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Impact of Office Productivity Cloud Computing on Energy Consumption and Greenhouse Gas Emissions

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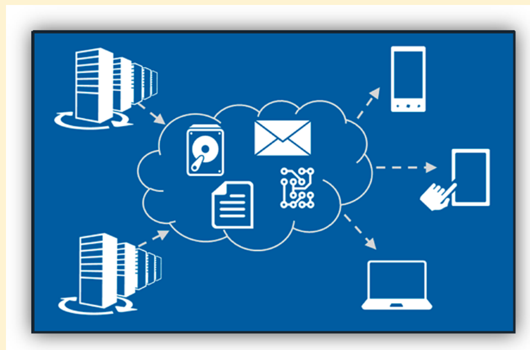
Supporting Information



ABSTRACT: Cloud computing is usually regarded as being energy efficient and thus emitting less greenhouse gases (GHG) than traditional forms of computing. When the energy consumption of Microsoft's cloud computing Office 365 (O365) and traditional Office 2010 (O2010) software suites were tested and modeled, some cloud services were found to consume more energy than the traditional form. The developed model in this research took into consideration the energy consumption at the three main stages of data transmission; data center, network, and end user device. Comparable products from each suite were selected and activities were defined for each product to represent a different computing type. Microsoft provided highly confidential data for the data center stage, while the networking and user device stages were measured directly. A new measurement and software apportionment approach was defined and utilized allowing the power consumption of cloud services to be directly measured for the user device stage. Results indicated that cloud computing is more energy efficient for Excel and Outlook which consumed less energy and emitted less GHG than the standalone counterpart. The power consumption of the cloud based Outlook (8%) and Excel (17%) was lower than their traditional counterparts. However, the power consumption of the cloud version of Word was 17% higher than its traditional equivalent. A third mixed access method was also measured for Word which emitted 5% more GHG than the traditional version. It is evident that cloud computing may not provide a unified way forward to reduce energy consumption and GHG. Direct conversion from the standalone package into the cloud provision platform can now consider energy and GHG emissions at the software development and cloud service design stage using the methods described in this research.

1. INTRODUCTION

Cloud computing is increasingly being utilized by consumers and organizations.[1] High energy efficiency is expected and can be achieved as it redistributes software processing and storage to efficient and centralized locations.[2−4] Cloud computing enables the delivery of software services such as processing and storage to a user from a centralized location. As a consequence, processing and thus energy load is shifted to often more efficient hardware compared to traditional distributed computing. In some cases, the requirement of a consumer maintained server infrastructure is removed altogether.

The data center stage of cloud computing's data model is often the focus of the efficiencies realized by cloud computing. There are many established methods and techniques used to achieve this.[2] Commercial studies[5,6] have focused upon the once only activity of reducing server numbers when moving established computing to cloud computing, estimating it could reduce GHG emissions by 90%. The energy consumption of increased networking activity when using cloud computing and the energy consumption of user devices were, however, not included within these studies.

Recent studies based on estimated data suggested simple office tasks completed with cloud computing have the potential to be more energy efficient.[3] Several studies[2−4] indicated that efficiency is highly dependent upon the type of cloud service and the usage pattern. The fact that the energy consumption of several cloud services have been modeled[3] highlighted the important role that the user device has on total service energy consumption; however, only theoretical values were modeled in this study.

Currently, the energy consumption and GHG impact of cloud computing is not often measured or understood. This lack of understanding emerges especially when analyzing the full data route of cloud services which includes the energy consumption of the data center, networking, and end user devices. Office 365 (O365) is a cloud companion to Office 2010 (O2010) which is the most popular office productivity suite used today. O365 and other cloud office productivity suites are likely to become commonly used and lead to a higher volume of cloud services in the near future. Hence, it is important to identify and assess the energy consumption of

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Table 1. Summary of the Activities Performed and Measured

product	activity	summary
Word	writing and editing a word document	manual retyping of a pre written segment of text (2,913 characters) over a 30 min period, including the creation of one table, inserting one JPG picture (886 KB) and formatting operations, final doc size = 243 KB
Excel	performing a CPU intensive calculation	measurement only during the calculation of 300 000 cells with a complex equation
Outlook	receiving, reading, writing and sending an email	using a live, large size mailbox (1.6GB) to receive a test email sent from a different account, manual retyping of a pre written segment of text (963 characters) and insertion of a JPG picture (886 KB) into an email, including formatting operations

these services over the full data route of services. Considering that the ICT sector has been estimated to emit 2−3%[7] of total worldwide GHG emissions, this analysis can potentially serve to ensure that the ICT sector continues to implement energy efficient software services and reduce overall energy consumption and GHG emissions.

