The carbon benefits of cloud computing

A study on the Microsoft Cloud

in partnership with WSP

This white paper is an update to "Cloud Computing and Sustainability: The Environmental Benefits of Moving to the Cloud," published in 2010. In this paper, we have expanded the older study to show how the Microsoft Cloud can accelerate energy savings and reduce carbon emissions.

Contents

Foreword

Today, a technology revolution is transforming virtually every aspect of life as we know it. The scale of its impact is on par with the discovery of electricity, such that some are calling this era the Fourth Industrial Revolution. Powering this revolution are cloud computing and the technological advancements that underpin it. With cloud computing, businesses, governments, institutions, and individuals are able to access nearly unlimited computing power at the push of a button, enabling them to gain insights and make discoveries previously not dreamed of in fields such as genomics, robotics, and artificial intelligence. And yet, even as the cloud unlocks humanity's vast potential, the exponential expansion of IT infrastructure raises questions about the environmental impacts from this growth.

At Microsoft, we are committed to sustainable operations in all parts of our business and beyond, for local and global good. Through our internal sustainability fee, we fund our commitments to carbon neutrality and renewable electricity, using the scale of our cloud datacenters to bring more green power onto the grid. We are harnessing the power of the cloud within our own business to address our environmental impact: our cloud-based programs to reduce resource consumption have already contributed to our 20 percent global energy reduction at our facilities. Overall, we are on path to a 75 percent reduction in our carbon emissions by 2030 relative to a 2013 base year.

We are equally committed to extending the benefits of the cloud beyond our operations to our customers, by working to deliver IT services with a smaller environmental footprint. Increasing demand for computing services is inevitable, and we aim to support this growth as responsibly as possible. We engaged external experts to conduct this study, comparing the Microsoft Cloud with traditional enterprise datacenter deployments. The results show that the Microsoft Cloud delivers impressive sustainability benefits, and point to the opportunity for business and society to reduce the carbon footprint associated with computing in support of a more sustainable future.

We invite you to read about the environmental advantages of deploying your applications in the Microsoft Cloud.

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Executive summary

Cloud computing makes it possible to collect, analyze, and store huge quantities of data, reduce the total cost of ownership of IT, and increase business agility. Today, datacenters supporting the cloud consume a significant, and growing, amount of energy.

Societally, moving from many on-premises servers to fewer large datacenters presents the opportunity to reduce overall IT consumption of energy and related carbon emissions. With this in mind, Microsoft commissioned a study to compare the energy consumption and carbon emissions[1] of four applications in the Microsoft Cloud with their on-premises equivalents:

- **Microsoft Azure Compute**
- **Microsoft Azure Storage**
- **Microsoft Exchange Online**
- **Microsoft SharePoint Online**

We selected these cloud applications as they together account for about half of the energy consumed in Microsoft datacenters. To gain as full and accurate a picture as possible, the study considered the full life cycle for the computing scenarios (from manufacturing to end-of-life).

The results show that the Microsoft Cloud is between 22 and 93 percent more energy efficient than traditional enterprise datacenters, depending on the specific comparison being made. When taking into account our renewable energy purchases, the Microsoft Cloud is between 72 and 98 percent more carbon efficient. These savings are attributable to four key features of the Microsoft Cloud (Figure 1): IT operational efficiency, IT equipment efficiency, datacenter infrastructure efficiency, and renewable electricity.

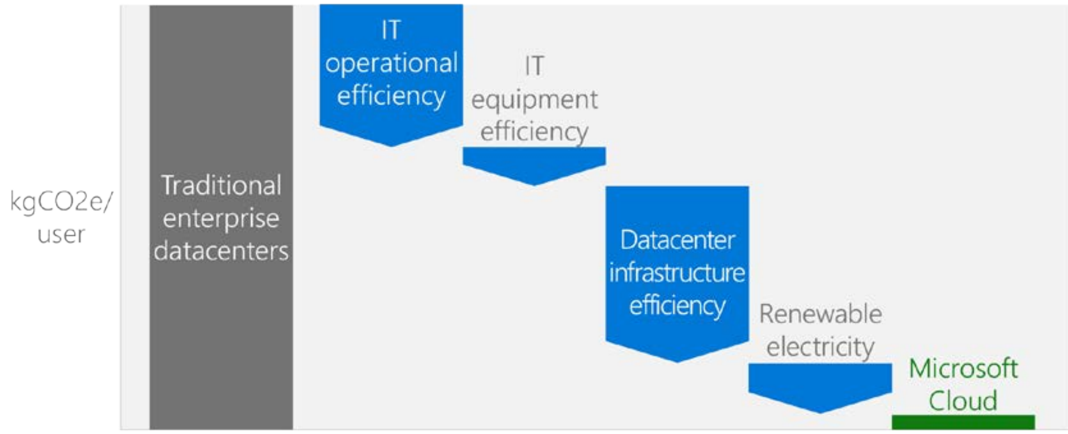

Figure 1*: The four features of the Microsoft Cloud that reduce environmental impact.
**kgCO2e = kilograms of carbon dioxide equivalent*

At Microsoft, our commitment is to create a cloud that is trustworthy, responsible, and inclusive. This study provides a current measurement of the potential energy efficiency and carbon savings that businesses can realize with the Microsoft Cloud. The impact of using our cloud services will improve even more as we continue to refine how we manage capacity, boost energy efficiency, reduce waste, and add new sources of renewable energy.

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[1] Throughout this paper, “emissions” and “carbon” refer to all greenhouse gas (GHG) emissions.

Introduction:

Cloud computing and increasing energy consumption

The world is now entering the Fourth Industrial Revolution, which, as described by the World Economic Forum, will feature major technological advances in artificial intelligence, robotics, genomics, materials sciences, 3D printing, and more. Businesses, governments, and civic institutions can now collect, store, and analyze data at an unprecedented scale, speed, and depth. Big data and deep analytics unlock the potential to make a positive impact throughout the world, from conserving the world's freshwater supply to optimizing energy use in buildings. These improvements add up to financial savings and carbon reductions at a global scale.

Cloud computing—large-scale, shared IT infrastructure available over the internet—is the engine enabling these technology advancements. And these advancements, in turn, are driving cloud uptake. At the same time, the cloud can help businesses reduce their total cost of ownership[2] and realize greater business agility by delivering significant economies of scale and enabling access to data and applications anywhere.

But as the world's use of cloud computing accelerates, so too does the energy consumed in the cloud. In the United States alone, datacenters consume about 70 billion kilowatt-hours (kWh) of electricity each year, roughly 1.8 percent of the total electricity consumed in the country. This number is expected to grow to 73 billion kWh by 2020, about the same amount of energy that 6 million homes consume in one year.[3] This number would be higher if not for the efficiencies realized in many commercial cloud datacenters.

