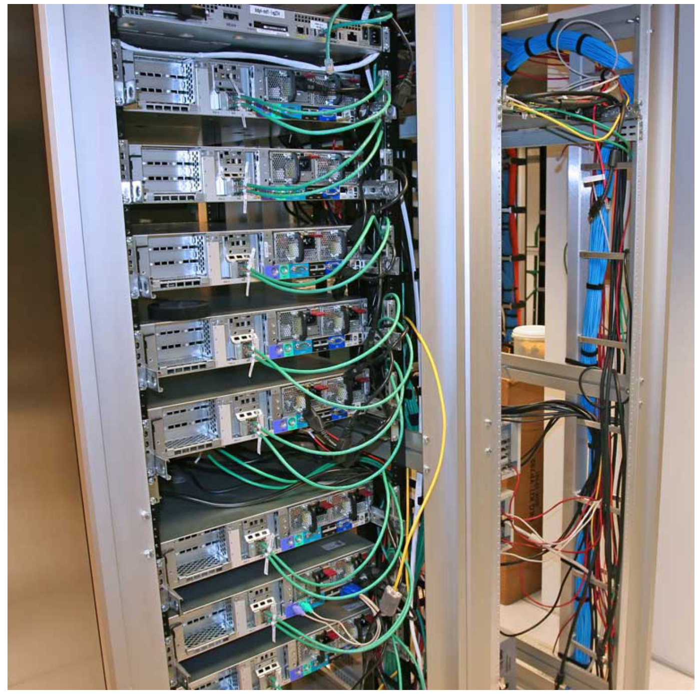

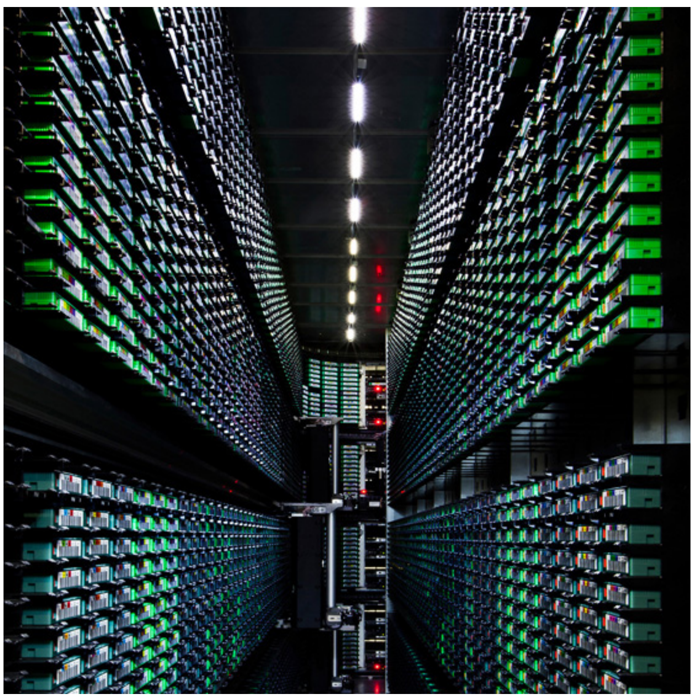

THE ENERGY EFFICIENCY POTENTIAL OF CLOUD-BASED SOFTWARE:

A U.S. Case Study

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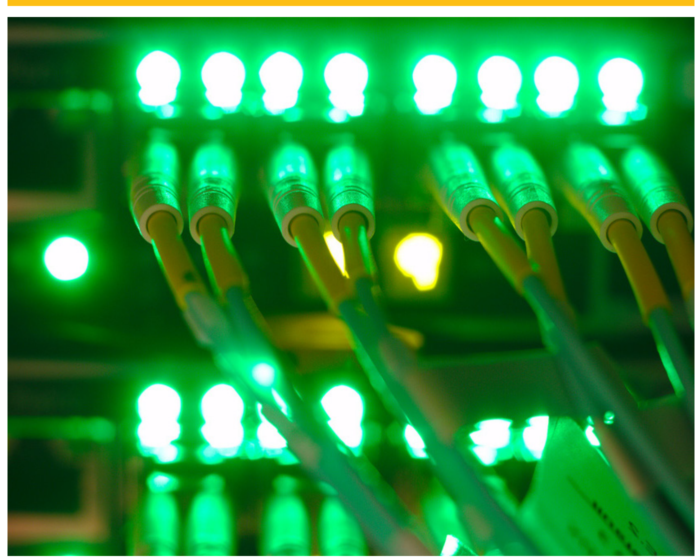

The Energy Efficiency Potential of Cloud-Based Software: A U.S. Case Study

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June, 2013

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Executive Summary

Introduction

The energy use of data centers is a topic that has received much attention, given that data centers currently account for 1-2% of global electricity use. However, cloud computing holds great potential to reduce data center energy demand moving forward, due to both large reductions in total servers through consolidation and large increases in facility efficiencies compared to traditional local data centers. However, analyzing the net energy implications of shifts to the cloud can be very difficult, because data center services can affect many different components of society's economic and energy systems. This report summarizes research by Lawrence Berkeley National Laboratory and Northwestern University to address this net energy analysis challenge in two important ways:

1. We developed a comprehensive yet user friendly open-access model for assessing the net energy and emissions implications of cloud services in different regions and at different levels of market adoption. The model—named the Cloud Energy and Emissions Research (CLEER) Model—aims to provide full transparency on calculations and input value assumptions so that its results can be replicated and its data and methods can be easily refined and improved by the global research community. The CLEER Model has been made freely available online.

2. We applied the CLEER Model in a case study to assess the technical potential of cloud-based business software for reducing energy use and greenhouse gas emissions in the United States. We focused on three common business applications—email, productivity software, and customer relationship management (CRM) software—which are currently used by tens of millions of U.S. workers (see table at right).

Software application	U.S. business users
Email	87,000,000
Productivity software	59,000,000
CRM software	8,000,000

Case study results

We used the CLEER Model to analyze the *technical potential* for energy savings associated with shifting U.S. business software to the cloud, which illustrates the energy and emissions savings that could be realized under a maximum possible adoption scenario. Our results suggest that the potential for energy savings is substantial: if all U.S. business users shifted their email, productivity software, and CRM software to the cloud, the primary energy footprint of these software applications might be reduced by as much as 87% or 326 Petajoules. That's enough primary energy to generate the electricity used by the City of Los Angeles each year (23 billion kilowatt-hours).

Figure ES-1(a) shows that most of our estimated energy savings were associated with email and productivity software, owing to their widespread use in U.S. businesses. Figure ES-1(b) demonstrates the primary driver of energy savings, namely, a substantial reduction in required data center energy use when shifting from many inefficient local data centers to fewer and more efficient cloud data centers.

Like all modeling efforts, our estimates are not without uncertainties. Despite these uncertainties, the energy savings potential of cloud-based software is likely to be substantial on a national scale given the vast differences between the energy efficiencies of local and cloud data centers.

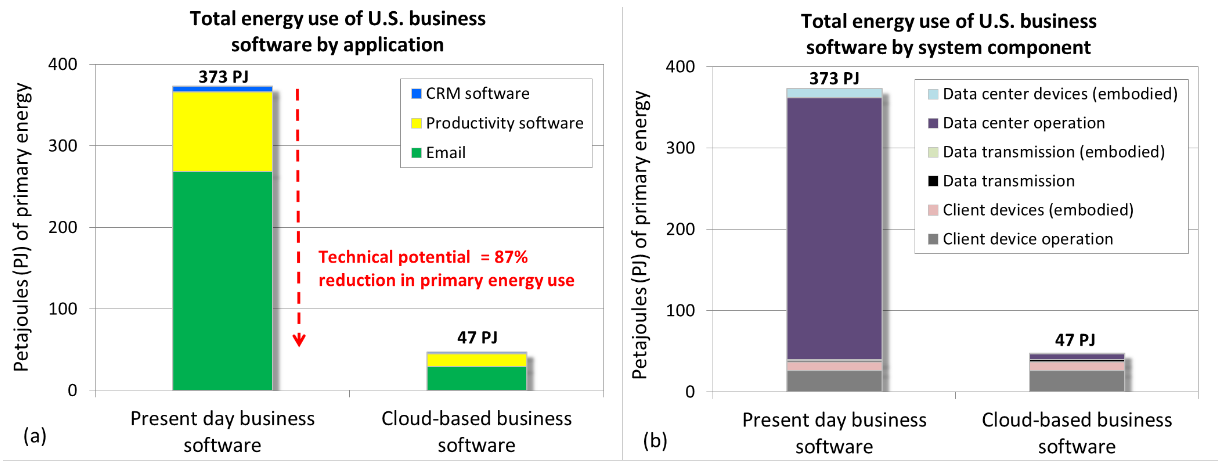


Figure ES-1: Primary energy use of present-day and cloud-based business software systems by: (a) application and (b) system component.

Key findings and outcomes

- The CLEER Model provides the first ever open-access, fully transparent systems model for energy analysis of cloud systems by the research community. Researchers can review, scrutinize, and improve upon its modeling framework and input assumptions, which should help enable and encourage more scientific research on the energy impacts of digital services.
- The case study demonstrates how the CLEER Model can be applied to research questions at different regional scales and that consider all societal end uses of energy affected by cloud services for more robust answers.
- Our results indicate substantial primary energy savings if U.S. businesses shift common software applications to the cloud.
- Our results further highlight the need for more comprehensive and credible public use data on all components of digital service systems—including data centers, network transmission systems, client devices, user behavior, and present day energy efficiency practices—to improve the accuracy of results moving forward.

The CLEER Model

The model can be accessed online at http://cleermodel.lbl.gov/. The modeling approach and key assumptions can be reviewed in the online technical documentation. Users can preload the input value assumptions of our U.S. business software case study, or analyze cloud systems questions of their choosing by selecting their own analysis boundaries and providing their own input values.