The aim of this research is to assess the impact that running cloud computing applications with O365 has on energy consumption and related GHG emissions. The purpose of this deep analysis is to begin the overall impact assessment of cloud computing. In order to achieve this, a model will be created to assess the energy consumption and GHG emissions of running cloud and traditional computing applications focusing upon O365 and O2010. Energy consumption will be converted into carbon dioxide equivalent (CO_2e) to represent the GHG emissions.

2. METHODS

In order to measure the total cloud service energy consumption, data was collected at three logical stages of a cloud service's data route; the data center (Section 2.2), network transfer (Section 2.3), and the end user device (Section 2.4). Where possible data was collected based upon a defined and controllable scope of activities (Section 2.1). Measurements were made for the running of the application across each stage including any idle time that occurred during the specified activity. Outside of the activity scope, the time that any stage could be idle or underutilized was not included because of the potential high variability in utilization from other activities. For the first two stages, the data modeling and calculations followed the method developed by Williams and Tang.[8] This method was developed for the distribution of software which has the same basic data route as cloud computing; however, the methods were modified and further detailed to a cloud scenario. For the user device stage, a customized extension cable was built to allow the direct measurement of voltage and current to be taken while undertaking predetermined activities on the device. The same activities were carried out for both O365 and O2010 versions of selected comparable products. The conditions of each activity were detailed and three repeat measurements were performed.

2.1. Scope. To represent a variety of computing types this analysis examined the Microsoft Word, Excel, and Outlook products which are included in both O365 and O2010 suites. Word was selected to represent a low overall computing resource requirement with high user input and interaction time. Excel was chosen to represent high data processing with low user interaction. Outlook represented software that relies upon an external server which requires constant uptime and access to retrieve emails. Outlook O2010 uses external servers for its service (Microsoft Exchange 2010), which also has a cloud based equivalent.

O2010 Professional Plus was installed on the relevant devices (Supporting Information Table S1) and was accessed using the Microsoft Windows 7 operating system (OS). A fully functional O365 test account was setup so that the online products could be accessed using Internet Explorer 9 (IE9). Microsoft Outlook 2010 can interface with either a hosted or user owned server running Microsoft Exchange. Therefore, for Outlook in O2010 an extra stage was added to include analysis of a dedicated Microsoft Exchange server.

For the testing of Word, a commonly used third "mixed" access mode was also tested. This method involves using O365 to store and manage the document while using O2010 to edit the document. The process is fully automated and selectable by the user at the point of opening the document. This method was tested in Word only; although, this feature is available in Excel the Excel testing was focused on data processing location only.

Measurements and setup of the operational server devices, which host the cloud based applications and the exchange server for O2010, were not controllable. Therefore, we utilized highly confidential server measurement data from Microsoft. Although not controllable by this research team, data was primarily collected by Microsoft's data center team using server rack based power meters. Within the data we were able to segment the servers used for Office 365. The identified servers were also utilized by other cloud services; therefore, a new method was created to apportion Office 365 from the other services.

For each of the products analyzed the end user device power consumption was measured while performing the activities listed in Table 1. The activities selected were chosen to best represent the computing types required for each product (explained above). Each activity was specified with sub activities, timings, and actions to be completed (full details are available from the authors). For Word and Outlook this involved starting and closing the program. For Excel, only the data processing activity was measured as this was the scoped focus. For each test device the software thread, process, and network activity statistics were recorded. This collection allowed an in-depth view of what was running during testing and enabled full analysis on any abnormal results.

2.2. Data Center. The developed model quantified the data center energy consumption of using the O365 and O2010 Outlook products during a user session. The user session is the instance that is created on the data center server in order to fulfill the user's activity request, therefore many sessions could be running at once. O365 data processing is carried out in Microsoft's data centers across the world depending upon user location and network conditions. The server that hosts Microsoft Exchange 2010 for Outlook O2010 is also located in Microsoft's data centers (this was only the case because Microsoft was the company being analyzed). Highly confidential nonpublishable server, disk storage, and product use data was obtained for each O365 and Outlook O2010 device.

The aim of this stage was to apportion the data center server and storage device energy consumption to a single O365 and Exchange 2010 session. The result of this stage was a single device energy consumption per session (Wh). This was calculated using eq 1, a modified version of eq 1, in Williams and Tang.[8]

$$\text{energy consumption per session} = SP \times S \times PUE \times t \times A_p \quad (1)$$

Here, SP is the average device power consumption (W), S is the relative size of the user session (%), PUE is the power usage effectiveness of the data center, and t is the time of each session (hour) (The following paragraphs explain these in more detail). A_p is an adjustment metric (%) for each O365 program. This adjustment was used to reflect that O365 application sessions were found to be smaller on average than other non O365 cloud sessions that are on the same server.