Following the Paris Agreement, as climate change gains public attention and as governments establish regulations to curtail carbon emissions, the environmental impact of computing is increasingly under scrutiny. At Microsoft, we embrace our responsibility to operate sustainably to reduce the climate impact of our business: we are committed to carbon neutral operations and purchasing renewable electricity. We are also committed to helping our customers understand and reduce the environmental impact of their computing.

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[2] Total cost of ownership is the total cost of an IT solution or product over time. The metric considers direct and indirect costs, capital expenses (such as IT equipment), and operating expenses (such as equipment upkeep and software).

[3] Arman Shehabi, Sarah Josephine Smith, Dale A. Sartor, Richard E. Brown, Magnus Herrlin, Jonathan G. Koomey, Eric R. Masanet, Nathaniel Horner, Inês Lima Azevedo, and William Lintner. *United States Data Center Energy Usage Report*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-1005775. 2016.

As part of this commitment, we conducted a study to assess the environmental implications of cloud computing. Specifically, our objectives were to:

1. Assess the energy use and carbon emissions associated with key applications within the Microsoft Cloud in comparison with their on-premises equivalents.
2. Improve our understanding of the energy and carbon benefits of computing using Microsoft and other commercial cloud services in general compared with on-premises implementations.

The study builds on the 2010 Microsoft report *Cloud Computing and Sustainability: The Environmental Benefits of Moving to the Cloud*. [4] To conduct this updated study, Microsoft engaged WSP, a global consultancy with expertise in environmental and sustainability issues, to model the environmental impact of using Microsoft Cloud services instead of on-premises deployments. Stanford University IT sustainability and compute energy expert Dr. Jonathan Koomey served as an in-depth technical reviewer.

This paper presents the research approach and findings of the study, demonstrating that Microsoft Cloud computing offers significant advantages in energy consumption and carbon emissions over on-premises deployments, findings that are consistent with both the original study and other industry research[5].

[4] *Cloud computing and sustainability: The environmental benefits of moving to the cloud.* Accenture, WSP. 2010.

[5] P. Thomond. *The enabling technologies of a low-carbon economy: A focus on cloud computing.* Microsoft and GeSI. 2013.

Research approach:

Life cycle evaluation of on-premises and cloud IT services

This analysis uses a quantitative model to calculate and compare the energy consumption and carbon footprint of IT applications and compute and storage resources in the Microsoft Cloud with equivalent on-premises deployments (Figure 2). The model draws on greenhouse gas accounting principles from the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) Corporate Standard and Product Life Cycle Standard.

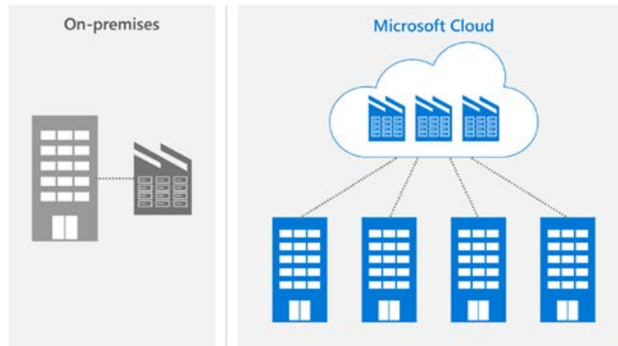

Figure 2: Study design: a quantitative evaluation of Microsoft Cloud services in comparison with on-premises deployment equivalents.

Cloud services

The study looks at four cloud services that account for nearly half of the energy consumed in Microsoft datacenters:

- Azure Compute
- Azure Storage
- Exchange Online
- SharePoint Online

Both Exchange Online and SharePoint Online were included in the original 2010 study.[6] However, in this study, the scope was expanded to include Azure services, which provide infrastructure as a service (IaaS), above and beyond software as a service (SaaS). Our aim was to generate a broader and more inclusive spectrum of data points to enable a more accurate assessment of the energy and carbon implications of different types of services used today.

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[6] *Cloud computing and sustainability: The environmental benefits of moving to the cloud.* Accenture, WSP. 2010. *Note:* The original 2010 report focused on three business applications: Exchange Online, SharePoint Online, and Microsoft Dynamics CRM Online.

On-premises deployment scenarios

The study considered a range of on-premises deployment scenarios relative to the four Microsoft Cloud services listed previously:

- Azure Compute comparisons:
  - Physical servers
  - Virtualized servers
- Azure Storage comparisons:
  - Direct attached storage
  - Dedicated storage
- Exchange Online and SharePoint Online comparisons:
  - Small deployments: 1,000 users
  - Medium deployments: 10,000 users
  - Large deployments: 100,000 users

Functional units

We analyzed the cloud services and on-premises deployments based on the functional unit for each cloud service—that is, the "useful output" offered by a deployment. We defined these functional units based on the level of service offered by the Microsoft Cloud. This allowed for an apples-to-apples comparison between the Microsoft Cloud and on-premises alternatives. The functional unit for each service is listed in the following table:

Service	Unit	Quality and performance criteria[7]
Azure Compute	Core-hour	Net computational output
Azure Storage	Terabyte-year	Number of data replications
Exchange Online	Mailbox-year	Mailbox size and replications
SharePoint Online	User-year	Provisioned storage and replications

Life cycle phases

A life cycle assessment provides a full picture of the environmental impact of a product or service, from the raw material extraction for equipment manufacturing through the end-of-life treatment of equipment. Assessing the full life cycle helps to ensure inclusion of all major emission sources. In this study, we assessed each of the four cloud services and their on-premises equivalents for energy consumption and carbon emissions impacts across four life cycle phases, as illustrated in Figure 3 and described following.

[7] The quality and performance criteria are proprietary to Microsoft and therefore specific numbers are not shared.

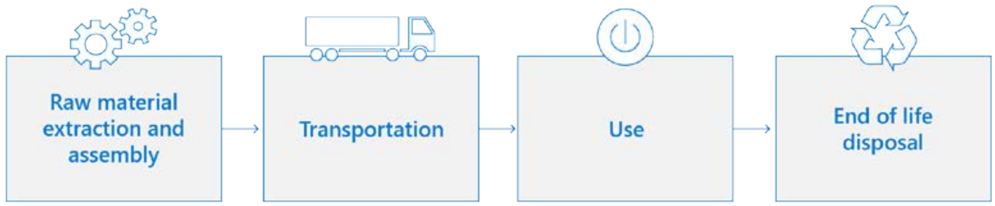

Figure 3: The life cycle phases used to define the boundary of energy consumption and carbon emissions considered in the analysis.

1. **Raw material extraction and assembly**—includes the energy consumption and emissions associated with the use of the raw materials and the assembly of servers, networking equipment, and hard drives.
2. **Transportation**—represents the energy consumption and emissions associated with transporting the servers and other IT equipment from the manufacturer to Microsoft datacenters or on-premises datacenters.
3. **Use**—encompasses the energy consumption and emissions from electricity used to run the servers, networking equipment, hard drives, and datacenter infrastructure, such as lighting, cooling, and power conditioning. Where relevant, includes energy from data flows over the internet.
4. **End-of-life disposal**—includes end-of-life energy consumption and carbon emissions associated with landfilling and recycling, based on conservative assumptions about recycling rates.