Introduction

The energy use of data centers, and their associated emissions of greenhouse gases (GHGs) and air pollutants, is a topic that has received much attention in both the public media and the scientific research community.[1,2,3,4] While the energy requirements of data centers are indeed significant—they currently account for 1-2% of global electricity use[5]—the emergence of cloud computing holds promise for reducing global data center energy demand in the near future. The primary advantage of cloud data centers is that they leverage virtualization and scalable computing strategies to maximize the utilization of servers, which drastically reduces the number of servers needed to provide digital services when compared to traditional local data centers. Cloud data centers are also typically engineered to minimize the energy needed for infrastructure systems (i.e., cooling and power provision systems), with many cloud data centers exhibiting power utilization effectiveness (PUE) values of 1.1 or less.[6,7,8,9,10,11] Combined, high server utilizations and low PUEs have made cloud computing the new standard for best practice data center energy efficiency.

A small but growing body of research suggests that the net energy benefits of cloud computing might be substantial if cloud services were adopted at large scales. For example, some recent reports and corporate case studies suggest that moving applications such as email, customer relationship management (CRM) software, groupware, and collaboration software from local data centers to the cloud can reduce the energy associated with software use by up to 95%, depending on the efficiency of the local data center that is replaced.[12,13,14,15]

Cloud data centers are also likely to play an increasing role in reducing demand for physical goods and services (a process known as dematerialization) through the provision of digital news and entertainment, e-commerce, and remote work and collaboration capabilities. For example, life-cycle assessment studies suggest that digital music can reduce the carbon dioxide (CO_2) emissions intensity of music delivery by 40%-80% compared to compact discs and that digital news can reduce CO_2 emissions of news delivery by 1-2 orders of magnitude compared to a newspaper.[16,17] As cloud data centers increasingly replace local data centers for providing digital services, the energy and emissions benefits of dematerialization might be even greater given the superior energy efficiency of cloud data centers.

While research to date has provided intriguing glimpses of the cloud's potential for societal energy and emissions savings in specific cases, the results of past studies can be difficult to synthesize into credible conclusions about the cloud's potential on a broader scales. In particular, the following issues make past research difficult to generalize:

- Results are often based on static, case-specific assumptions, which precludes application to other scenarios;
- Often key assumptions are not described in sufficient detail for one to change assumptions and arrive at new results;
- Proprietary models are sometimes used, which precludes scientific validation, critique, and refinement of the modeling methods by the research community;
- The limitations of the modeling methods may not be discussed in sufficient detail for proper consideration of uncertainties when interpreting results;

- Rapid change in information technologies and user behaviors can quickly make published case studies obsolete; and
- Given the focus on case results, modeling challenges and opportunities for future research are not always discussed.

The above issues presently serve as knowledge barriers to the energy analysis, corporate planning, and policy communities who seek to better understand the environmental implications of cloud services. While large-scale shifts to cloud computing are clearly already underway, a better understanding of the energy and emissions implications of these shifts—both positive and negative—is critical for enabling research and policy decisions that can steer cloud services down the most sustainable pathways in the years ahead.

This report summarizes research by Lawrence Berkeley National Laboratory and Northwestern University that aims to overcome these knowledge barriers in two important ways.

First, we developed a comprehensive yet user friendly open-access model for assessing the net energy and emissions implications of cloud services in different regions and at different levels of market adoption. The Cloud Energy and Emissions Research (CLEER) Model aims to provide full transparency on calculations and input value assumptions so that its results can be replicated and its data and methods can be easily refined and improved by the research community. The overarching purpose of the CLEER Model is to encourage and enable open scientific research on the positive and negative impacts of cloud services.

Second, we applied the CLEER Model to assess the technical potential of cloud-based business software for reducing energy use and CO_2 emissions in the United States. The purpose of this case study was twofold. First, the case study is meant to show how the CLEER Model can be applied to research questions at different regional scales and that consider all societal end uses of energy affected by cloud services for more robust answers. Second, the case study highlights the need for better public use data on the various components of cloud technology systems (e.g., data centers, network transmission systems, and client IT devices). The case study uses best available data to generate credible results, but also documents data limitations that should be addressed moving forward for greater analysis certainty. As such, the intent is to help synthesize knowledge from past work while providing a roadmap for more efficient knowledge generation in future work.

The CLEER Model

The CLEER Model is based on a bottom-up analysis of the major societal end uses of energy that are affected by cloud systems, including data centers, data transmission systems, client IT devices, commercial and residential buildings, and manufacturing, transportation, and waste management systems. It further includes key interrelationships between these end use systems. The scope of the CLEER Model is depicted schematically in Figure 1.

The model structure provides flexibility to assess a range of different cloud service models, technology and operations configurations, local conditions (e.g., electricity grid mix), and system responses in different regions, thereby ensuring broad applicability of results. It is designed to compare in a credible and transparent manner the energy use of present day systems for providing a digital (e.g., email) or physical (e.g., DVDs) service to the energy use of cloud-based systems that could provide that same service. At different scales of market adoption, the CLEER Model quantifies the net changes in regional energy use between present day and cloud-based systems—accounting for changes in both direct energy use and embodied energy—and calculates the resulting net changes in direct and embodied GHG emissions. Scale is defined as the number of organizations and/or end-users who shift from present-day to cloud-based systems. The results highlight how each particular component of the overall system contributes to the energy footprints of present-day and cloud-based systems, as well as which components account for the net energy and emissions differences between the two systems.

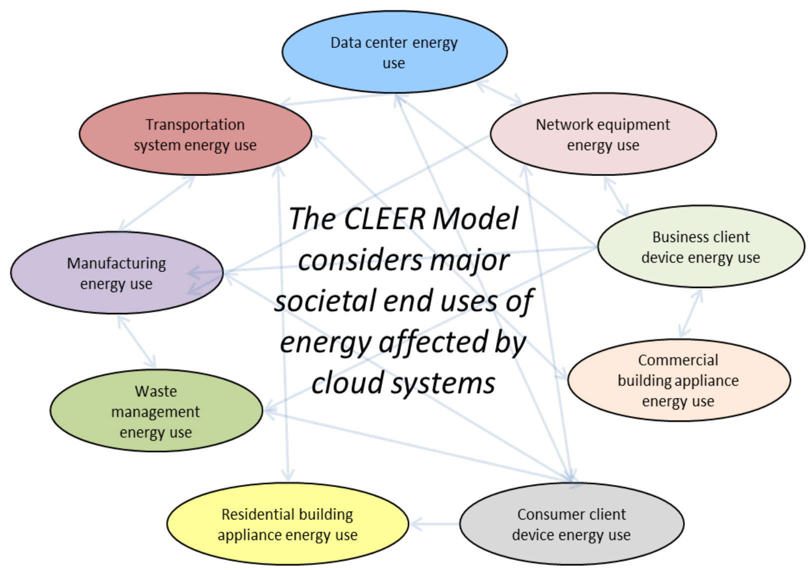
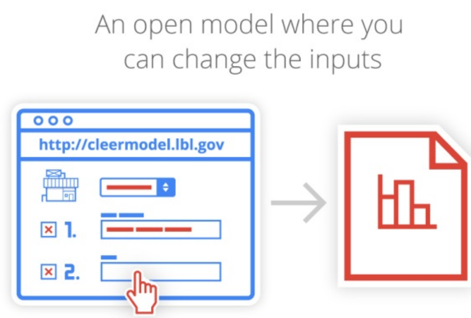


Figure 1: Schematic of the CLEER Model architecture

Each of the energy end use systems depicted in Figure 1 is represented by a sub-model in the CLEER Model framework. Users of the model are prompted to describe each relevant end use system in their analysis in terms of key parameters that affect the energy demand of that end use system. For example, to describe present-day data centers for providing email, the user must specify the numbers and types of servers, the average server power, the number of external hard disk drives (HDDs), and the PUE associated with the data centers that presently house these devices. The user then describes the cloud-based data centers that would provide the email service in terms of these same key parameters. The user can select which end use sub-models to consider, ranging from analysis of a single end use system (e.g., data centers) to inclusion of the many end use systems that might be necessary from a life-cycle perspective (e.g., the manufacturing and transportation of DVDs compared to data centers and network data transmission for streaming video). Thus, analysis boundaries can be tailored to the needs of the user for a given research question. All parameters that characterize the energy demand of each end use system in the CLEER Model are described in the model's online technical documentation.

The CLEER model was designed to provide an intuitive web interface that will allow the research community to generate results using user-defined assumptions and data inputs. Its output results are designed to provide decision makers with credible, research-based estimates that align with common metrics used in business and policy analysis. The analytical structure and data inputs have been made fully transparent, allowing users to evaluate the CLEER Model's underlying analytics, parameters, and assumptions. Given the nascent and rapidly evolving field of IT systems energy analysis, the transparency of model inputs—and how key inputs affect the energy use and emissions associated with different system elements—emphasize where further research and greater validation of (often difficult to come by) input data are needed to reduce analysis uncertainty. Most importantly, the CLEER Model enables users to change any assumptions to generate custom results that he or she finds most useful or credible for his or her particular analysis.

The CLEER model was developed using Google AppEngine so that it can be widely accessed using cloud services. The model is designed for the energy analysis research community, but it should also prove useful those in the business and policy communities who wish to better understand the environmental implications of shifts to cloud services. For transparency, the web interface includes documentation of all modeling methods and equations, including any embedded assumptions. For convenience, default values for key end use system parameters are provided based on credible data from the literature, which will enable novice users to generate reasonable results without in-depth background research. The CLEER Model also contains the input values associated with the U.S. case study for business software applications described below. These input values can be preloaded into the CLEER Model for further refinement and analysis by the research community. The CLEER Model and its supporting documentation can be accessed at: http://cleermodel.lbl.gov/.



U.S. case study

We chose three common business software applications for analysis in the CLEER Model, and assessed the technical potential for energy and emissions savings that might be realized if these three software applications were fully shifted to the cloud across the U.S workforce. Our chosen applications—email, productivity software, and CRM software, represent some of the most common software applications used in the workplace. As such, they provide an example that should be relevant to both the research and business communities, given their broad applicability and national-scale significance. Productivity software is defined here as bundled software that facilitates word processing, file sharing, collaboration, presentations, and data analysis tools such spreadsheets. CRM software is used for managing interactions with customers for sales, marketing, technical support, and other business functions.

