Sources of data center energy estimates: a comprehensive review

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Summary

Data centers are a critical component of Information Technology (IT), providing an environment for running computer equipment. Reliance on data centers for everyday activities has seen increased scrutiny of their energy footprint, yet the literature presents a wide range of estimates with challenging to validate calculations that makes it difficult to rely on their subsequent estimates. In this review, we analyze 258 data center energy estimates from 46 original publications between 2007 and 2021 to assess their reliability through examining the 676 sources used. We show that 31% of sources were from peer-reviewed publications, 38% were from non-peer reviewed reports, and many lacked clear methodologies and data provenance. We also highlight issues with source availability - there is a reliance on private data from IDC (43%) and Cisco (30%), 11% of sources had broken web links, and 10% were cited with insufficient detail to locate. We make recommendations to 3 groups of stakeholders for how to improve and better understand the literature - end-users who make use of data center energy estimates e.g. journalists; the research community e.g. academics; and policy-makers or regulators within the energy sector e.g. grid operators.

Keywords

IT energy consumption, data center energy consumption, sustainable computing, green IT, cloud computing, cloud sustainability.

Introduction

Data centers are an important component in Information Technology (IT) systems. Designed to provide a secure and reliable environment for running computer equipment such as servers, network switches, and data storage, they range in size from small cabinets through to large "hyperscale" warehouses containing hundreds of thousands of devices[1,2]. These facilities are deployed around the world to support the provision of IT services ranging from banking to email, and from video streaming to conference calls.

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Over the last decade, the number of global server instances has increased by 647%, storage capacity has grown 2,500%, and network traffic has increased by 1,000%[3]. Although the number of individual data centers is falling - from ~8.6 million in 2015 to 7.2 million in 2021[4] - the number of new hyperscale data centers is growing rapidly. At the end of 2021, 700 of these large facilities were in operation[5] and an average of 16 are coming online every quarter[6]. Increasing demand is generated as new applications are deployed and existing IT workloads migrate to public cloud services provided by companies such as Amazon and Microsoft[7]. Spending on public cloud was estimated to be $396 billion in 2021 and is expected to grow to $482 billion in 2022[8].

This growth has resulted in an increasing amount of scrutiny of the environmental impact of data centers. On the one hand, some argue that data center energy consumption has plateaued over the past decade - growing from 193.7 terawatt hours (TWh) in 2010 to 205.2 TWh in 2018, and is expected to grow to 209.6 TWh in 2023[3] - primarily due to the efficiencies gained through IT workloads migrating to cloud computing[3,9,10]. On the other hand, previous research claims that data center energy consumption is correlated with the rapid growth in network traffic and in some scenarios could reach 51% of global electricity demand by 2030[11–13].

This large variance presents multiple challenges. Firstly, it serves to confuse the general public who want to help tackle environmental issues - some claim that individual actions such as deleting duplicate photos or clearing out old chat messages has a meaningful impact[14]. However, if energy consumption really has decoupled from demand, those actions are meaningless and may confer a false sense of "making a difference" that could be better directed elsewhere[15].

Secondly, accurate estimates are important for energy system planning. Unexpected demand places stress on electricity transmission and local distribution capacity which has a long lead time for upgrades and can have knockon effects on other users of the electricity grid. For example, housing projects in West London are currently at risk of delays leading into the late 2020s due to unexpected demand from data centers equivalent to tens of thousands of homes[16]. Ireland has measured a 144% increase in data center energy consumption over the past 5 years - from 1.2 TWh in 2015 to 3.0 TWh in 2020 - and this demand is expected to grow to account for 27% of all Irish electricity demand by 2029[17]. Denmark has issued similar warnings, with data centers projected to account for 15% of Danish electricity consumption by 2030[18]. These examples highlight that accurate calculations of current and future data center energy demand are important to avoid unnecessary (or insufficient) capacity.