Data sources and key parameters

Primary data from Microsoft datacenters and equipment were used wherever possible, and secondary data such as industry averages were used as necessary.

Key parameters considered in the analysis included:

- Equipment counts and specifications.
- Device utilization.
- Power draw of servers, storage devices, and networking equipment used within the datacenters.
- Power usage effectiveness (PUE) of datacenters hosting the services.
- Data flows over the internet.
- Carbon intensity of electricity supply.

Equipment counts, equipment specifications, and power draw for Exchange on-premises deployments were determined using the Exchange Server Role Requirements Calculator for Exchange 2016. On-premises Exchange, SharePoint, compute, and storage equipment counts and specifications were supplied by industry experts whose primary role is to deploy these solutions for enterprises. The Microsoft Cloud analysis was based on actual data collected from current Microsoft datacenter operations.

For a detailed description of each of these key parameters and model assumptions, please see Appendix I and Appendix II.

Findings:

Smaller footprint with the Microsoft Cloud

The results of this study reveal significant energy efficiency improvements—from 22 to 93 percent—when switching from traditional enterprise datacenters to the Microsoft Cloud for any of the four services. The specific savings achieved vary by service and deployment scenario. The greatest relative savings are realized when smaller enterprise deployments transition to the cloud. The features driving these reductions for the Microsoft Cloud include more efficient operational practices, IT equipment, and datacenter infrastructure. These efficiencies translate into both energy and carbon savings. When also accounting for our purchases of zero-carbon electricity, emissions savings with the Microsoft Cloud can be as great as 98 percent.

Energy and emissions results by service and deployment scenario

Microsoft Cloud services achieve energy and emissions reductions in comparison with every on-premises deployment scenario assessed. The primary driver for energy and emissions reductions in each comparison is decreased electricity consumption per useful output during the use phase in the datacenters that run the Microsoft Cloud. Figure 4, following, shows the range of savings by service based on deployment scenario as described in the On-premises deployment scenarios section earlier.

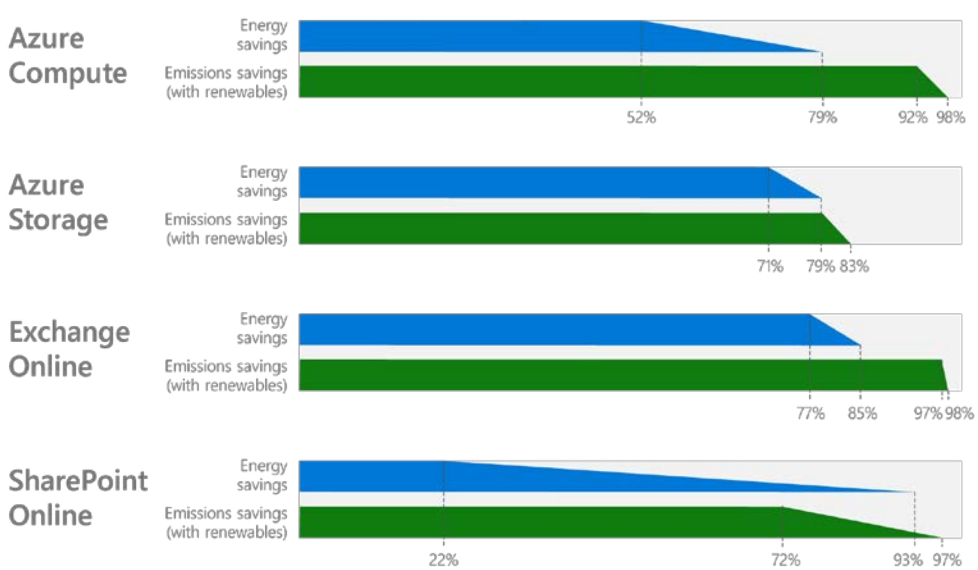

Figure 4: The range of energy and emissions savings by cloud service. "Energy savings" shows the energy savings of the datacenter electricity used in Microsoft Cloud services over the on-premises equivalents. "Emissions savings (with renewables)" shows the emissions savings of the Microsoft Cloud services over the on-premises equivalents, taking into account the purchase of zero-emission renewable electricity to power the Microsoft Cloud.

For detailed data sheets by service, see Appendix III.

Four energy- and carbon-reducing features of the Microsoft Cloud

Four main drivers contribute to the smaller energy and carbon footprint of the Microsoft Cloud (as illustrated in Figure 5). The first three—IT operational efficiency, IT equipment efficiency, and datacenter infrastructure efficiency—reduce the energy required to deliver the services. The fourth is the purchase of renewable electricity for more than 95 percent of our consumption, which translates into a smaller carbon footprint for electricity consumed in Microsoft datacenters. The remaining carbon emissions associated with the Microsoft Cloud are primarily from aspects of the life cycle outside Microsoft datacenters (that is, embedded carbon in the raw materials, equipment assembly, transportation, data flows, and end-of-life disposal).

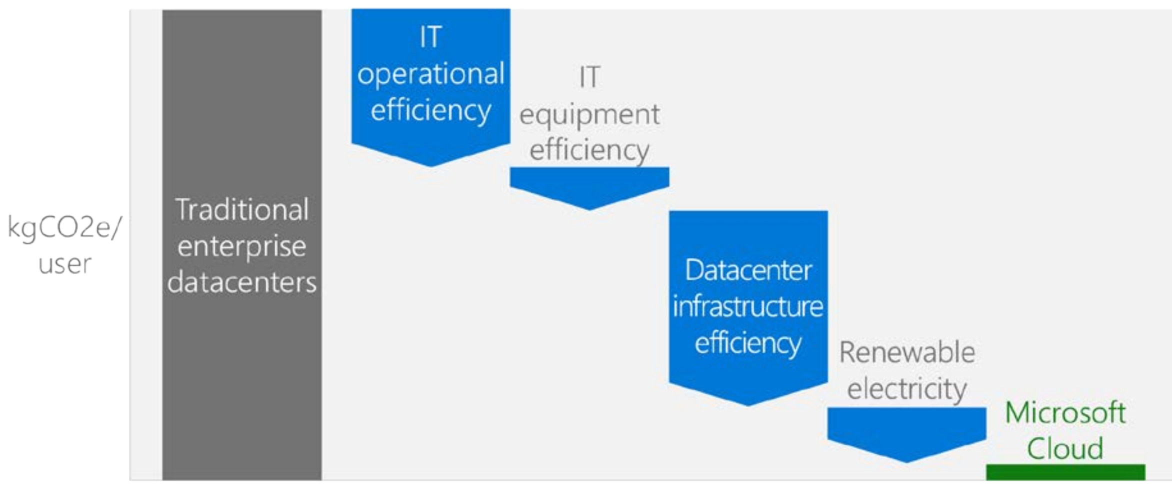

Figure 5*: The four features of the Microsoft Cloud that reduce environmental impact.
***kgCO2e** = *kilograms of carbon dioxide equivalent*

The first three drivers of the reduced footprint (IT operational efficiency, IT equipment efficiency, and datacenter infrastructure efficiency) typically apply across all commercial cloud service providers, and even some on-premises scenarios, but will vary depending on factors such as the physical infrastructure and operational standards. Only cloud providers and private datacenters that purchase or use large volumes of renewable electricity will be able to achieve a carbon footprint comparable with the Microsoft Cloud.