Additionally, these three software applications were chosen based on the existence of reasonable public data from past case studies, market reports, academic papers, and government surveys that allowed us to estimate workplace adoption, client device use, server characteristics, and other key analysis assumptions. Further details on our analysis approach are described in the next section.

Case Study Approach

This section provides a concise description of the case study approach and assumptions for estimating the net energy and emissions implications of shifting present-day business software to the cloud. Further details on our approach and assumptions can be found in the appendix.

Our aim was to estimate the *technical potential* for energy use and emissions savings associated with shifting to cloud-based systems. Estimates of technical potential provide illustrative upper bounds on potential savings but do not take into account economic, infrastructure, temporal, institutional, or policy barriers that might limit the savings that can be achieved in real-world systems.[18] Thus, our results should be interpreted as indicative of the energy and emissions savings that could be realized under maximum adoption of cloud-based solutions for business email, productivity software, and CRM software applications.

Figure 2 depicts the overall steps we took to define our case study analysis boundaries and to estimate credible values for key inputs into the CLEER Model. Since our case study focused on business software, we used the data center, data transmission system, and client IT device energy use sub-models to model the direct energy use of present-day and cloud systems. We also used the embodied energy sub-models for data center IT devices, data center building materials, network system IT devices, and client IT devices to model the manufacturing and end of life energy associated with these components. The aforementioned embodied energy sub-models contain both manufacturing and waste treatment end use systems (see Figure 1) for convenience, given their expected frequency of use by CLEER Model users.

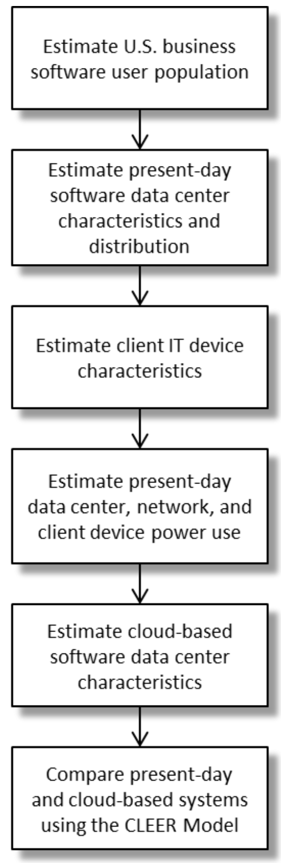


Figure 2: Case study analysis steps

U.S. workers using email, productivity, and CRM software

To estimate the total U.S. workers who presently use each business software application, we first estimated the number of U.S. workers who regularly use computers as part of their daily work tasks. In total, we estimate that there are presently 86.7 million U.S workers who use computers out of a total population of 140 million in the U.S workforce. Our estimate was derived using recent data from the U.S. Census Bureau on total U.S. employment by industry and occupation, and the percentages of each occupation that typically use computers at work (see Table A1). We further assumed that all U.S. business computer users would use email at work.

Of the 86.7 million U.S. workers who use computers, we estimated that 58.9 million regularly use productivity software applications such as word processing, spreadsheets, and file sharing and that 8 million use CRM software. The former estimate was made using data from the U.S. Census Bureau on common computer tasks by occupation and the latter estimate was made based on CRM software vendor market data. We further estimated the number of email, productivity software, and CRM software users by firm size in the United States (see Table A4). Our results are summarized in Figure 3, which depicts the number of present day users of each software application by firm size (3a) and worker occupation (3b). The majority of users of each software application are in large firms (greater than 500 employees) and in management, business, science, and art occupations. However, sizeable fractions of the users of each software application can also be found in the nation's smallest firms, that is, those with fewer than 100 employees.

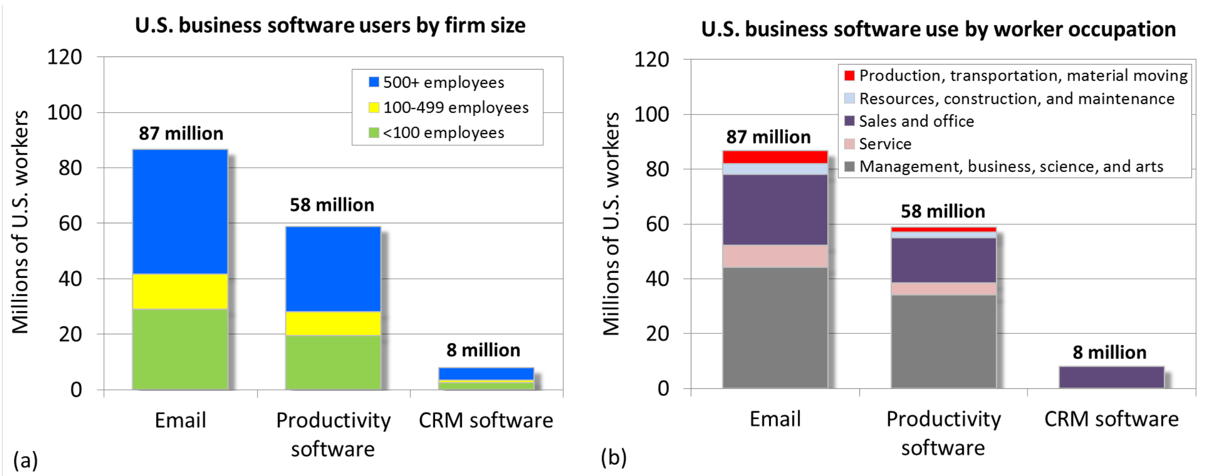


Figure 3: Estimated number of U.S. business software users by: (a) firm size and (b) occupation.

Present day hosting of business software

Next, we estimated the numbers of business software users who currently use non-server based and server-based versions of each software application. We define server-based software as that which requires internet communications for full functionality and non-server based software as that which does not. Email is an example of an inherently server-based software application. Productivity and CRM can be either server-based or non-server based applications, depending on the software arrangement. For example, CRM software can be non-server based in the form of a CRM database on one's local hard drive or it could be server-based in the form of a shared CRM database hosted on an enterprise server. The numbers of server-based software users of each application were further subdivided into users of software that is presently hosted in local data centers and users of software that is presently hosted in the cloud. Our estimates are summarized in Figure 4 by software application (left side) and firm size (right side).

The estimates in Figure 4 were derived based on recent estimates of server-based and cloud-based software use in Europe, given that similar data for the United States could not be found in the public domain.[19] Our estimates in Figure 4 suggest that, while a significant fraction of U.S. business software users may already be using cloud-based software, an even greater fraction is using business software that is presently hosted in local data centers. A smaller fraction is estimated to be using non-server based business software. Our remaining analysis steps were aimed at estimating the net energy implications of shifting present-day users of non-server based and server-based, locally-hosted software to software that is hosted the cloud.

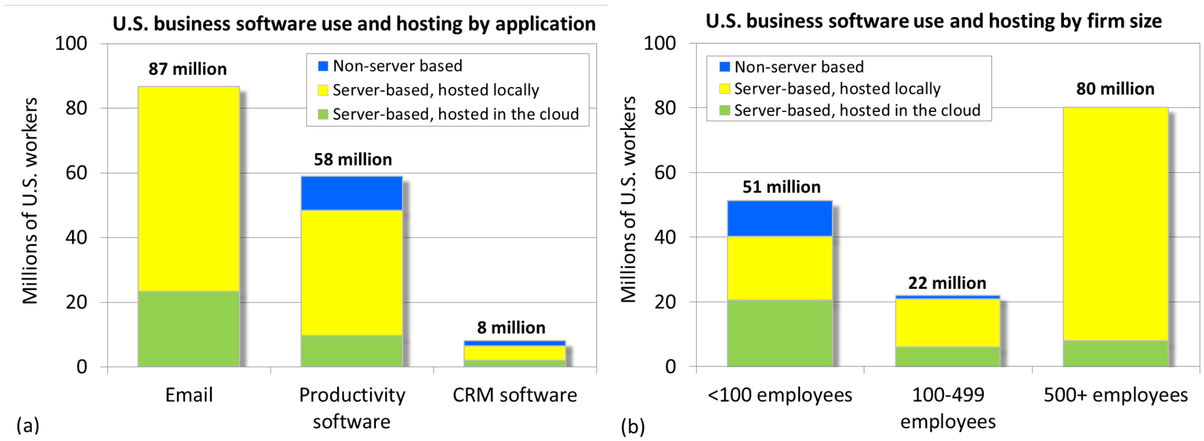


Figure 4: Estimated software hosting characteristics by: (a) application and (b) firm size.

Present day data center characteristics

Our next step was to estimate the present-day distribution of local software servers across different data center types in the United States. We define five different data center types for local hosting of server-based software: (1) server closets; (2) server rooms; (3) localized data centers; (4) mid-tier data centers; and (5) enterprise-class data centers. These five data center types align with established definitions from market research firm International Data Corporation (IDC), which are based on data center floor space and equipment characteristics.[20] We used data from IDC to estimate the number of local servers installed in each data center type by firm size and application, which recognizes that smaller firms are more likely to use onsite server closets, server rooms, and localized data centers than are the nation's largest firms, which typically use mid-tier and enterprise-class data centers (see Table A7). These estimates are summarized in Figure 5, which also includes our estimated numbers of cloud-based servers presently being used to host each application. The estimates in Figure 5 were derived by making assumptions about the average number of users hosted by a server for each firm size and data center type and the typical server redundancy associated with each firm size and data center type (see Tables A9, A10, and A11).

The estimates in Figure 5 suggest that the vast majority of servers associated with email, productivity software, and CRM software (4.7 million) are located in the nation's server closets and server rooms, and, to a lesser extent, its localized data centers. We note that these estimates are uncertain, given the lack of publicly available, recent data on the distribution of servers across data center types in the United States and the redundancy practices of different data centers. These uncertainties are particularly salient for the data center types and redundancy practices of the nation's many small firms, which are most likely to use server closets and rooms.