This is an important question to understand because the use of fossil fuels in the majority of electricity generation is a large source of greenhouse gas emissions. A recent review of the wider IT sector (user devices, networks, TVs, data centers) concluded that IT's share of global greenhouse gas emissions is 1.8-2.8%, but could be as high as 3.9%[19]. It is therefore important to understand the reliability of the estimates within the literature, to highlight the wide range of values and make readers aware of the differences, and to consider how to improve future research practices in this field. The first step to producing reliable results is to examine the sources and data inputs used in calculating data center energy estimates. This is where we focus our attention.

In this review we analyze the landscape of original data center energy estimates published between 2007 and 2021. Given the importance of cloud computing to data center energy consumption, this date range was chosen to coincide with the beginning of the public cloud era with Amazon Web Services launching in 2006[20], and the publication of a major data center energy report by Brown et al., 2007[21]. Although earlier works exist, the enactment of Public Law 109-431 in December 2006 by the United States Congress[22], which commissioned the publication of Brown et al., 2007[21], is one of the earliest indicators that interest in data center energy was gaining traction outside of academic and industry circles.

Although there are many aspects to data center sustainability, we focus on use-stage electricity as the area most studied and most relevant to the ongoing transition of the energy system to clean sources of power generation, however there is growing interest in other impacts such as embodied emissions and water consumption. We do not aim to criticize individual publications or suggest that a particular estimate is more accurate than another. Our goal is broad analysis of common methodological problems within this research field so that future readers can have more confidence in the reliability of estimates. This is especially important as energy grid operators plan for changes in future energy demand.

We start by describing the review methodology which leads into our findings. Publications falling within our research scope were assessed in terms of cited sources to gain a comprehensive understanding of data provenance within five main data center component categories (explained in later sections). We focus on source provenance and data inputs because they are the foundational component that determines scientific reliability. Any flaws in these aspects will undermine the calculations and erode confidence in findings. To support this approach, the sources of data were further broken down by key metrics such as reliability (data access, online visibility etc.) and type (peer-reviewed, self-published etc.), and a citation mapping was done to connect all examined papers with their relevant sources of data. This led to 676 individual data provenance traces.

Our analysis of the findings starts with a description of the different approaches to estimating data center energy, with examples of each approach from our review. After considering the data quality challenges which play a role in undermining the reliability of many of the publications we analyzed, and a discussion of the difficulties with future projections and technology change, we conclude with recommendations for how future data center energy research can be conducted with greater transparency and clarity.

Review methodology

In this section we summarize the methodology used to select and analyze the literature in this review. More detailed explanation and examples of publications excluded can be found in Notes S1 and S3.

A literature search was conducted to locate English-language publications with data center keywords such as “data center energy” (see Note S2) published since 2007. Only English-language publications were included in the review, but where these used non-English sources, such as Hintemann, 2015a[23] (in English) referencing Stobbe et al., 2015[24] (in German), those excluded references were recorded in Note S1.

For inclusion in the review (Figure 1), publications were selected if they provided original calculations assessing the energy consumption of all data centers within a specific geographical region (or globally), past, present or future. A clear methodology with calculations and sources must have been present to be considered within our review. Referencing estimates from other publications without modification would not meet the “originality” criteria. For example, Rong et al., 2016[25] restates estimates from Brown et al., 2007[21] and Koomey, 2011[26], thus was not included.

Use-stage energy consumption estimates were included if they covered the entire data center population of a given region. This was usually a country or geographic region, such as the entire United States, “Europe” (varying definitions), or globally. Each publication has one or more energy estimates. For each estimate, the geography and estimate year were extracted alongside the scenario name (if relevant) in Table S2.

All calculations were converted to annual electricity consumption in terawatt hours (TWh). For example, the results in Belkhir and Elmeligi, 2018[27] are provided in terms of carbon emissions, but the energy inputs are available so this paper was included. However, in Malmodin, Bergmark & Lundén, 2013[28], only carbon emissions are provided so this paper was excluded.