Direct measurement of the operational server was not possible; therefore, in order to determine the average server power consumption of an O365 related server, this research had rare access to power consumption measurement data on more than 2000 servers. Each server rack is monitored for power consumption and other server statistics that are reported every minute to a searchable database. Importantly, direct access to this data removed a level of complexity and estimation seen in previous studies. Previous research[8] has calculated server equipment power consumption using utilization rates of each server against the name plate power consumption because of a lack of measurement data. Each of the servers analyzed had marginally different power consumption due to user load variations and, in some cases, hardware variations. The average power consumption of all active O365 servers in the relevant data center was calculated and used in order to overcome these variations.

Each O365 session runs within one user session that is started on the server when the user logs onto their service; therefore, this is the start point at which the user service and thus the scope of this test occurs. We could not obtain data on the relative size of the specific session started for each of this research's test activities. Therefore, the average size (%) of a single O365 session was determined by obtaining the measured average number of total user sessions per server used by O365. This number was calculated from a year's worth of measurement data on all O365 related servers and was determined using software tools such as process monitor for Microsoft OS. Additionally, as the cloud services are relatively new, the measured number is likely to be a conservative estimate. We were unable to separate out O365 sessions and therefore the session size (%) value was adjusted for each product as each server contained other non-O365 Microsoft cloud services that were larger on average in terms of system resource (CPU, memory, etc.) than the O365 products. Average sessions sizes were reduced by 50% for the mixed access method in Word O2010 and O365 and by 30%, 10%, and 0% for Word, Excel, and Outlook in O365, respectively. Outlook O365 servers only hosted outlook mailboxes and thus were not adjusted. This method had a consequence of allocating the virtual servers management software to each of the sessions. This was acceptable as the management software is a vital part of each session's operation. Although this method estimates the size of each O365 product and is not directly measured, we believe that this best represents a realistic and conservative view of the power consumption of a user session when faced with no access to operational servers. A sensitivity analysis on this variable is performed in Section 4 of this paper.

Lastly, the PUE[9] was included to account for the extra cooling and maintenance power consumption used for each server. The relevant data center PUE was recorded against each O365 server.

The time of each session was set to 60 min. This was the time used for all testing and allowed an appropriate comparison between the user device and network calculations.

2.3. Network Transfer. The energy consumed by networking equipment for the transmission of data between the user device and server was accounted. The methodology employed for this stage[8] required data on the average number of hops taken to the O365 data center along with the total size of data transmitted per activity. O365 data center locations were known and the average number of hops taken from Reading, United Kingdom to the relevant data centers was estimated using Microsoft Windows trace route software (13 hops). For each activity performed, packet recording software (Microsoft Process Monitor) was used to capture the data sent and received through the network. This information was analyzed and any data items attributed to the use of O365 were summed by identifying the correct IP addresses used. Each activity was performed three times with the results being averaged.

2.4. User Device. The energy consumption of a device used to access either the O2010 or O365 products was measured during each activity. The aim of this stage was to determine the device's power consumption according to the activity being undertaken. Recent advancements in power management technologies have created devices that can vary power consumption according to the activity being undertaken.[10] A further segmentation between the software product and OS energy consumption was calculated in order to provide an approximate estimate of cloud computing as a proportion of a device's power consumption. Within the final results, total device power was reported. This approximation could also be used to estimate the impact of each software application on other devices which commonly have a large degree of overall power consumption variance (i.e., a large desktop PC).

The devices measured were chosen from a list of high quality devices available to the research team. A Lenovo U260 Laptop and Acer Iconia W500 Tablet device (Supporting Information Table S1) were analyzed as previous research[3] indicated that low power devices are best suited to cloud services and will be more common in the future.

In order to measure the power consumption of the devices a PC Oscilloscope was utilized (PicoScope 2202). The oscilloscope features a millisecond recording ability and logging frequency. Recording frequency is important when analyzing laptops and tablets as high frequency components are often used due to the miniaturization of some components.[11] Before testing the laptop and tablet device, any batteries were removed to exclude charging overhead. Using a custom-made extension (SI Figure S1) the Oscilloscope was used to measure the power consumption of the laptop and tablet. A multidevice power adapter was modified with a custom-made extension so that the voltage and current could be measured concurrently. The extension featured a 0.01 Ω sense resistor placed on the negative wire. This enabled current to be measured using a standard oscilloscope voltage probe using ohm's law. This method did exclude the overhead energy consumption of the power pack adapter for each device and so, user device power consumption results are likely to be slightly lower than true energy consumption.

