to create a list of specific cities with significant data center activity. The cities from this list were then matched to the corresponding census region. Since a more refined US distribution of data center activity is not currently available, we base the energy analysis reported here on an assumed equal baseline distribution of national data center energy use among the five cities. Each of these cities has significant data center activity and they collectively span much of the range of US climatic conditions.

Operational non-IT data center energy was estimated, specific to building size and location, using a custom-built analytical model. The same energy modeling approach has been used in previous studies [11–13] and is based on a combination of fundamental HVAC sizing equations and equipment characteristics observed through professional experience. A custom-built energy model was used since conventional energy modeling programs (e.g., DOE-2) are not designed to incorporate some of the HVAC characteristics unique to data centers, such as high return air temperatures (>22 °C) and high internal load densities. Data centers have floor-area-weighted power densities that are 15–100 times as large as those of typical commercial buildings [14]. In this study, the heat generated from data center occupants and heat transfer through the building envelope were assumed to be negligible relative to the heat produced by IT equipment.

As outlined in Table 2, energy use estimates were modeled for a reference data center design (*Baseline*) that provides minimal ventilation air and represents conventional data center operation. Such a design has a high intensity of energy demand owing to the exclusive use of compressor-based cooling to remove internal heat loads. Two HVAC economizer designs are modeled: *Economizer* and *Economizer Plus*. These economizer designs use air-side economizers to supply large flow rates of outside air into the data center during cool weather conditions. (An alternative design that was not analyzed in this study is the water-side economizer, which employs cooling towers to provide chilled water in the cooling system. Water-side economizers avoid exposure of IT equipment to excess outside air, but the energy savings potential of these systems are limited in many climates.) In practice, temperature and humidity controls are used to determine when the economizers are active. In the present study, airflow in the economizer designs is identical to the baseline design during periods when the economizer is inactive. The economizers operate when both the outside air temperature is less than the return air temperature setpoint and the outside air dewpoint is less than the return air drybulb temperature at the maximum allowed relative humidity (RH) in the space (i.e.,

Table 1
Estimated 2008 IT-device electricity use in US data centers by space type.[a]

IT electricity use (billion kWh/year)	
Server closet	4.3
Server room	5.5
Localized	6.2
Mid-tier	5.7
Enterprise	12.8
Total	34.5

[a] These five space types are defined by IDC and assumptions about the major differences among these spaces are reported in Masanet et al. [4].

Table 2
Modeled operational settings for each design scenario.

	Baseline	Economizer Scenarios	
		Economizer	Economizer Plus
Economizer use	No	Yes	Yes
Supply/return temperature (°C)	18/22	18/22	18/29
Humidity restrictions (RH)	40–55%	40–55%	1–100%
Upper drybulb lockout (°C)	n/a	22	29
Upper dewpoint lockout (°C)	n/a	19	29

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