For each publication, the methodology was analyzed and the key sources extracted, categorized, and then listed in Table S1. A key data/analysis source was considered one which appeared to form an important part of the calculation methodology, either specifically mentioned as being used for a calculation or judged to be the source for a category based on reading the methodology. The categories were selected to match those commonly used to describe data center components - servers, storage, network, and infrastructure - following the examples in Masanet et al., 2011[29] and Barroso et al., 2013[30] and 2018[2]. An additional category was used for market sources e.g., server shipments and growth projections.

The majority of publications relied on multiple data sources, of varying types, across these categories (Table S1). For the 46 publications in our review, we formed 676 individual mappings (by data center component category) of data provenance where each source was further categorized by the type of source information and data, and source reliability. Our analysis was limited to examining the first level of sources i.e., those cited by the publications in Table S1. We did not analyze the chain of citations through every listed source.

In many instances we found that cited sources were unavailable. In each case, the reason was indicated alongside each source listed in Table S1. Classifications are explained in Table 1.

In the case of a broken link (checked as of February, 2022), no further attempts were made to locate the source because it is important to highlight where web links are no longer active. “NF” was used where there was no link or publication identifier (such as a DOI number) and a search necessary to locate the document was not successful. It is also important to note that sources categorized as “EL” may also be closed-access in publication (but still accessible via a library journal subscription) and thus “EL” should not be read completely as open-source data.

Resource availability

The list of references analyzed is provided in Table S1. The data center energy estimates extracted from those references are provided in Table S2. The grouped sources used as a basis for the statistical analysis and visualizations are provided in Table S3. The code used to perform calculations and generate visualizations is available on Figshare at: https://doi.org/10.6084/m9.figshare.19163861

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, David Mytton (david@davidmytton.co.uk).

Findings

Bringing estimates together

In total, 46 publications were included in the review (Table S1) and we extracted 258 data center energy estimates (Table S2). 179 estimates were global in scope, 24 were for the USA and 19 for Europe (described in each publication as either EU25, EU27, EU28, Western Europe or Europe). Germany, Sweden and China also had regional estimates.

Figure 2 shows the range of estimates of global data center energy for the years 2010, 2020 and 2030. The difference between the min and max values is an order of magnitude, excluding estimates greater than 2,000 TWh for effective scaling of the visualizations (5 estimates in total, 2 from Andrae & Edler, 2015[11], 1 from Andrae, 2019c[31], 1 from The Shift Project, 2019[13] and 1 from Andrae, 2020a[32]). If included, the max value for 2030 would be 8,253 TWh from Andrae & Edler, 2015[11]. All estimates can be found in Table S2. As seen in Figure 5, the further into the future, the wider the ranges. This is to be expected given that past estimates can be calculated from actual data whereas future estimates must make assumptions about key parameters such as energy efficiency and server shipments.

Key data sources

A deeper dive through a comprehensive mapping of all publications to their respective sources (those falling within our scope and in the assessed data center categories) highlighted a few points. Overall, a small number of key sources of data were widely used across the papers assessed. Where industry and databases were concerned, International Data Corporation (IDC) and Cisco were cited in 20 (43%) and 14 (30%) publications respectively (some of these citing both organizations) whereas key works by Koomey and Andrae (various publications) were also heavily cited (43% and 22% respectively).

As seen in Figure 3, less than half of the sources (31%) were from peer-reviewed publications, with a similar proportion of publications (38%) coming from sources classified as 'Reports'. It is important to note that these reports, though largely composed of industry publications, include self-published reports by authors, implying limited validation of findings through the peer-review process. The most common year for the source was 2019, but this was skewed by Andrae's 2019 papers as the author had three individual publications in this year, an uncommon amount for any single author in a given year. Several of these were self-published via ResearchGate[33,34] and only included in this review because they were cited in a formally published article[31]. Sources without a publication year (classed as 'n/a', ~17%) were common, highlighting that much of the data within is being captured by databases and other means of dissemination, versus through official publications. This lack of information makes methods challenging to reproduce because the original source data cannot be pinpointed. Most sources were listed in the market category, where 27% fell under this data source type, and the majority of connections were for publications only using sources for just one category (ie., a single source was mapped to market data and no other category).