1. IT operational efficiency

The large economies of scale seen in cloud computing mean that commercial cloud services in general can operate with much greater IT operational efficiency than smaller, on-premises deployments.

- **Dynamic provisioning**—Emphasis on application availability can lead to overprovisioning of computing resources to avoid theoretical unmet demand. Improved matching of server capacity with actual demand minimizes waste. Microsoft manages capacity efficiently to avoid expensive overprovisioning, through monitoring and demand prediction that allow for continual capacity adjustment.

- **Multitenancy**—Microsoft uses multitenancy, occupying servers with multiple user types and a large user base with different demand patterns. Just as the electric grid interconnects thousands of users whose fluctuating power demands can balance one another, cloud infrastructure hosts thousands of companies and millions of users whose different use patterns can balance one another. This load diversity decreases overall fluctuations and makes loads more predictable. Generally, as the number of users increases, the ratio of the peak demand to the average demand for the user set decreases. Therefore, rather than sizing equipment to meet a single customer's peak load (for example, workers arriving at an office in the morning and immediately checking email), Microsoft sizes equipment to meet the time-coincident demand of the whole user set.
- **Server utilization**—Higher equipment utilization rates mean the same amount of work can be done with fewer servers, which in turn leads to less electricity consumed per useful output. While servers running at higher utilization rates consume more electricity, the overall performance gains more than offset the relative per-unit increase. As illustrated in Figure 6, increasing the utilization rate from 10 percent to 40 percent will allow a server to process four times the previous load, while the power draw by the server may only increase 1.7 times.[8] Moreover, newer processors are continually driving towards a more attractive load curve where power draw is significantly reduced at idle or low utilization rates. The typically faster equipment replacement rates for commercial cloud service providers position them to take advantage of these improvements sooner than in on-premises deployments.

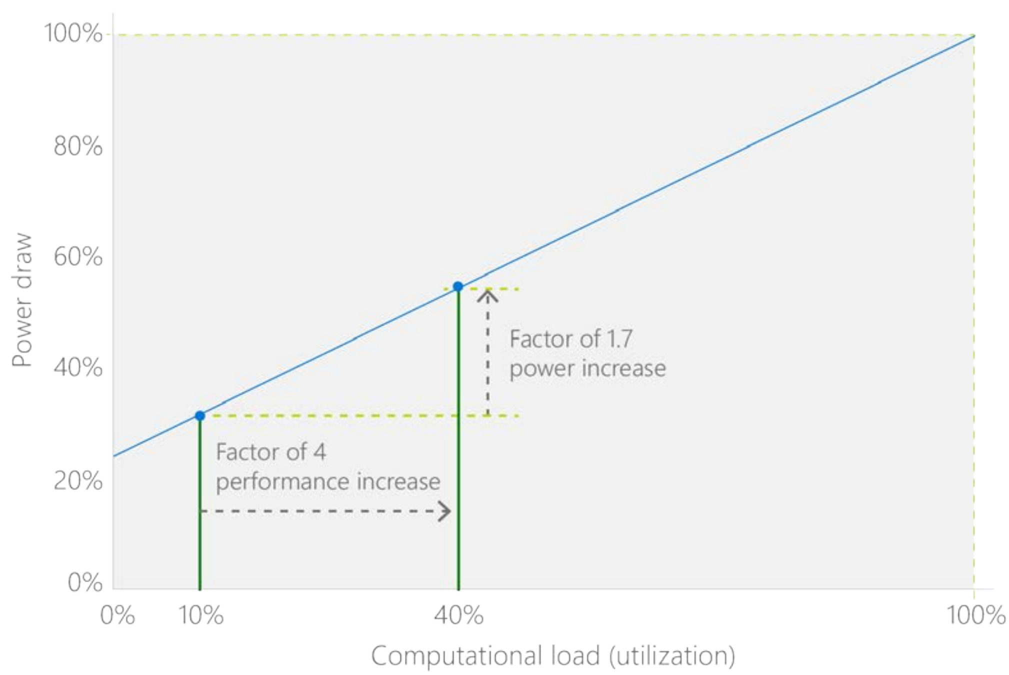

Figure 6: As utilization increases, power per computational output decreases.

[8] Based on representative sampling of volume servers manufactured in the last two years, as measured using SPECpower_ssj2008 protocol from the Standard Performance Evaluation Corporation (SPEC).

2. IT equipment efficiency

Because Microsoft spends a significant portion of operating expenses on electricity to run IT equipment, more so than the typical corporate IT department, we have a strong financial incentive to optimize IT efficiency. We take an active role in tailoring hardware components to the specific needs of the services we run, meaning the equipment runs leaner with a higher ratio of input energy going towards providing useful output than in traditional enterprise deployments. By collaborating with suppliers on the specification and design of servers and other equipment for maximum efficiency, Microsoft can realize benefits from scale that most corporate IT departments are unable to address. The results of this study suggest that more specialized, efficient IT equipment can reduce electricity consumption by 10 percent or more.

3. Datacenter infrastructure efficiency

Advanced infrastructure technologies in hyperscale datacenters reduce electricity requirements for overhead tasks such as lighting, cooling, and power conditioning. Power usage effectiveness (PUE)—the ratio of overall electricity consumption at the datacenter facility to the electricity delivered to the IT hardware—is a common measurement of how efficiently a datacenter uses electricity. The hyperscale datacenters that power the cloud are able to achieve better PUEs than typical enterprise datacenters. At Microsoft, we are committed to measuring PUE at each datacenter, and we are implementing better monitoring techniques and innovative design to continuously improve our PUE.

4. Renewable electricity

Consolidating distributed electricity demand from on-premises datacenters into the cloud unlocks the potential for large-scale purchases of green power that bring substantial renewable energy projects onto the grid that were not otherwise viable. We are committed to relying on a larger percentage of wind, solar, and hydropower electricity over time at our datacenters. Our goal is to achieve 60 percent direct purchase of wind, solar, and hydropower early in the next decade and then to keep improving from there. When we’re not able to eliminate energy use or directly power our operations with green energy, we obtain zero carbon electricity through the purchase of renewable energy certificates. Counting these certificates, we purchase renewable electricity for more than 95 percent of our consumption, including electricity associated with services hosted in the Microsoft Cloud. For further discussion of how this is included in the calculations, see Appendix III.