Voltage and current measurements were recorded every 10 ms (ms) or at 100 Hz over the course of each activity test. This recording frequency was considered acceptable after a number of initial tests completed with a 1 GHz oscilloscope did not report a significant difference in total energy consumption. For each measurement taken the power consumption (watts) was subsequently calculated. All activity related power measurements were summed and multiplied by the recording frequency (10 ms) to calculate the total energy consumed (Joules) which was then converted into a 60 min watt-hour (Wh) equivalent value.

In order to apportion the recorded energy consumption to the OS and the product, a method from the greenhouse gas protocol[12] was utilized. This method specifies the conditions and device configuration to measure software energy consumption. The devices were measured in an idle and active (activity) mode with the difference being attributed to the product (eq 2). During measurement a focus was placed upon ensuring that no other software interfered with the device while measuring idle or active modes. Following expert guidance[13] each device was wiped of any data and reinstalled with the OS, device drivers, updates, O2010 (where relevant), and IE9. Each device was left on for at least 24 h to ensure that any initial OS setup activities were completed. Furthermore, any waiting tasks and background tasks were disabled during tests. Each device was turned on for at least 30 min before testing to allow for internal temperature adjustment. The room temperature was taken during each measurement and was kept within a ± 2 °C variance. Power management settings that would put the device into a sleep, low power or standby state were disabled. However, power management was not fully disabled to allow specific hardware settings that manage individual components to run (e.g., Bluetooth or CPU scaling).

$$\text{product power} = \text{device power}_{\text{active}} - \text{device power}_{\text{idle}} \quad (2)$$

In an effort to understand the exact occurrences of each test and to account for any anomalies, each power measurement required a correlated device process, thread, and network activity recording. To accomplish this, the Microsoft "Process Monitor" software was setup to record the required statistics per activity. This software had the added benefit of removing its own impact which was minor. To ensure that power consumption and process monitoring results could be correlated, the date and time were synchronized on the PC recording power consumption and the device under test. The inbuilt Internet Time server synchronization feature of Windows 7 was utilized to achieve synchronization.

Idle state power consumption of the device was measured after the initial setup steps. Idle mode included activating network connections (using Wi-Fi) for all devices, but not prompting any user network activity. The power consumption in idle state was measured over a period of 45 min for each device, three times and averaged. Each measurement was analyzed and correlated to identify any anonymous measurements. Where low correlations were found the measurements were retaken.

The power consumption of performing each of the specified activities (Table 1) was measured. Each activity was performed three times and averaged. The result of each measurement was analyzed and correlated to the "process monitor" recordings to identify any anonymous measurements. The Wi-Fi connection of each device was utilized in the case of O365 testing to provide a fair comparison.

Tests were not repeatable to exact timing due to human input and different processes and timings occurring on the device. Thus, each of the three repeats performed for every activity were not expected to correlate perfectly. This, however, provided a realistic measurement for each activity. The use of testing software was considered, however the human element was considered essential to these tests and the impact of the testing software may have interfered with test results. The average of the three repeats was used to report results and the percentage error was calculated. Calculating the error allowed a view of how accurate our repeats were, if the error was large then the tests were analyzed for issues and repeated until the error was minimized.

2.5. Electricity Emission Factors. In order to relate each section's calculated energy (Wh) to CO_2e (g), a country specific CO_2e electricity emission factors (including generation and distribution losses) based upon a unit (kWh) of consumed electricity was sourced. Emission factors vary by country due to the power generation plants used, losses, and fuel type meaning that for each stage of the model the geographical location influenced the level of CO_2e impact. This research used emission factors for the UK, and Ireland at 0.52, 0.59, and 0.58 kg CO_2e/kWh, respectively.[14]

3. RESULTS

The model was run for each device which calculated the energy consumption (Wh) (Table 2) and the average GHG emissions (g CO_2e) (Table 3) of each model stage. Results illustrated that

Table 2. Energy Consumption of Each Application by Device and Measurement Section

laptop	data center		network		user device	
	Wh	% of total	Wh	% of total	Wh	% of total
idle					11.85	100.00%
Word 2010					12.78	100.00%
Word 0365	0.43	2.83%	0.06	0.38%	14.54	96.79%
Word 0365 + 2010	0.08	0.56%	0.01	0.07%	13.39	99.36%
Outlook 2010	0.84	6.13%	0.03	0.26%	12.79	93.62%
Outlook O365	0.04	0.33%	0.03	0.21%	12.84	99.46%
Excel 2010					17.70	100.00%
Excel O365	0.55	4.08%	0.00	0.00%	12.86	95.92%
tablet	**data centre**		**network**		**user device**	
	Wh	% of total	Wh	% of total	Wh	% of total
idle					8.85	100.00%
Word 2010					9.80	100.00%
Word 0365	0.43	3.76%	0.06	0.50%	10.82	95.73%
Word 0365 + 2010	0.08	0.75%	0.01	0.10%	10.05	99.16%
Outlook 2010	0.84	7.46%	0.03	0.31%	10.35	92.23%
Outlook O365	0.04	0.42%	0.03	0.27%	9.93	99.30%
Excel 2010					10.62	100.00%
Excel O365	0.55	5.76%	0.00	0.01%	8.95	94.24%