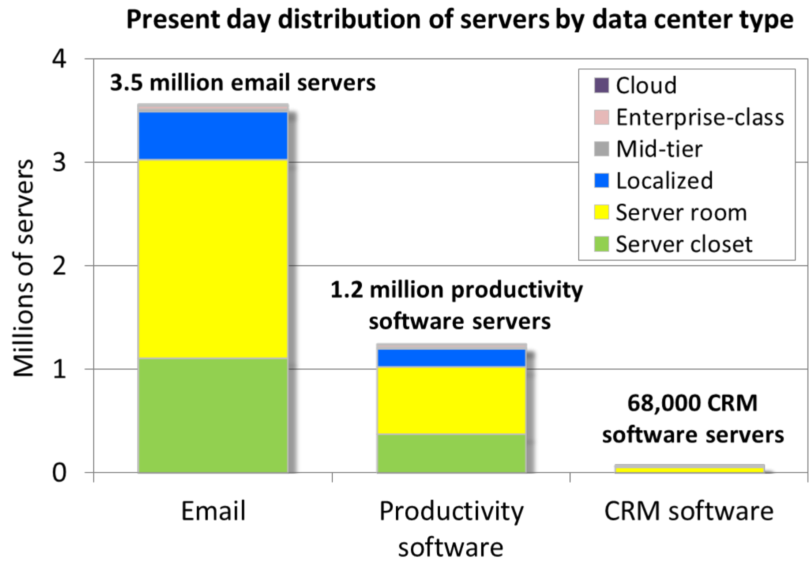


Figure 5: Estimated installed base of servers for each business software application by data center type

As a reality check, we considered that IDC and Gartner estimate a present installed base of 11-12 million servers in the United States and that data center type distribution data from Bailey et al. (2006) suggest that roughly 53% of this installed base may be found in server closets, server rooms, and localized data centers.[21,22,23] The combined IDC, Gartner, and Bailey et al. data suggest a current installed base of 6.1 million servers in U.S. server closets, server rooms, and localized data centers. Our estimate that 4.7 million of these 6.1 million servers are dedicated to local hosting of email, productivity software, and CRM software seems plausible given that: (1) small firms account for the majority of these data center space types; and (2) these three business software applications likely represent the dominant uses of local servers for small firms. However, these estimates should be revisited in future work. Data uncertainties in these and other case study analysis inputs are discussed further in the results section.

Client device characteristics

We next estimated the numbers and types of client IT devices that are typically used for business software access. Figure 6 summarizes our estimates for the numbers of desktop PCs, notebook PCs, smart phones, and tablet PCs that are used for email, productivity software, and CRM software by U.S. workers. These estimates were derived based on workplace technology survey data that characterized the frequency of business use of each device as well as the frequency of use of each device for each software application (see Table A14). We further estimated that desktop PCs would use a wired internet connection (e.g., fiber to building) for server-based software access, that notebook PCs would use a wired connection 70% of the time and a Wi-Fi connection 30% of the time, and that smart phones and tablets would use a Wi-Fi connection 33% of the time and a cellular data connection (3G/4G) 67% of the time. Our estimates for smart phone and tablet network access are based on a recent study of the wireless cloud by Bell Labs and the University of Melbourne.[24]

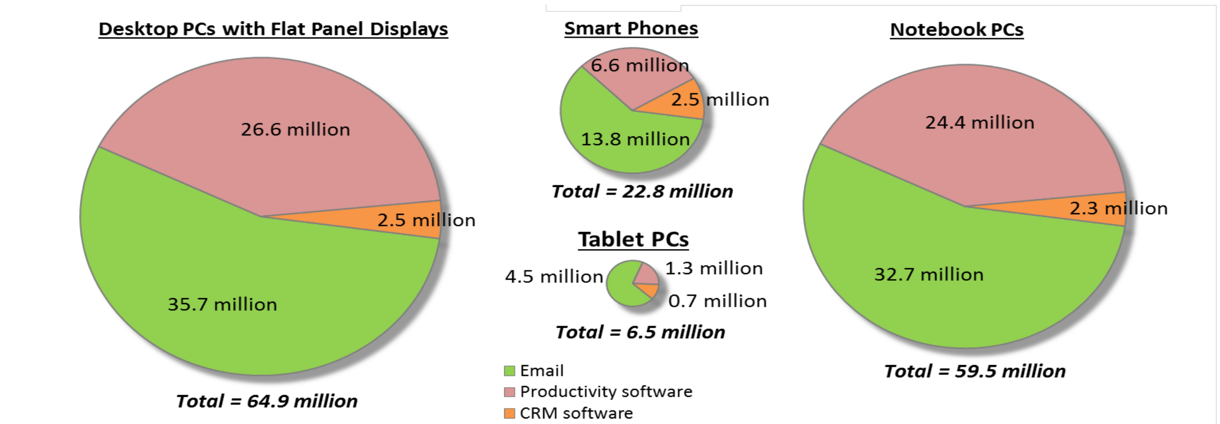


Figure 6: Estimated numbers and types of client IT devices used for business software by U.S. workers

Data center, network, and client device energy use

We compiled best available estimates of power and energy use for data center, network transmission, and client IT devices from the public literature and expert elicitation; these estimates are summarized in Table 1.

We classify both volume servers and midrange servers, and assume that all local hosting of business software occurs on the former and all cloud hosting of business software occurs on the latter based on industry data.[25] Our chosen PUE values for each data center type are based on previously published values for each data center type, expert elicitation, and energy modeling results for different data center infrastructure configurations.[26]

The estimates for the energy intensity of different network connection types are based on average values drawn from the literature, which included modeled, estimated, and measured network energy intensity values. [27,28,29,30,31,32] Our estimates of the "on" mode power use for business client IT devices are drawn from U.S. Department of Energy data on appliance energy use and other published sources.[33]

Lastly, we also considered the embodied energy associated with each of the devices listed in Table 1, as well as the embodied energy of data center building materials. We compiled estimates from published data in the life-cycle assessment literature (see Tables A21 and A22).

Table 1: Summary of power/energy data

Data center IT devices (W/device)	
Volume server	235
Midrange server	450
External HDD spindle	26
Data center PUE	
Server closet	2.5
Server room	2.1
Localized	2
Mid-tier	2
Enterprise-class	1.5
Cloud	1.1
Network data transmission (µJ/bit)	
Wired	100
Wi-Fi	100
Cellular (3G/4G)	450
Client IT devices, ON mode (W/device)	
Desktop PC	75
Notebook PC	25
Flat panel display	42
Smart phone	3
Tablet computer	5

Shifting to the cloud

Table 2 summarizes our estimates for the required number of cloud servers and external HDDs for hosting all email, productivity, and CRM software for the U.S. workforce. Compared to the present day, the server count for cloud-hosted software is substantially lower due to the much higher user per server capabilities of cloud-based servers. Further details on the assumptions and calculations behind the estimates in Table 2 are provided in the appendix.

Table 2: Number of data center IT devices: present day software compared to cloud-based software

	Present day software			Cloud-based software	
Software application	Volume server	Midrange servers	External HDDs	Midrange servers	External HDDs
Email	3,543,000	12,780	641,000	47,700	429,500
Productivity software	1,237,000	5,240	306,000	32,400	291,900
CRM software	68,500	1,010	32,800	4,390	39,500

Findings

Case study results

The results of our case study analysis are summarized graphically in Figure 7 and in greater detail in Table 3. We estimated that present-day systems for business email, productivity, and CRM software in the United States require 268, 98, and 7 Petajoules (PJ) of primary energy each year, respectively, when the direct energy use and embodied energy of all system components are considered. Combined, the present-day primary energy footprints of these three business software applications add up to as much as 373 PJ per year. In reality, there may be some overlap in the energy footprints of each software application if present-day data centers use the same redundant server to back up more than one software application. Thus, our combined estimate of 373 PJ per year should be interpreted as an upper bound.

The bubbles in Figure 7 shed light on how each component of present-day systems contributes to this energy footprint. Our estimates suggest that data center operations account for the vast majority (86%) of the primary energy footprint of present-day systems, followed by the operational energy use of client IT devices. Also notable is that the embodied energy associated with data center and client IT devices is non trivial, which reinforces the need for consideration of the embodied energy of IT devices in analyses of digital services moving forward.[34] Conversely, the embodied energy of data center building materials makes a negligible contribution to the overall primary energy footprint.

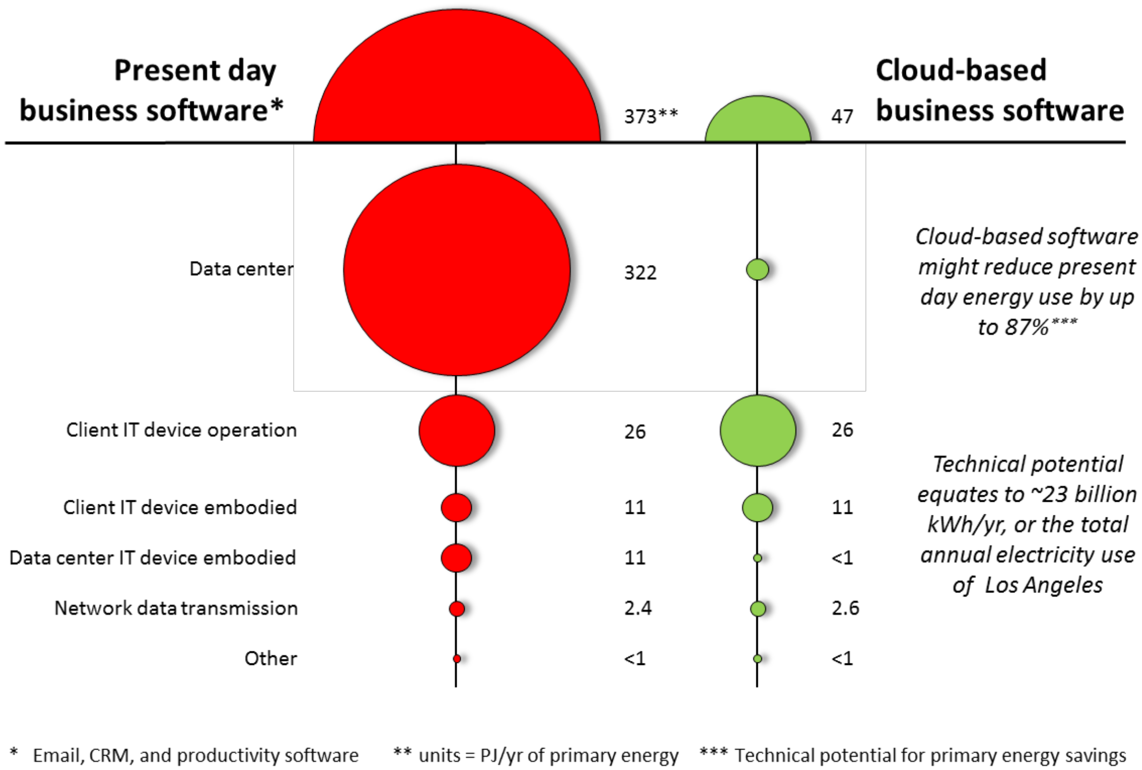


Figure 7: Estimated primary energy footprints of present-day and cloud-based U.S. business software

If all present-day systems would fully shift to the cloud, our results suggest that the primary energy footprint of U.S. business email, productivity, and CRM software could be reduced to around 47 PJ each year. The main mechanism of this energy use reduction can be seen clearly in Figure 7; namely, the operational energy use of data centers is significantly reduced when moving from local data centers to the cloud. This result is not surprising, given that the cloud is expected to use far fewer servers in far more efficient data centers compared to present-day local data centers. Our results also indicate smaller, but nontrivial, reductions in the embodied energy of data center IT devices in the cloud given that far fewer servers are required for the same computations. Lastly, we predict a small increase in the operational energy use of data transmission systems when shifting to the cloud, which can be attributed to increased data traffic associated with remote software access.