Case study A:

A global engineering consulting firm

To assess the sustainability of the Microsoft Cloud in a real-world setting, this case study compared the energy and carbon footprint of a global engineering consulting firm that hosts roughly 10,000 users in Europe on Exchange 2016 on-premises with the equivalent footprint in the Microsoft Cloud.

The firm's implementation of Exchange was not as robust as the services offered by Exchange Online because the firm's deployment only had three copies of each database spread over two datacenters and a 5-gigabyte (GB) size limit for each mailbox. In contrast, even the most basic Exchange Online plan offers 50 GB of mailbox storage and, for most customers, four database copies spread across four geographically distinct datacenters to allow high levels of data redundancy and availability (as shown in Figure 7).

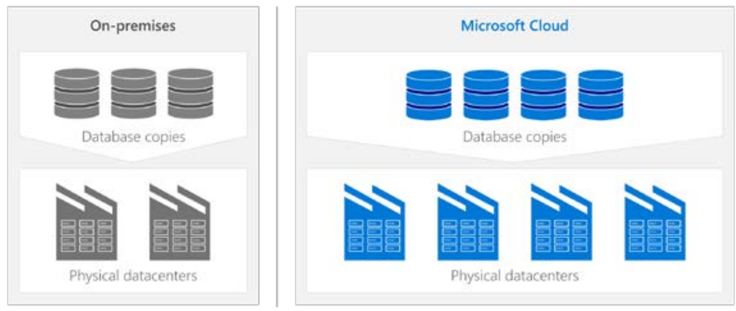

Figure 7: Contrasting the on-premises deployment of Exchange for a sample global engineering consulting firm (10,000 users) with the corresponding deployment in the Microsoft Cloud, which offers higher redundancy and availability.

Even while supporting a more robust Exchange environment than the on-premises deployment (with the additional infrastructure and energy demands that this entails), the Microsoft Cloud is estimated to reduce emissions by 93 percent compared with the on-premises environment (Figure 8). These emissions reductions are a result of 6,000 kWh in energy savings and Microsoft renewable electricity purchases.

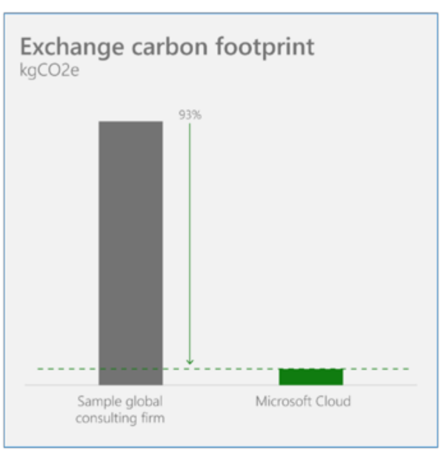

Figure 8*: Life cycle emissions results for an Exchange deployment for a sample global engineering consulting firm (10,000 users), showing emissions savings with the Microsoft Cloud versus on-premises.

***kgCO2e** = *kilograms of carbon dioxide equivalent.*

Case study B:

A global apparel company

To assess the sustainability of the Microsoft Cloud in a real-world setting, this case study compared the energy and carbon footprint of a global apparel company's use of Azure virtual machines in 2016 with its on-premises alternative.

For solutions included in this study, the company chose to use Azure instead of deploying on-premises. Therefore, the footprint of the company's virtual machines in Azure was compared against the footprint had the same machines been deployed in the company's typical on-premises environment. The on-premises scenario was modeled on the deployments currently used by the company at a combination of both large and small owned datacenters in addition to co-located datacenters. Calculations considered the physical machine processing power, virtualization ratios, utilization, server power consumption, datacenter PUE, and carbon intensity of the electric grid.

The study found that the virtual machines deployed in Azure had a carbon footprint 70 percent smaller than the modeled on-premises equivalent (Figure 9).

Azure provides both business and sustainability benefits by offering on-demand, global scalability in efficient, hyperscale, renewably powered datacenters.

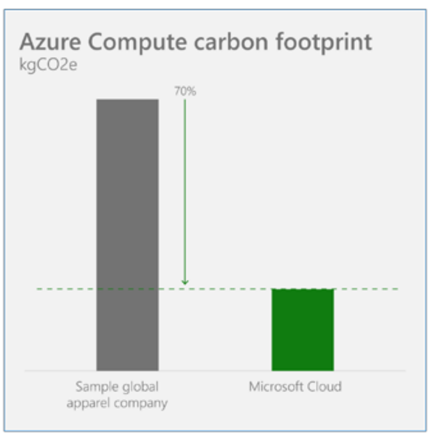

Figure 9*: Life cycle emissions results for an Azure compute deployment for a sample global apparel company, showing emissions savings with the Microsoft Cloud versus on-premises.

***kgCO2e** = *kilograms of carbon dioxide equivalent.*

Looking ahead:

Increasing the environmental benefits of the Microsoft Cloud

The increase in companies choosing to use cloud computing over on-premises deployments brings potential for global environmental benefit. Cloud solutions offer the dynamic provisioning needed to meet peak demands while creating less excess and unused capacity during non-peak times. These factors, combined with multitenancy and high server utilization rates, reduce energy consumption compared with on-premises deployment. Hyperscale computing creates further opportunities to improve performance and reduce energy waste with dynamic and focused resource management. These are distinct advantages to a cloud solution that are not readily available to on-premises deployments.

Technology innovation

The cloud is still in its technological infancy and is likely to show ongoing and significant improvements in operational efficiency. At Microsoft, we will continue to improve how we right-size and plan for excess capacity while still giving users the flexibility to add or remove services on demand. We are also researching cutting-edge technologies such as in-rack fuel cells that can almost double the energy efficiency of datacenters while reducing costs and improving reliability. With new data and ever-improving technologies, we will continue to make gains in energy efficiency and drive down waste within our datacenters to reduce unnecessary energy use and deploy high-performance, environmentally responsible solutions for our customers.

Internal sustainability fee

Microsoft is committed to accelerating environmental innovation through our internal sustainability fee, which we charge to all business divisions within Microsoft based on the carbon emissions associated with their energy use and business air travel. The fee sends a signal to each group to reduce emissions, while also generating funds that we invest in a number of sustainability-related initiatives, including some of the technology innovation discussed previously. We have also used a portion of these funds to help make electricity grids more reliable, flexible, and autonomous, and in turn deploy those approaches to enable low-cost, highly available renewable energy for the world. Our recent white paper Beyond Carbon Neutral highlights the impact and evolution of our sustainability fee.

Microsoft vision

At Microsoft, we have a vision to create a cloud that is trustworthy, responsible, and inclusive—a cloud for global good. A responsible cloud requires a commitment to foster sustainable environmental practices. For our part, we will continue to work to reduce the energy consumption and environmental footprint of our cloud services. This will help ensure that our customers can harness the significant business benefits of the cloud, such as greater business agility, improved business insights through big data, and reduced capital expenditure, while also minimizing the energy and carbon impact of their computing.