Table 3. GHG Emissions of Each Device Calculated by the Data Center (DC), Network (NW), and User Device (UD) Stages for Each Activity Performed

	tablet				laptop			
	grams of CO_2e							
	DC	NW	UD	Total	DC	NW	UD	total
idle			5.13	5.13			6.87	6.87
Word O2010			5.68	5.68			7.41	7.41
Word O365	0.25	0.04	6.27	6.56	0.25	0.04	8.43	8.72
Word 0365 + 2010	0.04	0.01	5,83	5.88	0.04	0.01	7.77	7.82
Excel O2010			6.16	6.16			10.27	10.27
Excel O365	0.32	0.00	5.19	5.51	0.32	0.00	7.46	7.78
Outlook O2010	0.49	0.02	6.00	6.52	0.49	0.02	7.42	7.93
Outlook O365	0.02	0.02	5.76	5.80	0.02	0.02	7.45	7.49

over 90% of the energy consumption for each activity came from the user device. The idle power consumption of the tablet and laptop were 8.85 and 11.85 W, respectively. The average relative standard error for device measurements was 2.98% and 4.04% for the laptop and tablet devices, respectively.

Results indicate that the power consumption to run Excel in O365 was on average 17.4% lower than running Excel in O2010. The power consumption for Outlook in O365 was 8.1% lower than in O2010. However, the power consumption for Word in O2010 was 16.4% less energy than in O365. The power consumption for the combination of Word in O365 and O2010 was 4.5% lower than O2010. The CO_2e emission differences correlated with energy differences; although, some slight variations of less than 0.2% were calculated because of the different emissions factors used where data centers were in different geographies.

The networking stage of the model contributed relatively minor amounts of energy to the total energy consumption because of the small amounts of data transferred for each activity (Supporting Information Table S2). For O365 the average data transmission size for Word, Outlook, and Excel was 5.37 MB, 2.51 MB, and 0.06 MB, respectively. Whereas data transmission for Outlook 2010 was 3.04 MB.

The additional energy consumption of each product over idle power was calculated for each device (Table 4). The average energy consumption and GHG emissions of each product was then calculated (Figure 1).

A review of the repeat measurements performed for each application on each device revealed a good correlation was achieved. Correlation was most important to the Excel calculations due to the short time that each measurement was undertaken. Supporting Information Figure S2 shows two Excel calculations for the laptop device with a Pearson Correlation of 0.97.

Table 4. Additional Energy Consumption of Each Product from Idle Power Consumption (Wh)

	tablet		laptop		average
	difference from idle (Wh)				
idle					
Word O2010	0.94	10.7%	0.93	7.8%	9.3%
Word O365	2.45	27.6%	3.17	26.8%	27.2%
Word 0365 + 2010	1.29	14.5%	1.63	13.7%	14.1%
Excel O2010	1.77	20.0%	5.85	49.4%	34.7%
Excel O365	0.64	7.3%	1.56	13.1%	10.2%
Outlook O2010	2.37	26.8%	1.81	15.2%	21.0%
Outlook O365	1.15	13.0%	1.06	9.0%	11.0%

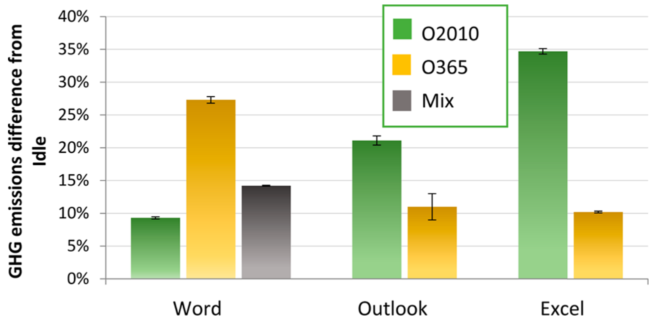

Figure 1. The average GHG emissions difference of each application from device idle state including the network and data center stages. Error bars indicate the average relative standard error of device testing.

