

RESEARCH

Open Access



# Assessing the suitability of the Greenhouse Gas Protocol for calculation of emissions from public cloud computing workloads

David Mytton

## Abstract

Efficiency improvements over the past decade have meant that data center energy usage has decoupled from the growth in IT workloads. Much of this efficiency improvement has been attributed to innovations made by “hyperscale” public cloud vendors, where a large proportion of new IT workloads are now being deployed. However, the move to the cloud is making it more difficult to assess the environmental impact of workloads deployed there. Although the large cloud vendors are amongst the largest purchasers of renewable electricity, customers do not have access to the data they need to complete emissions assessments under the Greenhouse Gas Protocol. Data such as Power Usage Effectiveness, emissions factors and equipment embodied energy are not available from public cloud vendors. This paper demonstrates how the Greenhouse Gas Protocol method of assessment of IT emissions does not work for public cloud environments and suggests how this can be tackled by the cloud vendors themselves.

**Keywords:** Cloud computing, Cloud environmental impact, Greenhouse gas Protocol, Data center emissions, IT emissions

## Introduction

Estimates of annual data center electricity usage vary from 200 terawatt hours (TWh) [43] to 500 TWh [11]. The lower of these figures would suggest that data centers consume 1% of global electricity [43], but this could be significantly higher. One study suggests that global data center energy usage was 270 TWh in 2012 [66]. Another study estimates that 104 TWh will be used by European Union data centers in 2020, which makes a global total of 200 TWh unlikely [9].

This uncertainty also extends to efficiency estimations. As of 2018, IT (Information Technology) workloads have grown significantly compared to 2010 -  $\times 6$  more compute instances,  $\times 10$  more network traffic and  $\times 25$  more storage in 2018, yet it is reported that data center energy usage has only grown by 6% over that time [49].

Some reports support this by showing that average Power Usage Effectiveness (PUE) is improving [9], but industry survey data suggests average PUE values have plateaued [45]. Future energy usage is uncertain: efficiency improvements may be “frozen” [61] and some scenarios suggest data center energy usage could double by 2030 [7].

Whether data center energy usage grows modestly or increases significantly, even with the increasing use of renewables in the technology sector [44] data center emissions and other associated environmental impacts still need to be accounted for.

In the past, IT was run in-house (also known as “on-premise”). IT teams would buy physical servers, disks and network devices from vendors such as Dell, Seagate and Cisco, then install them into data centers. These data centers might be built and operated by the company itself, or space would be rented (“co-located”) in large scale facilities, such as those run by

Correspondence: [david@davidmytton.co.uk](mailto:david@davidmytton.co.uk)  
Imperial College London, Centre for Environmental Policy, The Weeks Building, 16-18 Prince's Gardens, London SW7 1NE, UK



© The Author(s). 2020 **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Digital Realty or Equinix. The company would pay for the space required to deploy the number of servers they needed, install internet access and purchase power, typically over-provisioning their equipment to ensure they had spare capacity.

IT applications running on physical hardware have a known (or knowable) footprint. The equipment is self-contained and can be traced to a manufacturer so the embodied cost of components can be calculated. Data center characteristics such as power and cooling levels can be monitored. Emissions factors for the electricity mix can be determined. As such, it is possible to calculate the environmental footprint of a deployment.

Guidelines exist for creating energy efficient data centers [38] and metrics such as Power Usage Effectiveness (PUE) can be calculated [40].

PUE is a widely used metric and often cited to show progress in data center efficiency. For example, Google publishes quarterly and trailing 12-month PUE values going back to 2008 for their global fleet of 15 data centers [29]; the latest Google Q1 2020 fleet wide PUE is 1.09. However, PUE has been criticised when used as a measure of efficiency because it only considers energy. PUE can decrease when IT load increases even though efficiency may not have improved [16]. It has also been shown to correlate poorly with carbon emissions [47, 48] and should not be the only metric tracked [70].

Water Usage Effectiveness as a site based metric (WUE), combined with its complementary source based metric ( $WUE_{source}$ ) [57], are important environmental indicators because of the large volumes of water that data centers require, projected to be 660 billion litres for US data centers in 2020 [60]. Most of this water is used in electricity generation, which is why the  $WUE_{source}$  metric includes external water intensity factors, not just the operational water usage at a point in time [57]. Although moving to renewable sources of electricity generation helps reduce  $WUE_{source}$  because wind and solar energy have low water footprints [64], less than a third of data center operators track any water metrics [36]. Facebook is one of the few companies who report both PUE and WUE figures publicly [21]. Other metrics such as Renewable Energy Factor (REF) [41] and Energy Reuse Factor (ERF) [39] exist as international standards but are difficult to find in public disclosures.

Understanding when to refresh hardware is another element to consider. In a survey of European data centers, IT equipment older than 5 years was shown to consume 66% of energy despite only representing 7% of capacity [11]. However, replacing equipment less than 4.5 years old may cost more in hardware

than is saved on energy efficiency [11]. This highlights the importance of lifecycle analysis because hardware refresh rates and overall utilisation impact the environmental footprint of a data center, potentially offering more energy savings than decreasing PUE [10].

With the availability of cloud computing services from vendors such as Amazon Web Services (AWS), Google Cloud Platform (GCP) and Microsoft Azure, workloads are increasingly being deployed into public cloud services [23]. This trend is demonstrated by the growth of the global cloud computing market over the last decade. From just under \$6bn in 2008, as of 2019 it had reached \$208bn and is projected to grow to \$236bn in 2020 [23]. Server equipment purchases are growing at 3% per year, almost entirely attributable to “hyperscale” cloud vendors [60]. Estimates suggest 40% of servers will be in hyperscale data centers in 2020 [60].

This move to the cloud has made it much more difficult to estimate associated emissions. Public cloud vendor customers purchase virtual services so it is difficult to know what underlying physical resources are used because they have been abstracted by complex software or platform layers. Customers migrating to the cloud must also ensure their cloud architecture is equivalent to their on-premise hardware deployments in terms of availability and redundancy to ensure that comparisons are accurate. Cloud vendor customers have no insight into the energy usage of the services they buy, and often do not even know how many physical servers their applications are running on. Instead, they pay for precise usage such as CPU time, allocated memory or execution time. In theory the price should include the full costs of components like power and disks, but the number is not transparent. Much is hidden behind opaque cloud vendor pricing. Some vendors have used marketing efforts to explain why public cloud is “greener” than on-premise [1, 51] but do not provide specific, detailed numbers behind their claims. Models such as CLEER [47, 48] can make assumptions, but there are so many variables that their accuracy is questionable, particularly across use cases and as the model ages.