Appendix I:
Key parameters

The analysis considered the following key parameters:

- **Equipment counts:** the number of devices (servers, networking equipment, and storage devices) required to provision a given deployment. This includes excess capacity in both the cloud and on-premises scenarios to account for equipment required to meet peak loads or planned future growth.
- **Equipment specifications:** the specifications of servers, storage equipment, and networking devices used for the analysis. This includes number of cores, processor power, storage capacity, and power draw at different utilizations. Actual equipment specifications were used to model the Microsoft Cloud scenarios. Specifications for representative equipment, as determined by industry experts, were used to model on-premises deployment scenarios.
- **Device utilization:** the load that a device (server, networking switch, or storage device) handles relative to the peak load the device can handle. This number is expressed as a percentage.
- **Device power consumption:** the power consumed by a device, either measured directly, or extrapolated based on manufacturer specifications and device utilization.
- **Networking equipment power consumption:** the power consumed by networking equipment in the datacenter that is not directly measured or included explicitly in the deployment (for example, aggregation and core switches).
- **Datacenter PUE:** an efficiency metric that is the ratio of the total amount of electricity consumed by a datacenter to the amount of electricity delivered to the IT equipment. By definition, PUE is equal to 1 or greater, and the closer PUE is to 1, the more efficient the datacenter. PUE accounts for electricity used in the datacenter for lighting, cooling, power conditioning, and other support services.
- **Electricity from data flows over the internet:** the additional electricity use incurred in cloud computing and large on-premises deployments from sending data over the internet that would not occur in smaller deployments where IT resources are co-located with the users. This electricity use was considered for the Microsoft Cloud and for large-scale deployments based on assumed typical usage patterns of each service.
- **Electricity carbon intensity:** the average emission rate for the regionally specific mix of primary energy (such as hydro, natural gas, coal, and wind) used to generate electricity provided to the electric grid. In order to convert electricity into carbon emissions, the electricity consumption data is multiplied by the carbon intensity of the electric grid where

the electricity is consumed.[9] As discussed in the Renewable electricity section earlier, we purchase renewable electricity for more than 95 percent of our consumption. To demonstrate the carbon and energy savings possible with the Microsoft Cloud, we performed two separate analyses in this study:

1. One that did *not* take into account Microsoft's renewable electricity purchases. For this analysis, the emissions related to electricity consumption during the use phase were calculated using the carbon intensity from the local electric grid where Microsoft datacenters operate.

2. One that *did* take into account the zero emissions associated with our renewable electricity purchases.

The cloud service-specific results of these analyses are presented in Appendix III. Note that for the purposes of discussion in this paper, the study assumes on-premises deployments are located in the United States, whereas the Microsoft Cloud emissions are based on the average carbon intensity of the electric grid in the locations where Microsoft datacenters host a given service.

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[9] Electricity carbon intensities are obtained from the US Environmental Protection Agency (EPA)'s eGRID for the United States and the International Energy Agency (IEA) or national environmental agencies for all other countries.

Appendix II:
Model assumptions

Embedded emissions

- Embedded emissions include the emissions associated with the raw material extraction and processing of the IT equipment required for the service. These factors are sourced from the article "Characteristics of Low-Carbon Data Centers" by Masanet et al.[10]
- Embedded emissions are amortized over the expected lifetime of each device.

Transportation

- The model considers the emissions from transporting IT equipment from tier 1 suppliers to the datacenter. Shipment is assumed to be via truck and marine freight. Transportation for the equipment used in Microsoft datacenters is based on the actual location of the datacenters and Microsoft tier 1 suppliers. Emission factors for trucks and cargo ships are from the GaBi databases.[11]
- Transportation emissions are amortized over the expected lifetime of each device.

Use phase energy

- Device utilization is either measured directly or based on expected values provided by industry experts.
- The expected power consumption for equipment at different utilization rates is based on equipment specifications provided by Microsoft engineers or manufacturer-specified values. Where possible, manufacturer-specified values were validated against published test results performed using the SPECpower_ssj 2008 methodology.
- PUE is based on measured values for Microsoft datacenters and industry values, by datacenter type, for on-premises deployments.[12] The datacenter type for on-premises

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[10] Eric Masanet, Arman Shehabi, and Jonathan Koomey. "Characteristics of Low-Carbon Data Centers." *Nature Climate Change* 3 (2013): 627-630.
[11] thinkstep. GaBi Software-System and Database for Life Cycle Engineering, 1992-2017. thinkstep AG. Accessed February 24, 2017.
[12] Arman Shehabi, Sarah Josephine Smith, Dale A. Sartor, Richard E. Brown, Magnus Herrlin, Jonathan G. Koomey, Eric R. Masanet, Nathaniel Horner, Inês Lima Azevedo, and William Lintner. *United States Data Center Energy Usage Report*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-1005775. 2016.

implementations was matched to the deployment size and architecture (that is, larger deployments are housed in larger, more efficient datacenters).

- Energy use and emissions from data flows over the internet were estimated based on assumed typical data flow rates by application type. A kWh/gigabyte (GB) factor was used to estimate electricity consumption,[13] and emissions were calculated based on the carbon intensity of the electric grid where the datacenter is located.

End-of-life disposal

- End-of-life disposal includes emissions associated with landfill and recycling for servers, hard disk drives, and network switches.[14]
- The model assumes a conservative recycling rate of 20 percent. Even with a low assumed recycling rate, these emissions are negative due to the credit based on avoided use of virgin material from recycling.
- End-of-life emissions are amortized over the assumed lifetime of the device.

Model exclusions

Unless otherwise noted, the following are excluded given their negligible impact:

- Embedded carbon in the building, including cooling and air conditioning equipment.
- Microsoft corporate overhead, including administration and software development.
- Upstream emissions from extracting the fuel used to power the electric grid.
- Embedded emissions for certain IT equipment not exclusively used by the modeled service, such as datacenter switches not located in the server racks.

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[13] Joshua Aslan, Kieren Mayers, Jonathan G. Koomey, and Chris France. "Electricity intensity of Internet data transmission: Untangling the estimates." *Journal of Industrial Ecology*. doi:10.1111/jiec.12630. August 1, 2017.

[14] E. Masanet, et al. *Optimization of product life cycles to reduce greenhouse gas emissions in California*. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2005-110-F. August 5, 2005.

Appendix III:

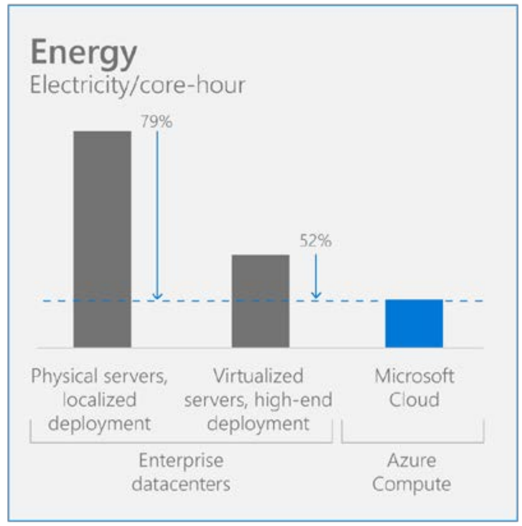
Energy and carbon benefits of Microsoft Cloud services

The following pages provide standalone datasheets that summarize the energy and carbon benefits of using each of the Microsoft Cloud services covered in this paper: Azure Compute, Azure Storage, Exchange Online, and SharePoint Online.