Our results suggest a technical potential for primary energy savings of up to 326 PJ per year if all U.S. workers shifted their email, productivity, and CRM software to the cloud, which is enough primary energy to generate the total electricity consumed by the City of Los Angeles each year (23 billion kWh).[1] Although technical potential estimates do not take into account economic, institutional, or other

[1] We base this estimate on the average primary energy intensity of electricity generation in the United States, which is approximately 13.8 MJ/kWh. Dividing 326 PJ by 13.8 MJ/kWh results in 23.6 billion kWh of electricity generated, which is roughly equal to the 2011 electricity use of all homes, businesses, and industries in Los Angeles (23.1 billion kWh) as reported by the California Energy Commission (http://www.ecdms.energy.ca.gov/elecbycounty.aspx)

barriers that might limit the realization of energy savings in practice, our results suggest that the national-scale potential for primary energy savings through shifts to cloud-based software are likely to be substantial even at less than full market adoption.

Table 3: Case study results by software application and system component

	Primary energy (TJ/yr)			CO_2 emissions (kt CO_2e/yr)		
Email	Present day	Maximum cloud adoption	% change	Present day	Maximum cloud adoption	% change
Client IT device operation	16,060	16,060	0%	790	790	0%
Client IT devices (embodied)	6,450	6,450	0%	400	400	0%
Data transmission system operation	1,520	1,600	5%	75	80	5%
Data transmission system devices (embodied)	280	300	5%	25	30	5%
Data center operation	235,200	3,900	-98%	11,540	190	-98%
Data center IT devices (embodied)	8,150	420	-95%	500	30	-95%
Data center building materials (embodied)	5	1<	-94%	1<	1<	-94%
Subtotal	267,670	28,770	-89%	13,320	1,500	-89%
Productivity software						
Client IT device operation	8,560	8,560	0%	420	420	0%
Client IT devices (embodied)	3,370	3,379	0%	200	200	0%
Data transmission system operation	750	790	5%	40	40	5%
Data transmission system devices (embodied)	140	150	5%	10	10	5%
Data center operation	82,300	2,680	-97%	4,050	130	-97%
Data center IT devices (embodied)	2,860	290	-90%	170	20	-90%
Data center building materials (embodied)	2	1<	-88%	1<	1<	-88%
Subtotal	98,000	15,820	-84%	4,900	830	-84%
CRM software						
Client IT device operation	930	930	0%	50	50	0%
Client IT devices (embodied)	1,130	1,130	0%	90	90	0%
Data transmission system operation	150	160	5%	7	8	5%
Data transmission system devices (embodied)	30	30	5%	2	3	5%
Data center operation	4,890	360	-93%	240	20	-93%
Data center IT devices (embodied)	170	40	-78%	10	2	-78%
Data center building materials (embodied)	1<	1<	-73%	1<	1<	-73%
Subtotal	7,300	2,650	-64%	390	160	-64%
Total	372,970	47,240	-87%	18,610	2,490	-87%

Note: totals and column sums might not be equal due to rounding; % change might not be equal to changes in row values due to rounding.

Examination of Table 3 reveals that potential energy savings are especially pronounced for email and productivity software, given that both are used by tens of millions of U.S workers and both are presently still predominantly hosted in local data centers. While still substantial, the potential energy savings are less pronounced for CRM software, owing to fewer overall users compared to email and productivity software, and the assumption that many CRM software users are already using cloud-based CRM software. Table 3 also summarizes our results for GHG emissions savings, which are similar in magnitude to primary energy savings.

Limitations

While our results suggest that the technical potential for energy savings through a shift to cloud-based business software is substantial at the national scale, as with all modeling efforts, our results are not without uncertainties. In particular, our reliance on publicly available data is a significant source of uncertainties, given that data were drawn from a number of different studies and sources that were published in different years and with differing scopes and regions of analysis. Furthermore, there exists a chronic lack of data in the public domain for deriving consistent and current analysis assumptions related to the installed base of servers, the use of different data center types by firms of different industries and sizes, the use of business software and client devices, and the efficiency and redundancy practices of data center operators.

However, a primary goal of the CLEER Model and our case study is to highlight the need for better and more transparent public use data moving forward, and to provide a user-friendly platform for utilizing the best data as they emerge over time. In support of that goal, all of the input values used in this case study can be preloaded into the CLEER Model for scrutiny and refinement by the research community. All input values and data sources are further summarized in the appendix of this white paper.

While every attempt was made to derive reasonable input values that were based on credible data sources, our assumptions and results should be reviewed and improved upon as better data emerge in the future. To better understand which input values are most responsible for variance in our case study results, we conducted sensitivity analyses for each business software application. Figure 8 presents the results of our sensitivity analysis on the net difference in total primary energy between present-day and cloud-based systems for email. Our sensitivity analysis results were similar for productivity and CRM software, given that the underlying physical systems are largely the same for all three software applications. We used Oracle Crystal Ball software to conduct a sensitivity analysis using a an Excel version of the CLEER Model analysis framework (the online CLEER Model does not support sensitivity analysis).[35]

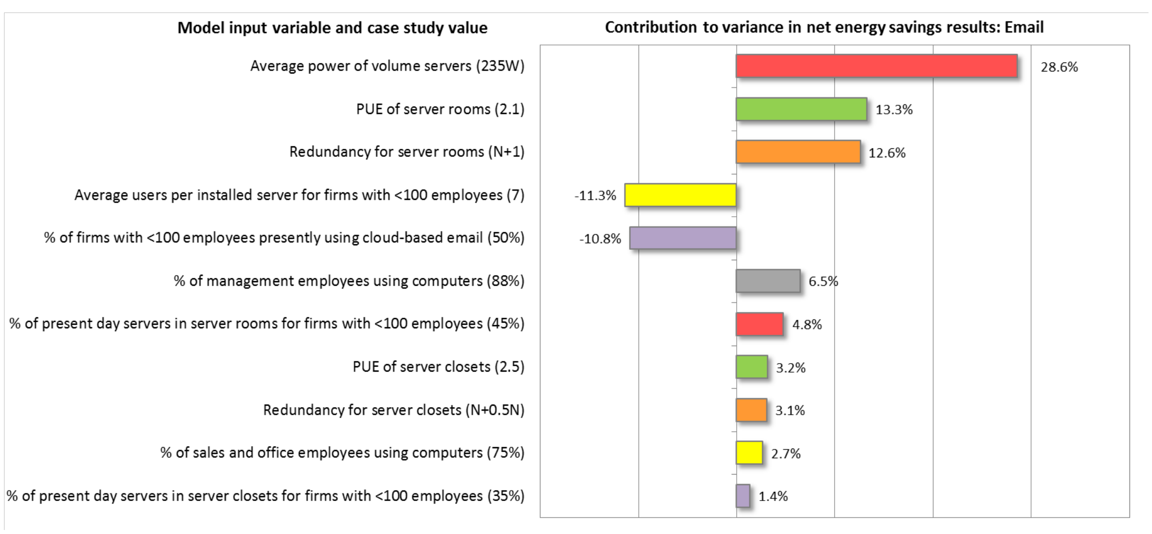


Figure 8: Sensitivity analysis of results for net primary energy savings of cloud-based email

The data in Figure 8 indicate that our input assumptions for volume server power use, PUE values for server closets and server rooms, server redundancy in server closets and server rooms, the average users per server for small firms, and the percentages of small firms already using cloud-based software are the greatest contributors to variance in our results. In other words, uncertainties surrounding the input values of these key variables are the major drivers of uncertainties in our case study results. Thus, the research community should pay particular attention to these key input assumptions and future work should focus on compiling or deriving better data for these input values to improve the accuracy of similar analyses moving forward.

It also bears repeating that our results are limited to estimates of the technical potential for energy savings, and that the actual savings realized may be limited by economic, institutional, policy, or other barriers in practice. Furthermore, our results represent a snapshot of today's technologies and business practices, but these technologies and practices can change rapidly for both cloud-based and non-cloud based software systems. However, a primary benefit of the CLEER Model is that it allows for easy update of input values over time to reflect technological and behavioral change.

Conclusions

This report introduces the CLEER Model as the first open-access, fully transparent model for estimating the net energy use and emissions of data center services across all major societal end uses of energy. The case study results presented here suggest that a shift from present-day systems for business email, productivity, and CRM software to cloud-based systems could save substantial amounts of energy if fully implemented across the U.S. workforce. Potential energy savings could be as high as 326 PJ per year, which is enough primary energy to meet the annual electricity needs of Los Angeles, the nation's second largest city. Potential savings are especially pronounced for email and productivity software, which are used by a large number of employees and currently rely on servers that are widely dispersed in mostly smaller data centers where servers are underutilized. Uncertainties surrounding input data and ultimate market adoption preclude a precise estimate of the technical potential for energy savings associated with the adoption of cloud-based software in the United States. However, these energy savings are likely to be substantial on a national scale despite these uncertainties given that we understand the driving mechanism behind the energy savings well: namely, the shift from many inefficient local data centers to far fewer and more efficient cloud data centers.