With an increased public awareness of environmental issues [69] and more businesses being covered by mandatory reporting [20], cloud vendor customers should expect to be able to calculate the environmental footprint of their IT environment just as if they were running it on-premise. This has been possible historically: the GHG Protocol reporting guidance assumes a range of measures such as server count, data center PUE and capacity are available [27].

However, the current approach by public cloud computing vendors makes it difficult to obtain that information.

Several studies [13–15, 17, 24, 25] have proposed new approaches where workloads can be dynamically moved based on various “follow-the-renewables” criteria [15] about the underlying data center e.g. regional wind power availability. These techniques can work well if the system has access to data to make the right decisions e.g. emissions factors related to the data center energy input, external temperatures related to cooling requirements, wind speeds in the relevant geographies for each data center, etc. If the customer is running their own data center or is deployed in a co-location facility, then they should be able to get access to this information. However, this is not possible with public cloud. As this paper will discuss, the major cloud providers do not release most of these underlying data, and if they report anything it is usually only in aggregate, not real-time.

This paper develops a framework for understanding the boundaries of a public cloud computing environment, then uses that framework to evaluate whether the Greenhouse Gas (GHG) Protocol is suitable for calculating emissions from cloud workloads. It also considers what cloud vendors have done and should do in the future to allow customers of public cloud to calculate their own environmental footprint.

### Defining cloud vendor components

A Cloud Vendor is a commercial organisation that builds and operates the cloud services. These are sold to the public whereby anyone can sign up with a credit card to become a customer, usually on a pay-as-you-go basis. The components which make up the Cloud Vendor are public in the sense that anyone can pay to use them, and the resources are shared amongst all customers. This is also known as “multi-tenant”. Some Cloud Vendors offer services only available to specific sectors e.g. AWS GovCloud for the United States Government, and some products from Cloud Vendors are run in private data centers e.g. Azure Stack, but for the purposes of this paper, a Cloud Vendor is one which primarily sells on a public model. Private clouds run by organisations on their own on-premise equipment are excluded from this definition.

The core cloud services are the three Primitives: Compute, Storage and Networking.

1. **Compute** is most commonly in the form of Virtual Machines (VMs) sized based on the desired quantity of memory (RAM) and processor (CPU)

cores, then billed based on the number of seconds or minutes the VM is running. VMs are known as “multi-tenant” because they run on physical server resources shared amongst other customers. This contrasts with Dedicated Hosts (e.g. from [3]), and is one of the reasons why Cloud Vendors can achieve high efficiency at “hyperscale” [47, 48, 60]. Other Compute units also exist, such as those sold through products like AWS Lambda or Google Cloud Functions. These are billed only whilst the code is executing with fees based on CPU and memory used over the (usually per hundred millisecond) execution time [32].

2. **Storage** exists in the form of arbitrarily sized disk volumes which can be attached to VMs, mimicking physical disk drives in servers. Different types of volume exist depending on the performance requirements e.g. solid-state disk (SSD) vs spinning disk [33]. Other types of storage are available, such as AWS Simple Storage Service (S3) which was one of the original cloud services launched in 2006 [2].
3. **Networking** links all the services together with internal and public data transfer from network interfaces attached to VMs through to virtual load balancers and firewalls. These exist as a Software Defined Network (SDN) as opposed to dedicated, physical devices for each customer.

Cloud Vendors also offer a range of other Software Services, such as Databases and Queues. These are supporting infrastructure services used by customers in their own applications but are built and maintained by the Cloud Vendor, ultimately running on top of the Primitives. If a customer is using a Database they are also making use of Primitives, but these are abstracted away so the customer is unaware. This can be seen when a Primitive component suffers an outage that then affects many other services which rely on it, such as the June 2019 GCP Networking Incident [31].

Just like their physical equivalents, Primitives run inside data centers located in specific geographical regions operated by the Cloud Vendor. Customers can choose in which region they wish to deploy their resources, and different regions have different pricing e.g. an AWS EC2 t3.micro VM instance running in N. Virginia, USA costs \$0.0104/h whereas the same instance type running in Sydney, Australia costs \$0.0132/h [4]. Bandwidth costs also vary with some regions being significantly more expensive than others e.g. data transfer in Oceania is  $\times 17$  more expensive than Europe [58].

These Primitives are visible to the customer. It is the underlying physical infrastructure that is hidden — the servers, disks, routing equipment housed inside a cooled data center facility, powered by electricity. This means the customer has no insight into the equipment lifecycle or the electricity required to cool and power that equipment. This change from managing on-premise equipment not only abstracts away the underlying infrastructure, it subsequently abstracts the environmental impact caused by that equipment. For example, the location of a data center has a strong relationship to energy usage due to local climate conditions, seasonality, and the emissions factor of the power mix for the electricity grid the data center is connected to [46].

To understand the full environmental impact of cloud environments, we must consider all components that make up “cloud” services (Fig. 1).

**Using the GHG Protocol to assess cloud vendor emissions**

The GHG Protocol Guidance for the ICT Sector [27] Section 4.5 provides an accounting method for

calculating GHG emissions related to data centers. This section discusses whether the GHG Protocol is appropriate to assess Cloud Vendor emissions.

**Assessment of GHG Protocol required primary data from the perspective of a cloud vendor customer**

The tables below examine each primary data input required to calculate data center emissions under the GHG Protocol Guidance for the ICT Sector [27]. This shows that the guidance is appropriate from the perspective of the Cloud Vendor but that this does not translate to the perspective of a Cloud Vendor customer. The three largest Cloud Vendors by usage [22] – Amazon Web Services (AWS), Microsoft Azure (Azure) and Google Cloud Platform (GCP) – are used to analyse whether the data is available to Cloud Vendor customers.

The first column describes the data item as taken from the GHG Protocol Guidance. The second column assesses whether this data is available from the perspective of a Cloud Vendor customer.