Azure Compute

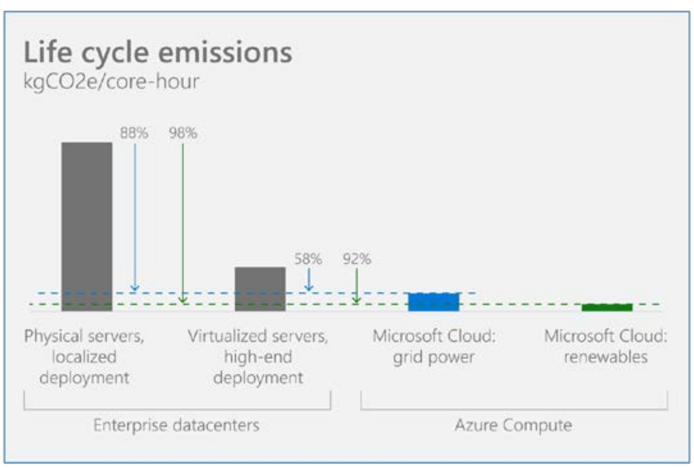
We conducted a study with industry experts to determine the energy use and carbon emissions associated with Azure Compute compared with compute equivalents deployed in traditional enterprise datacenters. Our methodology considered the impact of the IT equipment and operations, datacenter infrastructure, and information flows over the internet required to provide a cloud service and its traditional on-premises equivalent.

The results show that **Azure Compute is 52–79 percent more energy efficient** than compute equivalents deployed in traditional enterprise datacenters *(right)*, depending on the type of enterprise deployment.



In addition to providing greater energy efficiency through the Microsoft Cloud, we purchase renewable electricity for more than 95 percent of our consumption, which includes the datacenters that power Azure Compute. **When renewable energy is taken into account, carbon emissions from Azure Compute are 92–98 percent lower** than traditional enterprise datacenter deployments of compute equivalents *(below)*.

The graph below shows the emissions savings of transitioning compute functions from traditional enterprise datacenters to the Microsoft Cloud, using two approaches: (1) reflecting emissions associated with standard grid power for the Microsoft Cloud datacenters; and (2) taking into account zero carbon emissions associated with renewable electricity purchased for the Microsoft Cloud datacenters.

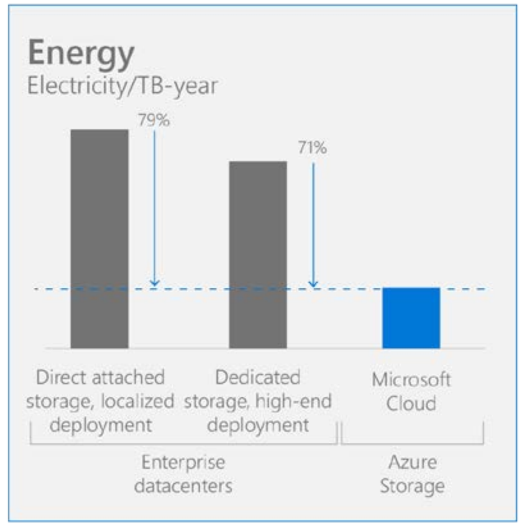


kgCO2e = *kilograms of carbon dioxide equivalent.*
Microsoft Cloud: grid power *includes emissions associated with datacenter electricity consumption before taking into account the purchase of renewable electricity.*
Microsoft Cloud: renewables *reflects zero emissions for renewable electricity purchased for datacenters. The residual emissions are primarily from life cycle emissions not associated with datacenter operations.*

Azure Storage

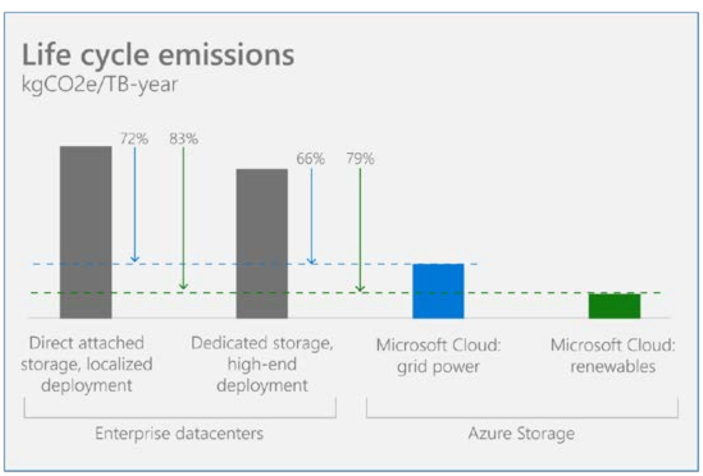
We conducted a study with industry experts to determine the energy use and carbon emissions associated with Azure Storage compared with storage equivalents deployed in traditional enterprise datacenters. Our methodology considered the impact of the IT equipment and operations, datacenter infrastructure, and information flows over the internet required to provide a cloud service and its traditional on-premises equivalent.

The results show that **Azure Storage is 71–79 percent more energy efficient** than storage equivalents deployed in traditional enterprise datacenters *(right)*, depending on the type of enterprise deployment.



In addition to providing greater energy efficiency through the Microsoft Cloud, we purchase renewable electricity for more than 95 percent of our consumption, which includes the datacenters that power Azure Storage. **When renewable energy is taken into account, carbon emissions from Azure Storage are 79–83 percent lower** than traditional enterprise datacenter deployments of storage equivalents *(below)*.

The graph below shows the emissions savings of transitioning storage from traditional enterprise datacenters to the Microsoft Cloud using two approaches: (1) reflecting emissions associated with standard grid power for the Microsoft Cloud datacenters; and (2) taking into account zero carbon emissions associated with renewable electricity purchased for the Microsoft Cloud datacenters.