The case study also demonstrated the function and value of the CLEER Model as a comprehensive and transparent resource for the research community. The analytical structure and data inputs have been made fully transparent, allowing users to evaluate the CLEER Model's underlying analytics, parameters, and assumptions. All of the input values associated with the case study presented here can be preloaded into the CLEER Model for review and improvement by other researchers, which can hopefully enable further scientific progress on understanding the net energy implications of cloud-based software services. The inclusion of sub-models for all important societal end uses of energy allow for application of the CLEER Model to more complex life cycle studies of cloud systems, such as digital versus physical media provision. Most importantly, the CLEER Model enables users to change any assumptions or input values to generate custom results that he or she finds most useful or credible for his or her particular analysis, and to account for technology and behavioral change over time.

Our hope is that, together, the CLEER Model and case study presented here can provide foundational resources from which other researchers and decision makers who seek to understand the net energy and emissions implications of cloud services can build more comprehensive and impactful analyses. We further hope that these resources can enable and encourage more research activity and interest, as well as demand and impetus for better public use data that can lead to more accurate and useful analyses.

Appendix: Case Study Approach and Assumptions

This appendix describes the case study approach with documentation of the data sources and assumptions associated with each input value in the CLEER Model. The input values presented here can also be preloaded into the CLEER Model for further analysis by selecting the appropriate application type (email, productivity, or CRM software) from the dropdown menu on the CLEER Model homepage. Further details on the mathematical framework of the CLEER Model can be found in the online technical documentation.

U.S. workers using email, productivity, and CRM software

We defined the population of U.S. workers using each software application by starting with employment data from the United States Census Bureau. Table A1 summarizes total U.S. employment in 2011 by industry and type of occupation.[36] We considered occupation the best proxy for computer use, given that the nature of one's job is typically more indicative of daily workplace tasks (including computer use) than one's industry of employment. For each occupation, we multiplied the total number of workers by the percent that uses computers at work. The percent of workers using computers for each occupation was estimated based on 2003 data from the U.S. Census Bureau on the computer tasks associated with each occupation (2003 is the latest year for which such data are available).[37] We extrapolated these 2003 data to the present day based on the historical growth in computer use among all U.S. workers (from 56% of workers in 2003 to 62% of workers in 2010).[38] Our results are shown at the bottom of Table A1. We estimated that there are 86.8 million computer-based workers in the United States as of 2011, with the largest numbers in management, business, science, arts, sales, and office occupations.

Next, we estimated the number of computer-based workers by firm size in Table A2. These estimates were made using U.S. Census Bureau data on employment by firm size for each industry listed in Table A1 along with the percentages of workers using computers by occupation for each industry.[39] Classification of computer-based workers by firm size is important because data center characteristics can vary greatly by firm size, as we discuss in subsequent sections. For example, small firms are more likely to host business applications in server closets and server rooms while large firms are more likely to host business applications in larger, more efficient mid-tier and enterprise-class data centers.[40]

We then estimated the number of computer-based workers who use email, productivity, and CRM software by firm size. Total users of email and productivity software were estimated based on the data in Table A3, which were derived by extrapolating 2003 data on the computer tasks of each occupation to the present day using the approach described above.[41] We further assumed that all present day computer-based workers use email. No publicly available data could be found on the extent of productivity software use in the U.S. workforce. Therefore, we used the percent of computer-based workers using word processing software as a proxy for the percent using productivity software. We estimated the number of present day users of CRM software in the U.S. workforce at roughly 8 million. This estimate was based on published data on the number of global licenses for CRM software from major vendors (Oracle, Salesforce.com, SAP, Microsoft Dynamics, and others) and the reported U.S. share of the global CRM software market (58%).[42,43,44,45] We assigned all CRM software use to the "sales and office" occupation category.

Table A4 summarizes our estimates for the number of computer-based U.S. workers using email, productivity, and CRM software by firm size based on the data in Tables A2 and A3.

Present day hosting of email, productivity, and CRM software

We define present day software applications as either server based or non-server based, where server-based software requires internet communications for full functionality and non-server based software does not. Email is an example of an inherently server-based software application. Productivity and CRM can be either server-based or non-server based applications, depending on the software arrangement. For example, CRM software can be non-server based in the form of database on one's local hard drive or it could be server-based in the form of a shared corporate database hosted on an enterprise server.

Table A5 summarizes our estimates of the percent of each application that is presently comprised of server-based software by firm size. No publicly-available data could be found on the penetrations of server-based applications for email, productivity software, and CRM software in U.S. firms. Therefore, we derived the estimates in Table A5 from data published for Europe in Thomond et al. (2011).[46]

Server-based software can either be hosted in cloud or non-cloud data centers. Table A6 summarizes our estimates of the percent of server-based software for each application that is presently hosted in cloud data centers, which were also based on estimates published for Europe in Thomond et al. (2011). Together, Tables A5 and A6 define the present day share of cloud-based software by application and firm size. For example, we estimate that 50% of firms with fewer than 100 employees use server-based CRM software and that 50% of this server-based CRM software is presently hosted in the cloud. Consequently, our estimates suggest that 25% of firms with fewer than 100 employees already use cloud-based CRM software. Conversely, the remaining 75% of these firms could technically still shift their CRM software to the cloud.

Table A1: Computer-based workers by occupation in the United States

	U.S. employment by occupation (thousands)					
Industry	Total	Management, business, science, and arts	Service	Sales and office	Natural resources, construction, and maintenance	Production, transportation, and material moving
Agriculture, forestry, fishing and hunting, and mining	2,720	879	98	163	1,317	261
Construction	8,564	1,387	60	540	6,183	385
Manufacturing	14,666	4,224	264	2,039	953	7,186
Wholesale trade	3,895	717	55	2,049	195	884
Retail trade	16,336	1,764	735	11,435	653	1,732
Transportation and warehousing, and utilities	6,988	992	182	1,761	664	3,382
Information	2,951	1,537	83	912	301	118
Finance and insurance, real estate and rental and leasing	9,234	4,146	379	4,368	203	139
Professional, scientific, management, administrative and waste management services	15,080	7,977	2,865	2,956	407	875
Educational services, and health care and social assistance	32,601	20,180	7,433	4,043	293	652
Arts, entertainment, recreation, accommodation and food services	13,210	2,246	8,666	1,731	145	410
Other services, except public administration	7,057	1,545	2,682	1,002	1,094	734
Public administration	7,099	2,925	2,229	1,455	305	185
Total workers	*140,400*	*50,520*	*25,729*	*34,451*	*12,714*	*16,942*
Percent of workers using computers		88%	31%	75%	29%	29%
Total workers using computers	*86,775*	*44,311*	*8,002*	*25,871*	*3,714*	*4,878*

Note: totals, column sums, and row sums might not be equal due to rounding

Table A2: Estimated computer-based workers by occupation and firm size

Occupation	Number of computer-based employees (thousands) by firm size			
	<100 employees	100-499 employees	500+ employees	*Total*
Management, business, science, and arts occupations	14,168	6,876	23,267	*44,311*
Service occupations	3,180	1,195	3,627	*8,002*
Sales and office occupations	8,367	3,178	14,326	*25,871*
Natural resources, construction, and maintenance occupations	1,942	556	1,215	*3,714*
Production, transportation, and material moving occupations	1,517	722	2,639	*4,878*
Total	*29,174*	*12,527*	*45,075*	*86,775*

Note: totals, column sums, and row sums might not be equal due to rounding

Table A3: Estimated percent of computer-based workers using software applications by occupation

Occupation	Percent of computer-based workers using software application		
	Word processing	Internet and email	Spreadsheets
Management, business, science, and arts occupations	77%	100%	71%
Service occupations	55%	100%	49%
Sales and office occupations	64%	100%	62%
Natural resources, construction, and maintenance occupations	51%	100%	53%
Production, transportation, and material moving occupations	41%	100%	50%

Number of computer-based workers (thousands) using application by firm size

Table A4: Estimated present day computer-based workers by software application and firm size

Software application	Number of computer-based workers (thousands) using application by firm size			
	<100 employees	100-499 employees	500+ employees	*Total*
Email	29,174	12,527	45,075	*86,775*
Productivity software	19,632	8,566	30,777	*58,974*
CRM software	2,579	980	4,416	*7,975*

Note: totals, column sums, and row sums might not be equal due to rounding

Table A5: Estimated server-based software use by firm size

Software application	Percent of application users using server-based software by firm size		
	<100 employees	100-499 employees	500+ employees
Email	100%	100%	100%
Productivity software	50%	90%	100%
CRM software	50%	75%	100%

Table A6: Estimated cloud-based software use by firm size

Software application	Percent of server-based software use that is presently hosted in the cloud by firm size		
	<100 employees	100-499 employees	500+ employees
Email	50%	33%	10%
Productivity software	50%	20%	10%
CRM software	80%	50%	10%

Present day data center characteristics

We define six different data center types for hosting server-based software: (1) server closets; (2) server rooms; (3) localized data centers; (4) mid-tier data centers; (5) enterprise-class data centers; and (6) cloud data centers. The first five data center types align with established definitions from market research firm International Data Corporation (IDC), which are based on data center floor space and equipment characteristics. Further details on these space type definitions can be found in Masanet et al. (2011) or Brown et al. (2007).[47,48] We define the cloud data center type as large, multi-customer facilities with highly virtualized servers, scalable computing, and onsite hosted software.