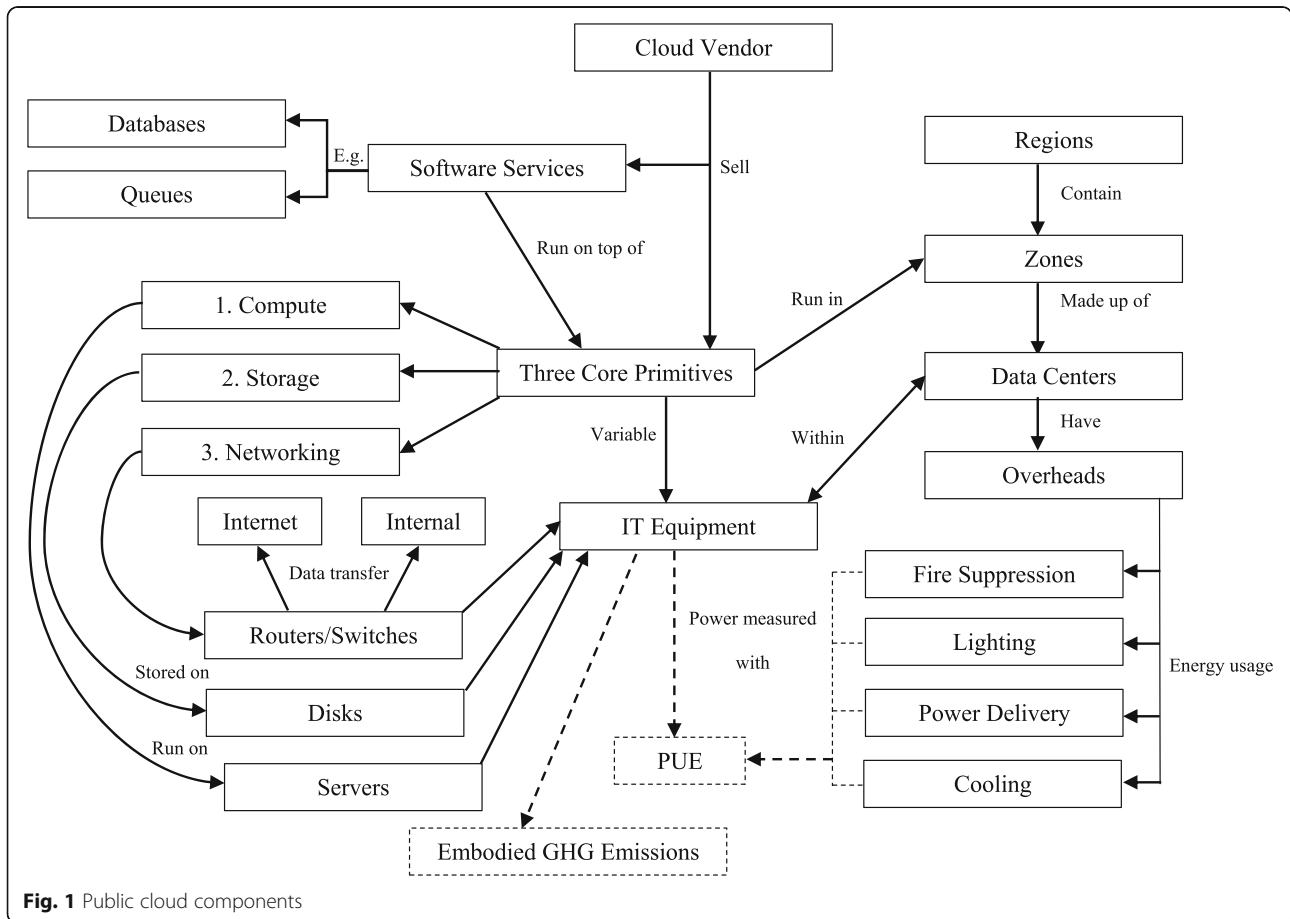


Fig. 1 Public cloud components

**Table 1** Availability assessment of primary data item - users - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“use profiles and number of users at any given period of time”	<b>Yes</b> – if relevant, this can be calculated based on application usage over a given period. Transactions may be an alternative (below).

**Users (Table 1)**

**Licensing or service level agreements (Table 2)**

**Transactions (Table 3)**

**Data centers (Table 4)**

**Server count (Table 5)**

**Network link equipment count (Table 6)**

**Device utilisation (Table 7)**

**Power consumption by type of IT hardware (Table 8)**

**Data center Power Usage Effectiveness (PUE) (Table 9)**

**Emission factors - equipment (Table 10)**

**Emission factors - electricity (Table 11)**

**Assessment of GHG Protocol required secondary data from the perspective of a cloud vendor customer**

The GHG Protocol suggests using certain secondary data if the above primary sources are unavailable: “Internet transfer” and “Embodied emissions for hardware” [27].

**Internet transfer and the network**

Internet transfer is derived by using estimates of the energy intensity of the internet: 0.06 kWh/GB for fixed line networks in 2015 [8]. This study also shows this number decreasing by 50% every 2 years.

However, this only considers external traffic on the internet – it does not account for internal network traffic which makes up a significant amount of data transfer [42] and is doubling every 12–15 months [62]. Mobile

**Table 2** Availability assessment of primary data item - licensing or service level agreements - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“the units of service defined, for example, the number of users for a specified period of time”	<b>Yes</b> – if relevant, this can be calculated based on application usage over a given period.

**Table 3** Availability assessment of primary data item - transactions - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“for example, measured IOPS (input-output operations per second) or WebAPIs/requests processed by the platform, over a specified time period”	<b>Yes</b> – if relevant, this can be calculated based on the application usage over a given period. Users may be an alternative (above).

traffic is another significant exclusion when 71% of the global population expected to have mobile connectivity by 2023 and smartphone traffic growing 7% annually [18]. Examining mobile connectivity is an opportunity area for future research.

**Embodied GHG emissions**

“Embodied emissions for hardware” cannot be calculated without details of the underlying hardware, which are not provided by any Cloud Vendor.

**Data center capacity**

Data center capacity is used in the GHG Protocol guidelines and consists of calculating energy (in kWh) and capacity (in kilowatts or floor area). These figures are not provided by Cloud Vendors.

A 2019 Greenpeace report [19] produced estimates of overall capacity in Virginia, USA, one of the largest data center regions, by using Freedom of Information

**Table 4** Availability assessment of primary data item - data centers - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“number and location”	<b>Partial</b> – the customer can determine which location (region) they deploy to, but the concept of “zones” cannot necessarily be mapped to a single data center.  For example, Google Cloud Platform has the concept of Zones within Regions. The Region location is defined but the Zone location is not. A Zone may be one or many clusters where a cluster represents distinct physical infrastructure (power, cooling, network) within a data center. Further, zones are not necessarily physical, potentially differing across customers [34].  For certain types of Compute Primitives e.g. Azure Functions, code is deployed to a specific region but there may be multiple zones within the region and a zone may be one or many physical data centers [53]. AWS has a single region in Virginia [6] but has 55 physical data centers in that geography [19].

**Table 5** Availability assessment of primary data item - server count - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“number of servers provisioned to host and fulfill the cloud application and data storage requirements. This includes redundancy for business continuity and disaster recovery”	<b>Partial</b> – the customer can determine which location (region) they deploy to. For VMs as Compute Primitives there is usually a one to one relationship between a VM running on (part of) a single physical server. However, it may not always be the same physical server if the VM is live migrated [35]. For other types of Compute Primitives e.g. Azure Functions, requests may be served across multiple servers.

requests to obtain backup generator permits, publicly reported lease details and renewable energy deals. This approach allows an estimate of the overall data center GHG emissions to be calculated for a specific geography, but does not provide enough granularity for individual Cloud Vendor customers to calculate their specific GHG emissions, particularly if deployed in different regions around the world.