4. SENSITIVITY ANALYSIS

Accurately calculating the number of O365 sessions per server was deemed a variable of uncertainty during data collection. Indeed, the number of sessions was estimated using measured data (Section 2.2). This variable was, therefore, considered using a sensitivity analysis in order to understand its impact (Figure 2). For Word and Excel, which use the same servers, the range of 1−1000 sessions was analyzed, for Outlook 1−15 000 sessions was used. These ranges were suggested to be suitable by Microsoft data center engineers for the current software and hardware being analyzed. It was noted that Microsoft employs a number of techniques to avoid having a low number of sessions per server such as load balancing and future load planning. In reality it would be very rare to find a server with a low number of sessions; although, the number of sessions is relative to the average size of each session. Each of the sessions was modeled against the data center section of the model for each application and did not contain networking or user device model sections. An extra function was included to take into consideration the expected variation in server power as server sessions increase and decrease. A linear ±15% variation[15] was factored against the average server power consumption with the average server power consumption being set to the midway point of each range of sessions (500 and 7500, accordingly).

For all applications the sensitivity analysis highlights that the number of server sessions is a critical variable and determines a cloud service being more or less efficient than its traditional counterpart. The greatest rate of change (99%) in energy

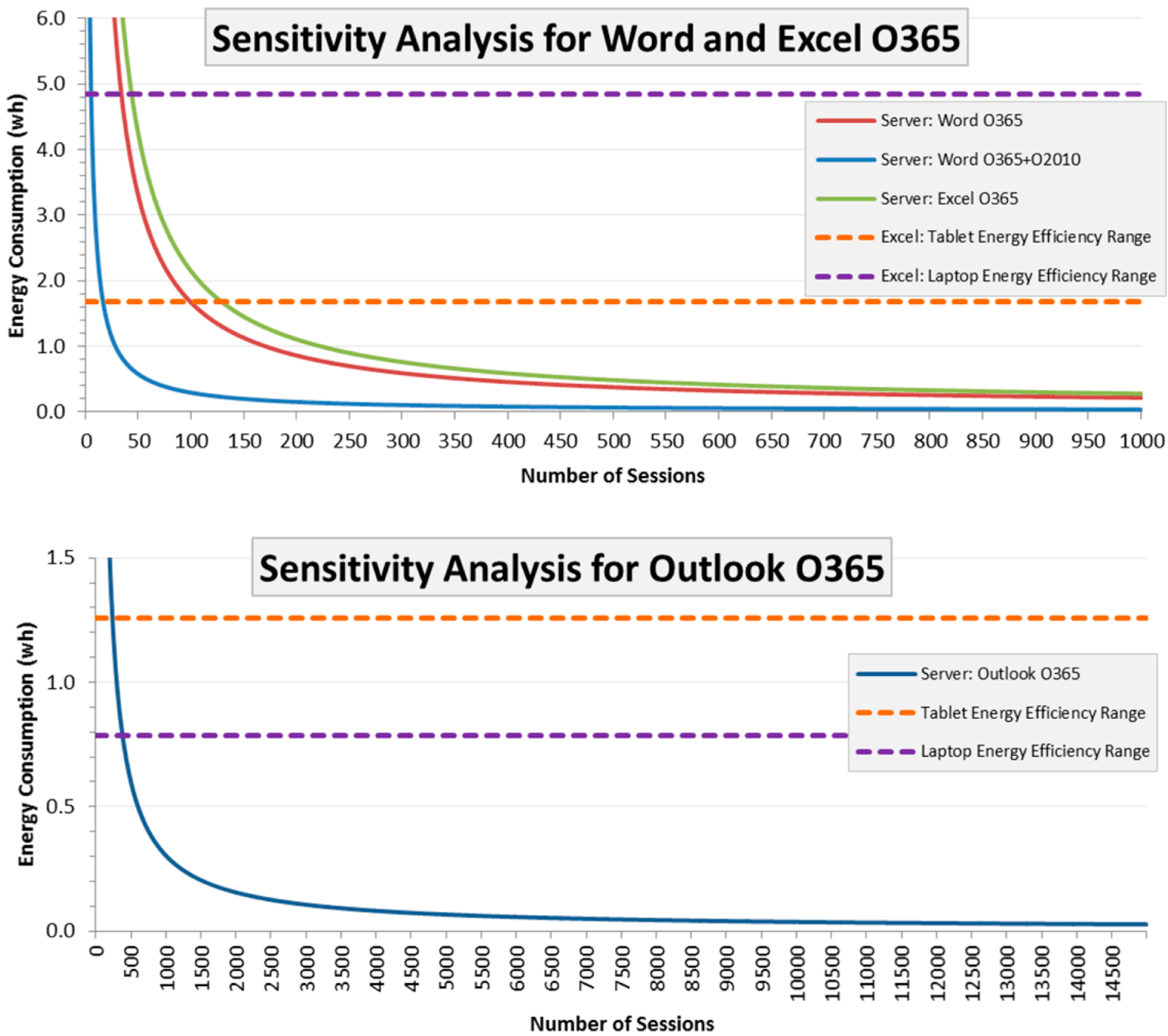

Figure 2. Sensitivity analyses for Word, Excel, and Outlook O365 server sessions. The energy efficiency range of each user device has been overlaid for Outlook and Excel which indicates the energy that can be consumed by the server before it becomes less efficient than O2010 (i.e., total O2010 energy minus O365 user device and networking energy). Word was not plotted here as it was already less efficient in O365.