Clearly, all server-based software requires servers. Our estimates for how the servers presently hosting non-cloud software are distributed across different data center types are summarized in Table A7. The estimates in Table A7 were derived based on information in Bailey et al. (2006) and Hardcastle (2012) describing the distributions of servers across U.S. data center types and the data center types used by different sized U.S. firms.[49,50]

Table A7: Estimated distribution of non-cloud servers by data center type and firm size

Data center type	Percent of non-cloud servers located in each data center type by firm size		
	<100 employees	100-499 employees	500+ employees
Server closet	35%	4%	2%
Server room	45%	9%	4%
Localized	10%	38%	8%
Mid-tier		21%	23%
Enterprise-class	10%	27%	63%

Based on the data in Tables A4 through A7, we derived the estimates presented in Table A8. The data in Table A8 summarize the number of users of each application by software type (non-server based or server-based) and data center type (for server-based software). These data represent our best estimates of how server-based email, productivity, and CRM software is presently hosted for U.S. computer-based workers using publicly available information.

Table A8: Estimated number of users by application, software type, and data center type

	Number of application users (thousands)							
		Server-based software by data center type						
Software application	Non server-based software	Server closet	Server room	Localized DC	Mid-tier DC	Enterprise-class	Cloud	Total
Email		6,283	9,052	7,968	11,011	29,233	23,228	*86,775*
Productivity software	10,672	2,541	3,948	5,103	7,608	19,575	9,527	*58,974*
CRM software	1,535	185	317	489	985	2,623	1,841	*7,975*

Note: totals and row sums might not be equal due to rounding

The number of servers required in each data center type to host the users in Table A8 is a function of firm size and data center technology characteristics. We assumed that for each firm with fewer than 500 employees, there will be dedicated servers for email, productivity software, and CRM software in server closets, server rooms, localized data centers, and mid-tier data centers. This assumption reflects a non-virtualized, traditional dedicated server arrangement for small firms. Therefore, the average number of users per installed server for a small firm is equal to the number of employees for that firm. The data in Table A9 reflect this assumption, wherein data on average employees per firm for each firm size category were obtained from the U.S. Census Bureau.[51] We further assumed in Table A9 that firms with greater than 500 employees and enterprise-class data centers would host 1,000 users per server (reflecting high server utilization), and that cloud data centers would host 2,000 users per server (reflecting high server utilization and virtualization).[52,53,54]

Table A10 summarizes our estimates for server redundancy by data center type, which reflect traditional redundancy strategies in smaller data center types (server closets, server rooms, and localized data centers) where dedicated servers are common.[55] Table A11 presents our estimates for the average number of application users per installed server by application type and data center type, which were based on the data in Tables A4 through A7, A9, and A10. It can be clearly seen that the redundancy has a large effect on the ratio of application users to installed servers. Our estimated application users per installed server are particularly low for server closets and server rooms after redundancy is considered. These results can be explained by the predominance of users from small firms we attributed to server closets and server rooms (see Tables A4 and A7), our conservative assumption that each small firm will have dedicated servers (see Table A9), and our server redundancy assumptions for closets and rooms (see Table A10). These assumptions should be revisited in future studies if better data on server closets and rooms, and their redundancy practices, become available in the public domain.

Table A9: Estimated number of application users per installed server by firm size and data center type

Data center size	Average users hosted per server by firm size <100 employees	 100-499 employees	 500+ employees
Server closet	7	164	1,000
Server room	7	164	1,000
Localized DC	7	164	1,000
Mid-tier DC	-	164	1,000
Enterprise-class	1,000	1,000	1,000
Cloud	2,000	2,000	2,000

Table A10: Estimated server redundancy by data center type

Data center type	Redundancy
Server closet	N+0.5N
Server room	N+1
Localized DC	N+1
Mid-tier DC	N+0.2N
Enterprise-class	N+0.1N
Cloud	N+0.1N

Table A11: Estimated average number of application users per installed server, before and after redundancy

	Average application users per installed server by data center type					
Software application	Server closet	Server room	Localized DC	Mid-tier DC	Enterprise-class	Cloud
Email	8 [6]	9 [5]	34 [17]	555 [462]	1,000 [909]	2,000 [1,818]
Productivity software	10 [7]	12 [6]	58 [29]	540 [450]	1,000 [909]	2,000 [1,818]
CRM software	14 [9]	19 [9]	100 [50]	718 [598]	1,000 [909]	2,000 [1,818]

Note: numbers in brackets represent average application user per installed server after considering redundancy

Table A12 summarizes our estimates for the number of servers presently installed for hosting U.S. users of each software application by data center type. As a conservative approach, we used the post-redundancy values in Table A11 to estimate the number of installed servers presently supporting the user population for each application and data center type. We estimate the vast majority of present day servers to be found in non-cloud data centers, with particularly high concentrations in the smallest of data center types. The data in Table A12 were derived by dividing the estimated users per application in Table A8 by the estimated users per installed server in Table A11 for each data center type and rounding to the nearest increment of 100.

Table A12: Estimated installed servers for each software application by data center type

Software application	Total servers by data center type Server closet	Server room	Localized DC	Mid-tier DC	Enterprise-class	Cloud
Email	1,111,000	1,910,000	467,300	23,800	32,160	12,800
Productivity software	376,000	647,500	175,000	16,900	21,500	5,200
CRM software	19,800	34,300	9,800	1,600	2,900	1,000

Table A13 summarizes our estimates for the number of external hard disk drives (HDDs) required per server in each data center type. We first assumed an annual transfer of 3.6 Gigabytes (GB) per user of each application based on data from Cisco Systems on annual data traffic for web browsing, email, instant messages, and other applications.[56] We estimated the percent of data traffic related to email based on our own bottom-up estimate of the average size and frequency of emails sent per day. No similar data could be found in the public domain on the annual data transfers associated with server-based productivity or CRM software; hence, we assumed 3.6 GB/year per user for each application as a conservative assumption. Next, we assumed a 1 Terabyte (TB) storage capacity for each external HDD spindle.   Finally, we estimated the number of external HDD spindles that would be required to store the annual data transferred by all users of each software application (see Table A8) with an average HDD capacity utilization of 40%.[57] Note that we assume no external storage for server closets and rooms. This assumption was based on the estimated low numbers of users per server for these data center types (see Table A11) and our data center type definitions.[58]

Table A13: Estimated external HDD spindles per server by data center type

Data center type	External 1 TB HDD spindles per server
Server closet	-
Server room	-
Localized DC	0.7
Mid-tier DC	2.3
Enterprise-class	4.5
Cloud	9

Client device characteristics

We characterize business client devices (i.e., the user electronics that access software applications) by device type and data access mode. Table A14 summarizes our estimates for the percentages of present day application use that are attributable to four different client devices: desktop personal computers (PCs), notebook PCs, smart phones, and tablet computers. The estimates in Table A14 were derived based on workplace technology survey data from Forrester and Forbes, which characterized the frequency of business use of each device as well as the frequency of use of each device for each software application.[59,60] The workplace technology data were further calibrated against published data on the total installed base of each device.[61] We assumed that the use of other client devices such as netbooks or non-internet enabled mobile phones would be negligible. The data in Table A15 were derived by assuming one business client device per user of each software application (see Table A8). This assumption neglects the possibility of multiple client devices per user that might access each software application simultaneously; we make the simplifying assumption that only one client device per user will access each software application at any given moment. Hence, the device numbers in Table A15 should provide credible but conservative estimates of the total client device energy use per year for each software application. We assumed that all desktop PCs would be accompanied by a flat panel display.

Table A14: Estimated percent of software application use by business client devices

	Percent of application use by client device			
Software application	Desktop PC	Notebook PC	Smart phone	Tablet
Email	41%	38%	16%	5%
Productivity software	45%	41%	11%	2%
CRM software	31%	29%	31%	9%

Table A15: Estimated number of business client devices in use for each application

	Number of client devices (thousands)				
Software application	Desktop PC	Notebook PC	Flat panel display	Smart phone	Tablet
Email	35,714	32,762	35,714	13,774	4,526
Productivity software	26,651	24,449	26,651	6,608	1,266
CRM software	2,497	2,290	2,497	2,467	712

Our estimates for how business clients presently access server-based software applications are summarized in Table A16. We made the simplifying assumption that all desktop PCs would use a wired internet connection (e.g., fiber to building). We assumed that 30% of server-based software data accessed by notebook PCs would be via Wi-Fi connections, based on survey data from Forrester on the mobile work habits of workers in information-related occupations.[62] Lastly, we assumed that mobile devices (smartphones and tablet PCs) would rely on Wi-Fi and cellular data access networks for 33% and 67% of all server-based software use, respectively, based on a recent study of the wireless cloud by Bell Labs and the University of Melbourne.[63]

Table A16: Estimated data access modes for each business client device

	Percent of data accessed by access mode		
Client device	Wired	Wi-Fi	Cellular
Desktop PC	100%		
Notebook PC	70%	30%	
Smart phone		33%	67%
Tablet		33%	67%

Data center, network, and client device energy use

We calculated annual data center energy use based on power use data for each data center IT device and values of power utilization effectiveness (PUE) for each data center type from published research reports and papers.[64,65,66] To estimate the annual energy use of transmitting software application data over network systems between the data centers and business client devices, we used conservative values derived from multiple sources in the literature along with expert elicitation.[67,68,69,70,71,72] Our estimated values for data center device power, PUE, and network system energy use are summarized in Tables A17 and A18. The network energy values in Table A17 include cumulative terrestrial and submarine transport, core, metro, and access network energy use (the last of which includes customer premises equipment and base stations).

Table A17: Estimated power/energy use of data center IT devices and network data transmission

	Data center IT device power (watts)			Data transmission (micro Joules per bit)	
	Volume server	Midrange server	External HDD	Wired/Wi-Fi	Cellular
Average power/energy use	235	450	26	100	450

Table A18: Estimated PUE by data center type

Data center type	Average PUE
Server closet	2.5
Server room	2.1
Localized DC	2
Mid-tier DC	2
Enterprise-class	1.5
Cloud	1.1

Table A19 summarizes our estimates for the power use and operating hours associated with business client devices. Power use data for desktop PCs, notebook PCs, and flat panel displays in each mode were obtained from the U.S. Department of Energy's 2011 Building Energy Data Book.[73] Power use data for mobile devices were derived from published values in the literature.[74,75] Operating hours in each mode for desktop PCs, notebook PCs, and flat panel displays were based on commercial PC use data in Masanet and Horvath (2006).[76] Operating hours in "on" mode for mobile devices were based on device usage data in Teehan (2013). No publicly available data could be found on the time spent by smart phones and tablets in "sleep" and "off" modes. Thus, the data in Table A19 for represent our best estimates based on personal observation.