Using data center capacity to calculate GHG emissions for an individual customer is not practical because capacity is shared by many customers even on a single server within a single data center. This approach only works if customer equipment takes up physical space in the data center (or the virtual equivalent).

**Results**

The GHG Protocol provides a methodology for assessing data center emissions but it assumes that the assessor has access to various data inputs. The assessment above demonstrates that these inputs are not available to Cloud Vendor customers. This means that the GHG Protocol cannot be used by a Cloud Vendor customer to calculate their GHG emissions – they do not have the data to do so.

GHG Protocol [27] Section 4.6.2 acknowledges that it is challenging to make assessments in public cloud environments and suggests an alternative approach based on

**Table 6** Availability assessment of primary data item - network link equipment count - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“number of in-data-center routers and switches required to fulfill WebAPI requests and process web transactions. This includes redundancy for business continuity and disaster recovery”	<b>No</b> – Cloud Vendor customers have no visibility of the underlying network infrastructure.

**Table 7** Availability assessment of primary data item - device utilisation - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“computational load that a device is managing relative to the specified peak load”	<b>No</b> – unless the customer selects to use dedicated hosts such as AWS/Azure Dedicated Hosts or GCP Sole-Tenant Nodes (and pays the additional costs), the Cloud Vendor provides no visibility of the utilization of the underlying devices.

estimates. However, it assumes the availability of data such as server and VM totals e.g. “Estimated count of physical servers dedicated to the service (divided by the total number of servers in the data center)”. Estimates have been made for the emissions of entire facilities, such as the Greenpeace report discussed in above. However, this does not allow calculations to be apportioned on a per customer basis because server counts are unavailable. More granular data is required.

The analysis above shows that data required to calculate emissions using the GHG Protocol is only available to Cloud Vendors. One solution is for Cloud Vendors to publish the required data so that customers can complete their own calculations. Figures such as PUE have been released by some Cloud Vendors, as discussed in Table 9, however these are too limited to satisfy the requirements of the GHG Protocol. Most of the required data is considered a competitive secret that is heavily guarded by Cloud Vendors. For example, Google has

**Table 8** Availability assessment of primary data item - power consumption by type of IT hardware - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“calculated energy consumed by a server at a given rate of device utilization and estimated power for networking and storage equipment”	<b>No</b> – no information is available about the type of underlying hardware so no energy calculations can be completed. Indeed, “hyperscale” Cloud Vendors design many of their own hardware components [30, 50] with no publicly available power assessment.  Some vendors have released their hardware designs under the open source Open Compute program, such as Microsoft’s Project Olympus [67]. This would allow independent assessment of the equipment power consumption but would require additional information about how this hardware is deployed into Microsoft Azure cloud environments.

**Table 9** Availability assessment of primary data item - data center power usage effectiveness (PUE) - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“defined as the ratio of overall power drawn by the data center facility, to the power delivered to the IT hardware. This is a data-center-specific metric and accounts for energy consumption of active cooling, power conditioning, lighting, and other critical data center infrastructure”	<p><b>Partial</b> – industry average PUE is 1.67 [65].</p> <p>AWS does not report PUE data but has a website footnote that states their internal-data shows PUE under 1.2 [5].</p> <p>GCP reports their quarterly and trailing twelve-month (TTM) PUE values for “large-scale Google Data Centers”. For Q4 2019 fleet-wide TTM PUE was 1.10 with campus specific TTM PUE ranging of 1.07–1.15 [29]. However, this does not include all GCP Regions e.g. London and Tokyo are available regions but do not have published PUE data.</p> <p>Microsoft Azure does not report PUE data but states they “have met [their] goal of averaging 1.125 power usage effectiveness (PUE) for any new datacentre” [56].</p>

barred public officials from releasing data about water usage which has resulted in controversy in drought regions [59]. As a result, the GHG Protocol is not appropriate for calculation of emissions from public cloud computing workloads by Cloud Vendor customers.

If Cloud Vendors are not willing to release the underlying data, they must be the ones to complete the calculations on behalf of their customers. The next section will consider how a Cloud Vendor might approach this calculation.

### Calculating cloud vendor emissions per customer

All Cloud Vendors provide customers with access to detailed reporting about their usage and the associated cost. By apportioning usage for billing purposes, Cloud Vendors have demonstrated they can perform detailed resource accounting to bill customers on a granular level. They can therefore do the same for apportioning GHG emissions.

**Table 10** Availability assessment of primary data item - emission factors - equipment - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
“factors for the embodied emissions of relevant IT equipment, ideally obtained from equipment manufacturers”	<b>No</b> - no information is available about the type of underlying hardware so no emission factors can be calculated.

Several Cloud Vendors have demonstrated they have the underlying data needed to calculate GHG emissions because they have produced marketing materials containing competitive comparisons [1, 51] and/or aggregated data in annual reports [28, 52]. Combined with the accounting mechanisms for billing, this should allow Cloud Vendors to provide customers with an emissions report as well. This section considers a conceptual approach for how such a report would be constructed.

### Calculation inputs

The GHG Protocol assumes that all workloads run on physical servers within a single data center, an assumption which does not hold in Cloud Vendor environments. The framework in Fig. 1 can be used alongside the GHG Protocol components discussed in section 3 to define the emissions boundary for each customer on a per cloud product/service basis.

#### Example: virtual machine (VM)

A VM is deployed for a time period in a specific zone within a specific cloud region. Cloud Vendor zones can be made up of one or more data centers [34, 53] but this is not visible - the zone is the lowest level abstraction exposed to customers. To provide a complete GHG emissions assessment, the Cloud Vendor would need the following:

- Zone accounting: the time period each VM is running in each data center that makes up the zone within the region. VM pricing is usually based on CPU core and memory allocation by hour so the relevant functional unit for the zone accounting would be the same as the billing unit. A calculation would be produced for each data center then combined to provide the zone total.
- Emissions factors – equipment: the embodied emissions for the physical equipment (servers, racks, switches, etc) assigned to support the allocated CPU core and memory in each data center that makes up the zone within the region. This must consider the total fixed embodied emissions for the lifecycle of the equipment, and the utilisation of the equipment over the period so the total can be apportioned amongst all customers utilising that equipment. Although cloud vendors tend to have high utilisation rates, these are still lower than 50% [47, 48, 60].
- Emissions factors – electricity: each data center has its own energy mix, which will change dependent upon the local electricity grid. Zone accounting provides the date and time that each VM is running in each data center so the electricity emissions factors can be applied for the relevant period. A data