consumption was found over the first 25% of server sessions; equating to 250 sessions for Excel and 2750 for Outlook. Therefore, we can infer that keeping server sessions above the first 25% session range would result in significantly less result variability, desensitizing this variable. The number of sever sessions (confidential) measured and used for this research were all significantly beyond 250 for Excel and 2750 for Outlook.

The energy efficiency range of each user device was plotted for Outlook and Excel onto the sensitivity analysis chart (Figure 2). This range was calculated by subtracting the O365 user device and networking energy from the total O2010 energy consumption for each application on each device. The resulting range was, therefore, the energy that can be consumed by the server before it becomes less efficient than O2010. For the tablet, 129 and 236 sessions were the minimum required for Excel O365 and Outlook O365, respectively, to be more energy efficient than O2010 counterparts. For the laptop, 43 and 379 sessions were found to be the minimum required for Excel O365 and Outlook O365, respectively. Word was not included as O365 Word was already less efficient than its O2010 counterpart.

5. DISCUSSION AND CONCLUSION

This research measured and calculated the energy consumption and GHG emissions from using three different office productivity software products in both a cloud and traditional computing scenario. This research has three main implications for cloud computing technology and software vendors in general. First, a new methodology to calculate and measure a cloud service was created and validated using modeling and data measurements across the data center, network, and end user device data stage. Second, the results indicated that cloud computing was more energy efficient for software services that use high levels of processing, storage, or those that require constant uptime but relatively low data transfer sizes. This information can assist cloud service designers in designing software services in an environmentally efficient manner. Finally, the results of this study concurs with previous studies[2−4] that suggested the efficiency of cloud computing is highly dependent upon the type and usage of cloud services; nevertheless, cloud can assist in reducing GHG emissions. This was demonstrated as the modeling results revealed that cloud computing for Excel and Outlook consumed less energy and emitted less GHG than traditional computing. However, cloud computing consumed and emitted more energy and GHG for activities in Word. Word was used to represent a form of computing with low processing and storage and a high user input. The standalone version of Word's power consumption was 14.1% lower than its cloud counterpart.

Word in O2010 is a refined 20+ year old product that has been designed to consume a low user device resource amount. This is demonstrated through the results as Word's O2010 measured power consumption was on average only 9.3% higher than idle power consumption. While, Word's O365 power consumption was on average 27.2% higher than idle. This large difference stems from the user device consuming significantly more energy when hosting Word within IE9 than running Word in O2010. On further investigation of the process, thread, and task trace of Word in O365, the constant user input and page refreshing that occurred within IE9 was found to cause the high energy consumption. For example, spell check was updated and monitored which affects IE9's processing use. It is clear that full cloud computing is less suited to word processing activities than traditional computing in this case.

A third alternative mixed access method was also measured. If O2010 is installed on a local machine it can be used to access a relevant Word or Excel file hosted by O365. The power consumption of this mixed access method for Word was 14.1% higher than idle. Although its energy consumption was 4.5% higher than Word O2010, the added benefits of the O365 service such as multidevice access may outweigh the extra energy and GHG costs for some users. Excel was not measured in the mixed access method as the data processing location would have been on the same device as O2010 and, thus, no change would be measured for data processing alone.

Excel test results highlighted the positive GHG impact of moving high processing requirements to efficient cloud servers as the power consumption was on average 17.4% lower in O365 than O2010 for Excel. Excel was measured because of its ability to process large and complex equations which causes the CPU of a device to be heavily utilized, increasing device power consumption. Excel in O365 is currently function limited which meant that the activity performed only analyzed the processing of 300 000 cells. For repeatability in O2010, this limited the time of measurement to 4 and 10 s for the laptop (Supporting Information Figure S2) and tablet, respectively. Although the small intervals were mathematically transformed to a 60 min time period this result requires further validation and data.

Results of Outlook testing revealed that the power consumption of Outlook in O2010 was 9% higher than in O365. Outlook was examined as it already uses an external Exchange 2010 server to host mailboxes. Cloud computing uses the same data setup; however, Exchange O365 is optimized to host more than one set of mailboxes on a more efficient hardware platform. The data used to analyze Outlook 2010 was Microsoft's own internal mail system and thus represented an already heavily optimized system. Most organizationally run Outlook Exchange 2010 servers are not optimized to this level and do not have the support and knowledge of the data center specialists. This highlights that using Outlook in O365 compared to O2010 would be likely to result in a higher energy and GHG reduction than found in this research; although, further case study data is required to validate this.