Table A19: Estimated use patterns and power use for business client devices

	Client device power (watts)				
Mode	Desktop PC	Notebook PC	Flat panel display	Smart phone	Tablet computer
ON	75	25	42	3	5
SLEEP/IDLE	4	2	1	3	5
OFF	2	2	1	-	-
	Annual hours of use (hours/yr)				
Mode	Desktop PC	Notebook PC	Flat panel display	Smart phone	Tablet computer
ON	988	988	988	720	540
SLEEP/IDLE	3,172	3,172	3,172	4,020	-
OFF	4,600	4,600	4,600	4,020	8,220

We further estimated the percentages of "on" mode time that are dedicated to each software application for each device, which are summarized in Table A20. We allocated proportions of "sleep/idle" and "off" mode energy use to each software application and device based on these "on" mode use percentages. We assumed that 28% of "on" time is dedicated to email use for desktop and notebook PCs based on recent workplace survey data from the McKinsey Global Institute and that 10% of "on" time is dedicated to email use for smart phones and tablet PCs based on market research data in Teehan (2013).[77,78] For users of CRM software, we estimated 20% "on" time for desktop and notebook PCs based on data from the McKinsey Global Institute that suggest 39% of workplace time is spent on "role specific tasks;" we attribute half that time (~20%) to productivity and CRM software use in the absence of more precise data. We further estimated 20% "on" time for smart phones and tablets dedicated to CRM software based on data from Forrester, which suggest that users of that software might be equally likely to use mobile devices.[79] Lastly, we estimated 10% "on" time for mobile devices using productivity software based on the same Forrester data, which suggest that workers are more likely to use traditional desktop and notebook PCs than mobile devices for productivity software.

Table A20: Estimated percent of client device "on" time dedicated to software applications

	Percent of device "on" time dedicated to application				
Software application	Desktop PC	Notebook PC	Flat panel display	Smart phone	Tablet
Email	28%	28%	28%	10%	10%
Productivity software	20%	20%	20%	10%	10%
CRM software	20%	20%	20%	20%	20%

Embodied energy and emissions

The CLEER Model allows for consideration of the embodied energy and emissions associated with data center building materials, data center IT devices, network system equipment, client devices, and other physical goods that might comprise a societal service system (e.g., DVD manufacturing for consideration of physical versus streaming video provision). Our definition of embodied energy and emissions includes the energy and emissions associated with material or device manufacturing and end of life treatment (i.e., landfill disposal or recycling).

Tables A21 and A22 summarize our assumptions for the embodied energy and emissions associated with data center building materials. The data in Table A21 characterize the materials intensity (kilograms of material per square meter of data center floor space) of common data center building materials based on a Microsoft data center, typical values of embodied energy and emissions from the literature, and U.S. average recycling rates.[80,81,82,83] Table A22 summarizes our factors for allocating the embodied energy use and emissions of data center building materials to data center IT devices based on the estimated floor space occupied by each device.

Table A21: Estimated embodied energy and emissions of data center building materials

Material	Materials intensity (kg/m^2)	Embodied energy (MJ/kg)	Embodied CO_2 (kg CO_2e/kg)	% recycled
Structural steel	52	24	1.8	85%
Concrete	730	1	0.13	57%
Extruded polystyrene insulation	1	86	2.7	57%
Steel electrical conduit	21	24	1.8	85%
Copper	37	48	2.9	85%
Steel cooling pipes	10	24	1.8	85%

Table A22: Estimated floor space requirements of typical data center IT devices

Data center IT device	Floor space (m^2/device)
Volume servers	0.05
Midrange servers	0.2
External HDD	0.01
Network devices	0.1

Table A23 summarizes our assumptions for the embodied energy and emissions associated with data center IT devices and business client devices. The embodied energy and emissions values were based on best available data from the literature.[84,85,86,87] We assumed a high recycling rate for data center IT devices based on the expectation that most data center operators would have established recycling and stewardship practices in place for end of life equipment. We assumed lower recycling rates for U.S. business client devices based on recent national e-waste recycling data for personal computer equipment from the United States Environmental Protection Agency.[88]

Table A23: Estimated embodied energy and emissions of IT devices

Device	Primary energy (MJ/device)			CO_2 emissions (kg CO_2e/device)			% recycled
	Manufacturing	Landfill	Recycling	Manufacturing	Landfill	Recycling	
Volume server	9,350	10	-440	570	1	-30	90%
Midrange server	37,390	41	-1,760	2,280	4	-120	90%
External HDD	380	0.1	-18	23	1	-2	90%
Desktop PC	2,260	7.2	-191	138	0.6	-13	40%
Notebook PC	1,270	2.3	-112	81	0.2	-8	40%
Flat panel display	990	4.1	-118	55	0.3	-8	33%
Smart phone	230	0.2	-17	28	0.03	-2	11%
Tablet computer	1,880	0.4	-167	121	0.01	1	11%

Comprehensive and consistent data on the numbers and types of devices that comprise the data transmission infrastructure could not be found in the public domain. Thus, we expressed our embodied energy and emissions data for network systems as ratios of embodied energy to operational energy and embodied emissions to operational energy, respectively. These simplifications were made in light of the very few data that exist in the public domain on the manufacturing energy use and emissions of network devices, and the fact that only simple ratios could be extracted from the existing literature sources. In our case study, we assumed 2.4 joules of embodied primary energy per joule of network operational energy and 0.2 kg of embodied carbon dioxide equivalents per joule of network operational energy, where network operational energy was calculated using the data in Table A17.[89,90,91]

Shifting from present day systems to the cloud

The data in Tables A1 through A23 summarize our key data sources and assumptions for estimating the present day energy use and CO_2 emissions associated with the use of email, productivity, and CRM software in the U.S workforce. To estimate how present day energy use and CO_2 emissions might change by shifting these three software applications to the cloud, we used the following approach:

a) We used the U.S. national average grid mix to convert all direct electricity use results to primary energy (13.8 MJ/kWh) and CO_2 emissions (0.6 kg CO2/kWh)
b) We calculated the required number of cloud data center servers for hosting all uses in the cloud by dividing the total U.S. users of each software application (see Table A8) by the post-redundancy average users per server in cloud data centers (see Table A11)
c) We assumed a 5% increase in network data traffic when shifting all software applications to the cloud to account for the possibility increased data traffic through remote software access[92]
d) We assumed all cloud data centers would have a PUE of 1.1 (see Table A18)
e) We assumed no change in the types of client devices or their usage patterns

Table A24 summarizes our resulting estimates for the required number of cloud servers and external HDDs for hosting email, productivity, and CRM software for the U.S. workforce. Compared to the present day, the server count for cloud-hosted software is substantially lower due to the much higher user per server capabilities of cloud-based servers. However, the number of external HDD spindles is expected to decrease less drastically with a shift to the cloud due to the greater external storage capacity associated with cloud data centers.

Table A24: Number of data center IT devices: present day compared to cloud-based software

	Number of data center IT devices				
	Present day software			Cloud-based software	
Software application	Volume server	Midrange servers	External HDDs	Midrange servers	External HDDs
Email	3,543,000	12,780	641,000	47,700	429,500
Productivity software	1,237,000	5,240	306,000	32,400	291,900
CRM software	68,500	1,010	32,800	4,390	39,500

Our results are summarized in Table A25. More detailed results can be viewed by preloading and running the cases study assumptions for email, productivity software, and CRM software in the CLEER Model.

It is critical to note that the results in Table A25 represent our estimated *technical potential* for energy use and emissions savings associated with shifting from present day systems to cloud-based systems for software provision. Estimates of technical potential provide illustrative upper bounds on potential savings but do not take into account economic, infrastructure, temporal, institutional, or policy barriers that might limit the savings that can be achieved in real-world systems.[93] Thus, the results in Table A25 should be interpreted as illustrative of the energy and emissions savings that could be realized under maximum adoption of cloud-based solutions for these three software applications.

Table A25: Comparison of energy use and emissions, present day versus cloud-based software systems

	Primary energy (TJ/yr)			CO_2 emissions (kt CO_2e/yr)		
Email	Present day	Maximum cloud adoption	% change	Present day	Maximum cloud adoption	% change
Client IT device operation	16,060	16,060	0%	790	790	0%
Client IT devices (embodied)	6,450	6,450	0%	400	400	0%
Data transmission system operation	1,520	1,600	5%	75	80	5%
Data transmission system devices (embodied)	280	300	5%	25	30	5%
Data center operation	235,200	3,900	-98%	11,540	190	-98%
Data center IT devices (embodied)	8,150	420	-95%	500	30	-95%
Data center building materials (embodied)	5	1<	-94%	1<	1<	-94%
Subtotal	267,670	28,770	-89%	13,320	1,500	-89%
Productivity software						
Client IT device operation	8,560	8,560	0%	420	420	0%
Client IT devices (embodied)	3,370	3,379	0%	200	200	0%
Data transmission system operation	750	790	5%	40	40	5%
Data transmission system devices (embodied)	140	150	5%	10	10	5%
Data center operation	82,300	2,680	-97%	4,050	130	-97%
Data center IT devices (embodied)	2,860	290	-90%	170	20	-90%
Data center building materials (embodied)	2	1<	-88%	1<	1<	-88%
Subtotal	98,000	15,820	-84%	4,900	830	-84%
CRM software						
Client IT device operation	930	930	0%	50	50	0%
Client IT devices (embodied)	1,130	1,130	0%	90	90	0%
Data transmission system operation	150	160	5%	7	8	5%
Data transmission system devices (embodied)	30	30	5%	2	3	5%
Data center operation	4,890	360	-93%	240	20	-93%
Data center IT devices (embodied)	170	40	-78%	10	2	-78%
Data center building materials (embodied)	1<	1<	-73%	1<	1<	-73%
Subtotal	7,300	2,650	-64%	390	160	-64%
Total	372,970	47,240	-87%	18,610	2,490	-87%

Note: totals and column sums might not be equal due to rounding; % change might not be equal to changes in row values due to rounding.

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