**Table 11** Availability assessment of primary data item - emission factors - electricity - required under the GHG Protocol for assessment of ICT emissions

GHG Protocol Description	Data available to Cloud Vendor customers?
<p>“the emission factor for the electricity used should be appropriate for the region where the electricity is consumed. Electricity grid emission factors are published nationally, and in some cases, regionally. Electricity grid emission factors should include the full life cycle of the energy source (i.e., include emissions from extraction and transportation of the fuel, as well as generation and transmission of electricity)”</p>	<p><b>Partial</b> – since actual electricity usage data is not provided by the Cloud Vendor, a regional average GHG emissions factor must be used [27]. Following the GHG Protocol Scope 2 Guidelines [26] would allow the factor to be determined.</p> <p>Each Cloud Vendor has a different electricity generation mix for each data center. For example, AWS reports that as of June 2015 the AWS “average power mix carbon intensity is 393 g/kWh” [12]. In 2015 Google reports a data center carbon intensity of 0.242 tCO<sub>2</sub>e/MWh which has reduced to 0.0495 tCO<sub>2</sub>e/MWh in 2018 [28]. Further, Google reports it has purchased 100% renewable energy to match its usage since 2017 [37].</p> <p>However, a customer cannot complete the calculation unless the GHG emissions factor can be linked to activity.</p>

center PUE calculation will allow the total electricity input to be apportioned between the fixed data center energy costs and the IT equipment.

#### **Example: serverless function**

Serverless functions are an emerging cloud computing technique [63] which allow small units of code to be executed in response to events, only using resources when they are triggered, and billed based on execution time in milliseconds. This allows them to be very efficient by only running when needed, but complicates accounting because it requires resources to be split into very small units across physical resources. Serverless products from Amazon, Google and Microsoft are deployed at a regional level which means for each instantiation a serverless function could execute on a different server in a different data center in a different zone.

This complicates emissions calculations and means the accounting mechanism needs to track the execution across many physical devices. Once this has been achieved the same approach as with a VM (4.1.1 above) would apply, but with the functional unit changing to match the billing unit for the Cloud Vendor product.

#### **Calculation output**

With the above data, a GHG emissions factor could be derived for each of the Cloud Primitives on a usage basis e.g. Compute emissions in CO<sub>2</sub> equivalent per second of usage per Zone. Once assigned to the Primitives, all services based on those Primitives can also provide a GHG emissions calculation. This would then be combined by the existing usage and billing data to report total GHG emissions to the customer.

#### **Microsoft sustainability calculator**

In Jan 2020, Microsoft announced the availability of a “Sustainability Calculator” [68] which allows customers of the Microsoft Azure cloud platform to calculate the carbon emissions of their cloud resources.

Based on the methodology in a 2018 paper [51], Microsoft is applying the approach described in GHG Protocol [27] using their internal data to provide a value that can be reported by their customers under Scope 3 Category 1 emissions. The paper describes using the same inputs as above (section 4.1.1) with the same boundaries shown in Fig. 1.

The Sustainability Calculator provides a geographic view of emissions by calculating the local electricity carbon intensity for each region the customer has deployed resources to. It considers the energy intensity of internet traffic between Microsoft data centers and by third party connectivity. The 2018 paper [51] uses the estimates in Aslan et al. [8] but it is not clear precisely which value has been applied to the Sustainability Calculator e.g. has it been adjusted to match the predicted decreases in the energy intensity.

Embodied emissions used by networking infrastructure outside of the specific application were excluded from the 2018 paper model, so it is unclear if they are included in the Sustainability Calculator. The calculator factors in efficiencies gained from the utilisation, provisioning and multi-tenancy benefits of cloud computing, however Microsoft has not released numbers demonstrating what these values are. There is no indication that the efficiency is better than the values provided by Masanet et al. [47, 48] and Shehabi et al. [60]. Embedded emissions in the IT equipment (including the full lifecycle emissions and disposal with a 20% recycle rate) are considered in the model but are sourced from Masanet et al. [47, 48] rather than Microsoft equipment specific values. Transportation of equipment is included in these estimates. Embedded emissions in the building and cooling systems are excluded. Energy during device utilisation is measured directly.

The result of the Sustainability Calculator is a number presented to the customer measured in total metric tons of carbon dioxide equivalent (MTCO<sub>2</sub>e). Gross emissions



without offsets are indicated alongside a net figure which includes the offsets purchased by Microsoft.

Microsoft has made the Sustainability Calculator available as an add-on to its PowerBI product [54]. Although the add-on itself is free of charge, PowerBI is not a free product and the Sustainability Calculator add-on is only available to Azure Enterprise customers [55]. As such, for the purposes of this paper the calculator could only be tested using sample data only.

The Sustainability Calculator is an example of an implementation of the conceptual approach described in this paper. It uses a published methodology [51] and has been independently verified [68]. Within the Sustainability Calculator user interface it notes:

"As part of the app's development, the methodology and its implementation went through third-party verification to ensure that it aligns to the World Resources Institute (WRI)/World Business Council for Sustainable Development (WBCSD) Greenhouse Gas (GHG) Protocol Corporate Accounting and Reporting Standard. The scope of the verification, conducted in accordance with ISO 14064-3: Greenhouse gases -- Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions, included the estimation of emissions from Azure service ... "

Whilst there are areas where additional transparency in the model and numbers would be beneficial to be able to fully assess against the relevant literature, and only certain "Enterprise" customers can access the Sustainability Calculator, Microsoft is currently the only Cloud Vendor offering customer-level reporting.

## Conclusion

The analysis in this paper has demonstrated that the GHG Protocol is not suitable for customers to assess the emissions of their IT environments located in the public cloud because the required information to calculate emissions is not provided by Cloud Vendors.

The GHG Protocol makes assumptions about the availability of data such as IT equipment embodied emissions and utilisation, which are not available to Cloud Vendor customers. Where metrics are provided, such as PUE, these are not published on a granular enough level due to how Core Primitives such as Compute and Storage are sold to customers. For example, the precise data center location is not revealed to Cloud Vendor Customers who instead are restricted to visibility of a "zone" or "region" that does not necessarily map to a physical facility. Even the secondary data suggested for use in cloud environments by the GHG Protocol –

estimated server counts for the workload and total number of servers in the data center - are unavailable.

Further, the GHG Protocol only considers a single metric – PUE – in its calculations. The criticisms of PUE discussed in section 1 show that other metrics such as  $WUE_{source}$ , REF, ERF and equipment refresh rates are just as important to understand the overall environmental footprint of a data center. This all suggests that the GHG Protocol is no longer relevant in a world where the majority of workloads are deployed in the cloud.