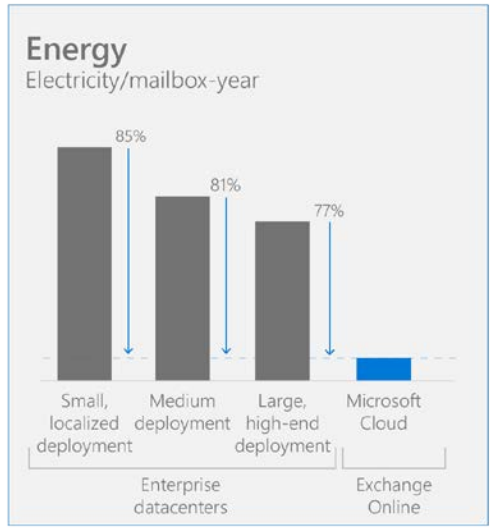


kgCO2e = *kilograms of carbon dioxide equivalent.*
Microsoft Cloud: grid power *includes emissions associated with datacenter electricity consumption before taking into account the purchase of renewable electricity.*
Microsoft Cloud: renewables *reflects zero emissions for renewable electricity purchased for datacenters. The residual emissions are primarily from life cycle emissions not associated with datacenter operations.*

Exchange Online

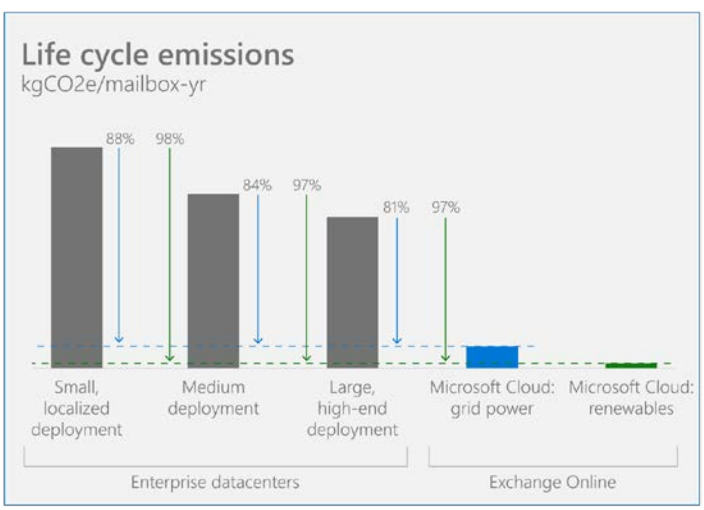
We conducted a study with industry experts to determine the energy use and carbon emissions associated with Exchange Online compared with Microsoft Exchange deployed in traditional enterprise datacenters. Our methodology considers the impact of the IT equipment and operations, datacenter infrastructure, and information flows over the internet required to provide a cloud service and its traditional on-premises equivalent.

The results show that **Exchange Online is 77–85 percent more energy efficient** than Microsoft Exchange deployed in traditional enterprise datacenters *(right)*, depending on the size of the enterprise deployment.



In addition to providing greater energy efficiency through the Microsoft Cloud, we purchase renewable electricity for more than 95 percent of our consumption, which includes the datacenters that power Exchange Online. **When renewable energy is taken into account, carbon emissions from Exchange Online are 97-98 percent lower** than traditional enterprise datacenter deployments of Exchange *(below)*.

The graph below shows the emissions savings of transitioning Exchange from traditional enterprise datacenters to the Microsoft Cloud using two approaches: (1) reflecting emissions associated with standard grid power for the Microsoft Cloud datacenters; and (2) taking into account zero carbon emissions associated with renewable electricity purchased for the Microsoft Cloud datacenters.

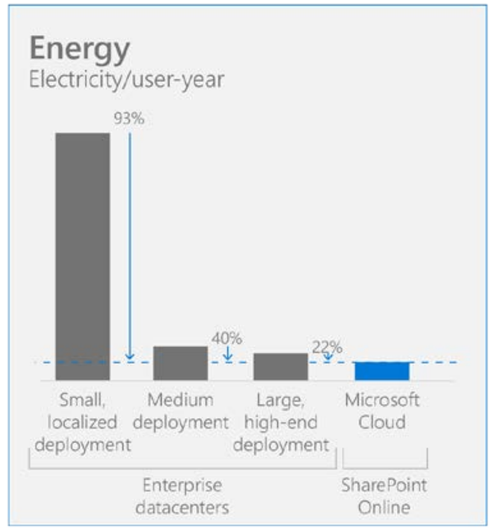


kgCO2e = *kilograms of carbon dioxide equivalent.*
Microsoft Cloud: grid power *includes emissions associated with datacenter electricity consumption before taking into account the purchase of renewable electricity.*
Microsoft Cloud: renewables *reflects zero emissions for renewable electricity purchased for datacenters. The residual emissions are primarily from life cycle emissions not associated with datacenter operations.*

SharePoint Online

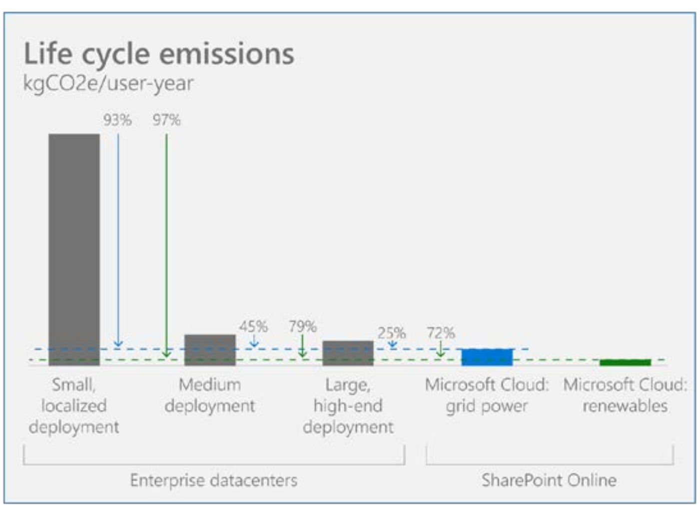
We conducted a study with industry experts to determine the energy use and carbon emissions associated with SharePoint Online compared with SharePoint deployed in traditional enterprise datacenters. Our methodology considers the impact of the IT equipment and operations, datacenter infrastructure, and information flows over the internet required to provide a cloud service and its traditional on-premises equivalent.

The results show that **SharePoint Online is 22–93 percent more energy efficient** than SharePoint deployed in traditional enterprise datacenters *(right)*, depending on the size of the deployment in the enterprise datacenter (small, medium, or large).



In addition to providing greater energy efficiency through the Microsoft Cloud, we purchase renewable electricity for more than 95 percent of our consumption, which includes the datacenters that power SharePoint Online. **When renewable energy is taken into account, carbon emissions from SharePoint Online are 72–97 percent lower** than traditional enterprise datacenter deployments of SharePoint *(below)*.

The graph below shows the emissions savings of transitioning SharePoint from traditional enterprise datacenters to the Microsoft Cloud using two approaches: (1) taking into account emissions associated with standard grid power for the Microsoft Cloud datacenters; and (2) taking into account zero carbon emissions associated with renewable electricity purchased for the Microsoft Cloud datacenters.



kgCO2e = *kilograms of carbon dioxide equivalent*.
Microsoft Cloud: grid power *includes emissions associated with datacenter electricity consumption before taking into account the purchase of renewable electricity.*
Microsoft Cloud: renewables *reflects zero emissions for renewable electricity purchased for datacenters. The residual emissions are primarily from life cycle emissions not associated with datacenter operations.*

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