The results of this study have positive implications especially for the design and development of office productivity cloud computing services. These results infer that by designing office productivity services to minimize server updating and network use (i.e., caching on the local device), energy consumption and GHG emissions can be reduced. Indeed a combined version of traditional "standalone" and cloud software may also be considered as a more efficient way to reduce overall energy consumption and GHG emissions.

The sensitivity analysis performed in this research provided a method to calculate the point at which cloud services become more energy efficient than running the traditional counterpart. This simple method could easily be modified and utilized by data center operators and cloud service vendors as a publishable metric to demonstrate how their services perform in terms of GHG emissions. Using this method would also remove any security issues surrounding the releasing of confidential data center information.

A new measurement and apportionment technique used to measure power consumption on a user device was developed and utilized. This technique measured the power consumption, thread and process, and network activity of a user device during its idle mode and the prescribed activities. Measurement of idle power consumption allowed the apportionment of activity energy consumption to be calculated. Steps were followed to ensure no other process interfered with measurements and each test was repeated three times for each activity. Even with a small number of samples, the tests were considered successful due to the average percentage error rate of ±3.51% between each set of repeats.

The apportionment approach used in this research implied that, on average, the power consumption of Word, Excel, and Outlook in O365 was 27.2%, 10.2%, and 11.0%, respectively, higher than idle. Results indicated a correlated increase in energy consumption between the products for O365 for the two devices analyzed; however, for O2010 a similar but not as clear increase in energy between products was observed. Also, for O2010 results for the laptop device were often higher than the tablet, which was due to the larger CPU capacity and throttling capabilities available on the laptop. Consequently, we acknowledge that a limitation of this research was analyzing only two devices per product. Therefore, an array of different devices including smart phones, high performance desktops, and new generation tablets should be measured to increase certainty per product.

During this research the user device was purposefully measured with only one user driven software process taking place and, therefore, did not take into account that multiple software processes can potentially occur at once. For example, while using Word in O365 one could also be listening to music, potentially making more use of the idle energy consumption of the OS as a consequence. A device is often most hardware efficient when running at medium to high resource utilization and with multiple workloads.[15] This is the very reason that cloud computing is successful in reducing overall energy consumption. To further improve results, testing under multiple controllable workloads, higher resource use, and different OS types should be carried out.

The scope of this research was limited to calculate the power consumption of using applications within a traditional or cloud scenario. This scope was purposefully tight and excluded the issue of the potential idle time power consumption of each data stage. This can be defined as the time that a device or stage is not being utilized for any user driven activity. A question remains around the influence of power management technologies which can allow any device to turn off when no activity is occurring; however, this relies on it being turned on and optimized. Power management is currently more advanced for consumer user devices, conversely, server power management is rare. The situation whereby a server is running in idle mode for long periods of time without any activity taking place could occur. This would call into question the overall effectiveness of cloud computing at reducing GHG emissions. Software techniques such as server multitenancy and load balancing and shifting can and are used to mitigate this issue. The sensitivity analysis performed here could provide cloud operators with a measure to ensure energy efficiency was being achieved by using the various techniques already on offer. These issues require data and further modeling research in order to quantify the full impacts.

This research explored office productivity cloud computing products and each was selected to highlight a particular computing type. Other cloud service types, such as cloud based gaming, have a high server processing, networkin,g and user device use. Multimedia cloud services (e.g., music) also have a high networking and user device impact. These services should be considered when assessing the overall analysis of cloud computing's energy impact.

The energy consumption location of cloud computing presents a unique opportunity to reduce GHG emissions. Organizations that run data centers and offer cloud services are increasingly investing in renewable energy projects and aiming for carbon neutrality.[16,17] Where software services are being moved to a cloud based scenario the energy consumed can not only be more efficient but also more carbon efficient and in some cases carbon neutral. Carbon neutrality would of course only be beneficial if the cloud service enabled a reduction of energy on the end user device. Carbon neutrality was not factored into this research's calculations.

The effect of multiple devices and OSs being able to access the same software service was not considered in this research. Cloud computing offers software services to end users and is not limited to a single device and OS unlike traditional computing. This is leading to the effect of software and service manufacturers increasingly offering a multiple device landscape to their users. An increase in the number of user devices may occur as a consequence of cloud computing and thus the implications of this with a focus on embedded carbon should also be considered.

■ ASSOCIATED CONTENT

Supporting Information

Additional material as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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