The solutions to this problem are limited. Transparency is necessary to assess the environmental footprint of any product or service. The lack of data makes it impossible for Cloud Vendor customers to comply with reporting requirements if they wish to include Scope 3 emissions. Either Cloud Vendors must release all the necessary data to allow customers to complete their own calculations or they must perform the calculations on behalf of their customers. Given how secretive the Cloud Vendors tend to be, the former is unlikely. As such, Cloud Vendors will need to provide the calculations in a GHG Protocol compliant manner instead.

Microsoft is the only Cloud Vendor offering this, having released a Sustainability Calculator in January 2020. However, it is limited to a small sub-set of customers.

To date, environmental sustainability has primarily been a marketing tactic for Cloud Vendors. All the marketing materials suggest that moving to the cloud can reduce your IT environmental footprint. Indeed, the big Cloud Vendors are the largest purchasers of renewable energy, have the lowest PUE values and are innovating with efficient, custom designed equipment. However, all this means little until those efforts can be backed by environmental data.

Cloud Vendors have been able to ignore this to-date, keeping their environmental efforts internal and vague. As climate risk increases, timely environmental data will become just as important as accurate accounting information. Cloud Vendors need to develop Sustainability Calculators available to all.

## Abbreviations

AWS: Amazon Web Services; CO<sub>2</sub>: Carbon Dioxide; CPU: Central Processing Unit; EC2: AWS Elastic Compute Cloud; ERF: Energy Reuse Factor; GCP: Google Cloud Platform; GHG: Greenhouse Gas; kWh/GB: Kilowatt hour per gigabyte; IT: Information Technology; ICT: Information Communication Technology; Iops: Input-output operations per second; MTCO<sub>2</sub>e: Metric tons of carbon dioxide equivalent; PUE: Power Usage Effectiveness; RAM: Random Access Memory; REF: Renewable Energy Factor; S3: AWS Simple Storage Service; SDN: Software Defined Network; SSD: Solid-State Disk; tCO<sub>2</sub>e/MWh: Tonnes of Carbon Dioxide Equivalent per Megawatt Hour; TWh: Terawatt hours; VM: Virtual Machine; WUE: Water Usage Effectiveness

## Acknowledgements

Not applicable.

**Author's contributions**

The author(s) read and approved the final manuscript.

**Authors' information**

Not applicable.

**Funding**

None.

**Availability of data and materials**

Not applicable.

**Competing interests**

David Mytton has a financial interest in StackPath, LLC., an edge computing company that has products which compete with those offered by the cloud vendors mentioned in this paper.

Received: 24 March 2020 Accepted: 24 June 2020

Published online: 08 August 2020

**References**

- Accenture (2010) Cloud Computing and Sustainability: The Environmental Benefits of Moving to the Cloud. Available from: <https://download.microsoft.com/download/A/F/F/AFFEB671-FA27-45CF-9373-0655247751CF/Cloud%20Computing%20and%20Sustainability%20-%20Whitepaper%20-%20Nov%202010.pdf> [Accessed 21 Mar 2020]
- Amazon. (2006) Amazon Web Services Launches. Available from: <https://press.aboutamazon.com/news-releases/news-release-details/amazon-web-services-launches-amazon-s3-simple-storage-service> [Accessed 21 Mar 2020]
- Amazon. (2020c) Amazon EC2 Dedicated Hosts. Available from: <https://aws.amazon.com/ec2/dedicated-hosts/> [Accessed 21 Mar 2020]
- Amazon. (2020d) Amazon EC2 Instance Pricing. Available from: <https://aws.amazon.com/ec2/pricing/on-demand/> [Accessed 21 Mar 2020]
- Amazon. (2020e) AWS & Sustainability. Available from: <https://aws.amazon.com/about-aws/sustainability/> [Accessed 21 Mar 2020]
- Amazon. (2020f) Regions, Availability Zones, and Local Zones. Available from <https://docs.aws.amazon.com/AWSEC2/latest/UserGuide/using-regions-availability-zones.html> [Accessed 21 Mar 2020]
- Andrae AS, Edler T (2015) On global electricity usage of communication technology: trends to 2030. *Challenges* 6(1):117–157. <https://doi.org/10.3390/challe6010117>
- Aslan J, Mayers K, Koomey JG, France C (2018) Electricity intensity of internet data transmission: untangling the estimates. *J Industrial Ecol* 22(4): 785–798. <https://doi.org/10.1111/jiec.12630>
- Avgerinou M, Bertoldi P, Castellazzi L (2017) Trends in data Centre energy consumption under the European code of conduct for data Centre energy efficiency. *Energies* 10(10):1470. <https://doi.org/10.3390/en10101470>
- Bashroush R (2018) A comprehensive reasoning framework for hardware refresh in data centers. *IEEE Transact Sustain Comput* 3(4):209–220. <https://doi.org/10.1109/TSUSC.2018.2795465>
- Bashroush R, Lawrence A (2020) Beyond PUE: tackling IT's wasted terawatts. Uptime Institute Available from: <https://uptimeinstitute.com/beyond-pue-tackling-it-s-wasted-terawatts> [Accessed 11 June 2020]
- Barr J (2015) Cloud computing, server utilization, & the environment. AWS News Blog Available from: <https://aws.amazon.com/blogs/aws/cloud-computing-server-utilization-the-environment/> [Accessed 21 Mar 2020]
- Basmdjian R (2019) Flexibility-based energy and demand Management in Data Centers: A case study for cloud computing. *Energies* 12(11):3301. <https://doi.org/10.3390/en12173301>
- Berl A, Gelenbe E, Di Girolamo M, Giuliani G, De Meer H, Dang M, Pentikousis K (2010) Energy-efficient cloud computing. *Comput J* 53(7): 1045–1051. <https://doi.org/10.1093/comjnl/bxp080>
- Berral JL, Goiri Í, Nguyen TD, Gavalda R, Torres J, Bianchini R (2014) Building green cloud services at low cost. In: 2014 IEEE 34th International Conference on Distributed Computing Systems, 30 June–3 July 2014. Madrid, Spain. IEEE:449–460. <https://doi.org/10.1109/ICDCS.2014.53>
- Brady GA, Kapur N, Summers JL, Thompson HM (2013) A case study and critical assessment in calculating power usage effectiveness for a data Centre. *Energ Conversion Manag* 76:155–161. <https://doi.org/10.1016/j.enconman.2013.07.035>
- Buyya R, Beloglazov A, Abawajy J (2010) Energy-efficient management of data center resources for cloud computing: a vision, architectural elements, and open challenges. arXiv 1006.0308 Available from: <https://arxiv.org/abs/1006.0308> [Accessed 21 Mar 2020]
- Cisco (2020) Cisco Annual Internet Report (2018–2023) White Paper. Cisco Available from: <https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html> [Accessed 21 Mar 2020]
- Cook G, Jardim E, Craighill C (eds) (2019) Clicking Clean Virginia The Dirty Energy Powering Data Center Alley. Greenpeace Available from: <https://www.greenpeace.org/usa/reports/click-clean-virginia/> [Accessed 21 Mar 2020]
- Department for Business, Energy & Industrial Strategy (2018) Consultation outcome: Streamlined energy and carbon reporting. Available from: <https://www.gov.uk/government/consultations/streamlined-energy-and-carbon-reporting> [Accessed 21 Mar 2020]
- Facebook (2020). Sustainability in numbers. Facebook. Available from: <https://sustainability.fb.com/sustainability-in-numbers/> [Accessed 11 Jun 2020]
- Flexera (2019) RightScale 2019 state of the cloud report from Flexera identifies cloud adoption trends. Flexera, Inc Available from: <https://www.flexera.com/about-us/press-center/rightscale-2019-state-of-the-cloud-report-from-flexera-identifies-cloud-adoption-trends.html> [Accessed 21 Mar 2020]
- Forrester (2019) Forrester data: cloud security solutions forecast, 2016 to 2021 (global). Forrester Research, Inc. Available from: <https://www.tatacommunications.com/wp-content/uploads/2019/02/Forrester-Report.pdf> [Accessed 21 Mar 2020]
- Gao Y, Zeng Z, Liu X, Kumar PR (2013) The answer is blowing in the wind: analysis of powering internet data centers with wind energy. In: 2013 Proceedings IEEE INFOCOM. IEEE, Turin, pp 520–524. <https://doi.org/10.1109/INFOCOM.2013.6566827>
- Gelenbe E (2012) Energy packet networks: adaptive energy management for the cloud. In: Proceedings of the 2nd International Workshop on Cloud Computing Platforms (CloudCP '12). Association for Computing Machinery, New York, pp 1–5. <https://doi.org/10.1145/2168697.2168698>
- GHG Protocol. (2015) GHG Protocol Scope 2 Guidance. Available from: [https://ghgprotocol.org/scope\\_2\\_guidance](https://ghgprotocol.org/scope_2_guidance) [Accessed 21 Mar 2020]
- GHG Protocol. (2017) ICT Sector Guidance built on the GHG Protocol Product Life Cycle Accounting and Reporting Standard. Available from: <https://ghgprotocol.org/sites/default/files/GHGP-ICTSG%20-%20ALL%20Chapters.pdf> [Accessed 21 Mar 2020]
- Google (2019) Environmental report 2019. Google Available from: [https://services.google.com/fh/files/misc/google\\_2019-environmental-report.pdf](https://services.google.com/fh/files/misc/google_2019-environmental-report.pdf) [Accessed 21 Mar 2020]
- Google. (2020). Data Centers: Efficiency. Available from: <https://www.google.com/about/datacenters/efficiency/> [Accessed 11 Jun 2020]
- Google Cloud Platform (GCP). (2017) Google Infrastructure Security Design Overview: Hardware Design and Provenance. Available from: [https://cloud.google.com/security/infrastructure/design/#hardware\\_design\\_and\\_provenance](https://cloud.google.com/security/infrastructure/design/#hardware_design_and_provenance) [Accessed 21 Mar 2020]
- Google Cloud Platform (GCP). (2019) Google Cloud Networking Incident #19009. Available from: <https://status.cloud.google.com/incident/cloud-networking/19009> [Accessed 21 Mar 2020]
- Google Cloud Platform (GCP). (2020a) Google Cloud Functions Pricing. Available from: <https://cloud.google.com/functions/pricing> [Accessed 21 Mar 2020]
- Google Cloud Platform (GCP). (2020b) Block Storage Performance. Available from: <https://cloud.google.com/compute/docs/disks/performance> [Accessed 21 Mar 2020]
- Google Cloud Platform (GCP). (2020c) Regions and Zones. Available from: <https://cloud.google.com/compute/docs/regions-zones/> [Accessed 21 Mar 2020]
- Google Cloud Platform (GCP). (2020d) Live Migration. Available from: <https://cloud.google.com/compute/docs/instances/live-migration> [Accessed 21 Mar 2020]
- Heslin K (2016) Ignore data center Water consumption at your own peril. Uptime Institute; Weblog Available from: <https://journal.uptimeinstitute.com/dont-ignore-water-consumption/> [Accessed 11 Jun 2020]
- Hölzle U (2018) Meeting our match: buying 100 percent renewable energy. The Keyword; Weblog Available from: <https://www.blog.google/outreach-initiatives/environment/meeting-our-match-buying-100-percent-renewable-energy/> [Accessed 21 Mar 2020]

38. Huusko J, de Meer H, Klingert S, Somov A (2012) Energy efficient data centers. Springer, Madrid. <https://doi.org/10.1007/978-3-642-33645-4>
39. International Standards Organisation (ISO). (2012) ISO/IEC DIS 30134–6 Information technology — Data centres — Key performance indicators — Part 2: Power usage effectiveness (PUE). Available from: <https://www.iso.org/standard/71717.html> [Accessed 11 Jun 2020]
40. International Standards Organisation (ISO). (2016) ISO/IEC 30134–2:2016 Information technology — Data centres — Key performance indicators — Part 2: Power usage effectiveness (PUE). Available from: <https://www.iso.org/standard/63451.html> [Accessed 11 Jun 2020]
41. International Standards Organisation (ISO). (2018) ISO/IEC 30134–3:2016/AMD 1:2018 Information technology — Data centres — Key performance indicators — Part 3: Renewable energy factor (REF) — Amendment 1. Available from: <https://www.iso.org/standard/72703.html> [Accessed 11 Jun 2020]
42. Jimenez M, Kwok H (2017) Building express backbone: Facebook's new long-haul network. In: Facebook Engineering. Weblog Available from: <https://engineering.fb.com/data-center-engineering/building-express-backbone-facebook-s-new-long-haul-network/> [Accessed 21 Mar 2020]
43. Jones N (2018) How to stop data centres from gobbling up the world's electricity. *Nature*. 561(7722):163–167. <https://doi.org/10.1038/d41586-018-06610-y>
44. Kamiya, G, and Kvarnström, O. (2019) Data centres and energy – from global headlines to local headaches? Available from: <https://www.iea.org/commentaries/data-centres-and-energy-from-global-headlines-to-local-headaches> [Accessed 21 Mar 2020]
45. Lawrence A (2019) Is PUE actually going UP? Uptime Institute. Weblog Available from: <https://journal.uptimeinstitute.com/is-pue-actually-going-up/> [Accessed 11 Jun 2020]
46. Lei N, Masanet E (2020) Statistical analysis for predicting location-specific data center PUE and its improvement potential. *Energy* 201. <https://doi.org/10.1016/j.energy.2020.117556>
47. Masanet E, Shehabi A, Koomey J (2013a) Characteristics of low-carbon data centres. *Nat Climate Change* 3(7):627–630. <https://doi.org/10.1038/nclimate1786>
48. Masanet E, Shehabi A, Ramakrishnan L, Liang J, Ma X, Walker B, Hendrix V, Mantha P (2013b) The energy efficiency potential of cloud-based software: A U.S. Case study. Lawrence Berkeley National Laboratory, Berkeley Available from: <https://eta.lbl.gov/publications/energy-efficiency-potential-cloud> [Accessed 21 Mar 2020]
49. Masanet E, Shehabi A, Lei N, Smith S, Koomey J (2020) Recalibrating global data center energy-use estimates. *Science* 367(6481):984–986. <https://doi.org/10.1126/science.aba3758>
50. Metz C (2016) Google's making its own chips now. In: Time for Intel to freak out. *Wired* Available from: <https://www.wired.com/2016/05/googles-making-chips-now-time-intel-freak/> [Accessed 21 Mar 2020]
51. Microsoft. (2018a) The carbon benefits of cloud computing: A study on the Microsoft Cloud. Available from: <https://www.microsoft.com/en-gb/download/details.aspx?id=56950> [Accessed 21 Mar 2020]
52. Microsoft. (2018b) 2018 Data Factsheet: Environmental Indicators. Available from: <http://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE3455q> [Accessed 21 Mar 2020]
53. Microsoft. (2019) What are Availability Zones in Azure? Available from: <https://docs.microsoft.com/en-gb/azure/availability-zones/az-overview> [Accessed 21 Mar 2020]
54. Microsoft. (2020a) Microsoft Sustainability Calculator. Available from: [https://appsource.microsoft.com/en-us/product/power-bi/coi-sustainability\\_sustainability\\_dashboard](https://appsource.microsoft.com/en-us/product/power-bi/coi-sustainability_sustainability_dashboard) [Accessed 21 Mar 2020]
55. Microsoft. (2020b) Connect the Microsoft Sustainability Calculator. Available from: <https://docs.microsoft.com/en-gb/power-bi/service-connect-to-microsoft-sustainability-calculator> [Accessed 21 Mar 2020]
56. Microsoft. (2020c) Azure global infrastructure. Available from: <https://azure.microsoft.com/en-us/global-infrastructure/> [Accessed 21 Mar 2019]
57. Patterson M, Azevedo D, Belady C, Pouchet J (2011) Water Usage Effectiveness (WUE): A Green Grid Data Center Sustainability Metric. In: The Green Grid. White Paper number: 35 Available from: <https://www.thegreengrid.org/en/resources/library-and-tools/238-Water-Usage-Effectiveness-%28WUE%29%3A-A-Green-Grid-Data-Center-Sustainability-Metric>. [Accessed 11 Jun 2020]
58. Rao N (2016) Bandwidth costs around the World. In: The Cloudflare Blog. Weblog Available from: <https://blog.cloudflare.com/bandwidth-costs-around-the-world/> [Accessed 21 Mar 2020]
59. Sattiraju N (2020) Google data centers' secret cost: billions of gallons of Water. *Bloomberg Green* Available from: <https://www.bloomberg.com/news/features/2020-04-01/how-much-water-do-google-data-centers-use-billions-of-gallons> [Accessed 11 Jun 2020]
60. Shehabi A, Smith S, Sartor D, Brown R, Herrlin M, Koomey J, Masanet E, Horner N, Azevedo I, Lintner W (2016) United states data center energy usage report. Lawrence Berkeley National Laboratory, Berkeley Report number: LBNL-1005775. Available from: <https://eta.lbl.gov/publications/united-states-data-center-energy> [Accessed 21 Mar 2020]
61. Shehabi A, Smith SJ, Masanet E, Koomey J (2018) Data center growth in the United States: decoupling the demand for services from electricity use. *Environ Res Lett* 13:124030. <https://doi.org/10.1088/1748-9326/aaec9c>
62. Singh A, Ong J, Agarwal A, Anderson G, Armistead A, Bannon R, Boving S, Desai G, Felderman B, Germano P, Kanagala A (2015) Jupiter rising: A decade of clos topologies and centralized control in google's datacenter network. *ACM SIGCOMM Comp Commun Rev* 45(4):183–197. <https://doi.org/10.1145/2785956.2787508>
63. Spiceworks (2019) 2019 State of IT. Spiceworks Available from: <https://www.spiceworks.com/marketing/state-of-it-2019/future-tech/> [Accessed 21 Mar 2020]
64. UNESCO World Water Assessment Programme (2020) The United Nations world water development report 2020: water and climate change. UNESCO, Paris Available from: <https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en> [Accessed 11 Jun 2020]
65. Uptime Institute (2019) Annual Data Center Survey Results. Uptime Institute Available from: <https://uptimeinstitute.com/resources/asset/2019-data-center-industry-survey> [Accessed 21 Mar 2020]
66. Van Heddeghem W, Lambert S, Lannoo B, Colle D, Pickavet M, Demeester P (2014) Trends in worldwide ICT electricity consumption from 2007 to 2012. *Comp Commun* 50:64–76. <https://doi.org/10.1016/j.comcom.2014.02.008>
67. Vaid K (2016) Microsoft reimagines open source cloud hardware. Microsoft Azure Blog: Weblog Available from: <https://azure.microsoft.com/en-gb/blog/microsoft-reimagines-open-source-cloud-hardware/> [Accessed 21 Mar 2020]
68. Walshe N (2020) Microsoft sustainability calculator helps enterprises analyze the carbon emissions of their IT infrastructure. Microsoft Azure Blog; Weblog Available from: <https://azure.microsoft.com/en-gb/blog/microsoft-sustainability-calculator-helps-enterprises-analyze-the-carbon-emissions-of-their-it-infrastructure/> [Accessed 21 Mar 2020]
69. Webster, B. (2019) Behind the manifestos: How green is my party? *The Times*. Available from: <https://www.thetimes.co.uk/article/behind-the-manifestos-how-green-is-my-party-t26jzgn> [Accessed 21 Mar 2020]
70. Whitehead B, Andrews D, Shah A, Maidment G (2014) Assessing the environmental impact of data centres part 1: background, energy use and metrics. *Build Environ* 82:151–159. <https://doi.org/10.1016/j.buildenv.2014.08.021>

## Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Submit your manuscript to a SpringerOpen<sup>®</sup> journal and benefit from:**

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► [springeropen.com](https://www.springeropen.com)