For the full suite of unique sources assessed, 11% of them simply were not found owing to broken web links, and a further 10% were classified as "NS", highlighting the lack of data visibility in data center estimations. Where the source year is concerned (where applicable), 22% of these data sources were published in or before 2010. This value quickly jumps to 65% in or before 2015, and 81% when considering just three years later in 2018. Thus, most publications are citing dated sources of information which are in turn, citing much older data (10% of sources are from 2007 and prior with two sources occuring before 1990). This is important given the rapid pace of technological change, discussed later.

Approaches for assessing data center energy

Methodological classifications

Similar to computer network energy intensity modeling techniques, such as those seen in Schien and Preist, 2014[35], approaches to data center energy estimates fall into three main categories - bottom-up, top-down, and extrapolation (Table 2).

Bottom-up modeling combines equipment specifications (such as server power draw) and data center infrastructure characteristics (such as facility Power Usage Effectiveness, PUE[36,37]) with shipment and installed base estimates to calculate overall energy consumption. Bottom-up estimates are often associated with historical energy consumption analysis, with predictions only made a few years into the future. The further out, the wider the range of estimates (Figure 5) due to the difficulty of accounting for energy efficiency improvements and changing trends in equipment[38,39]. For example, Malmodin et al., 2010[40] uses actual shipment and installed base data from 2005 and applies a growth rate extrapolation to cover 2007. A similar approach was taken by Masanet et al., 2020[3], which provides historical values up to 2018 and then makes projections out to 2023 based on a continuation of current trends. This method relies on the accuracy of values for installed base, equipment sales and shipments, as well as the ability to predict how technology will change in the future. For example, there is a general expectation that direct liquid cooling of data center equipment will become more widely deployed within the next 7 years[41], but few operators currently have high density racks that would justify it[42]. Predicting how this will actually change, and how that would impact energy consumption, is difficult.

Top-down modeling uses regional totals, such as those from government or organizational statistics or surveys, to estimate overall energy consumption. From the papers included in our analysis (Table S1), only one used a top-down approach - Malmodin et al., 2014[43]. This used national and corporate top-down estimates and/or measurements for operations in Sweden, alongside bottom-up equipment statistics, which are then extrapolated to a global estimate. The main advantage of this approach is that “actual” values can be used, such as total measured network data volumes and total energy consumption values from electricity meters. This means they are accurate, but high-level. The values can be apportioned by subscriber or customer, but the strength of that correlation is the main assumption for future projections. Accounting for technology change is even more difficult than with bottom-up approaches because of the limited breakdown of components that make up the estimate. Data availability relies on an organization to publish it or a government agency to collect it, which may change depending on the policy of the day, or may not represent all consumption in a given region (in the case of a single organization that does not have a monopoly).

Extrapolation approaches take a baseline value from either bottom-up or top-down estimates and assume a correlation between demand and energy consumption, applying a growth factor for future projections. This can be seen in Figure 4 and Figure 5 comparing the estimates by methodology - results from extrapolation have the same baseline as bottom-up methodologies (because these are often used for the baseline), but diverge quickly as the extrapolation reaches into the future.

Most extrapolation calculations are based on energy intensity per unit of data transmitted, with assumptions about energy efficiency improvements for future projections. For example, Corcoran & Andrae, 2013[44] uses estimates from Koomey, 2011[26] but adjusts the growth rate from 8% to 12% for 2011 and 2012. Their reasoning is that the introduction of new consumer cloud services will cause usage to grow, which will therefore increase the total energy consumption. Predictions are then made from the 2012 baseline for each year 2013 - 2017 based on three scenarios - low growth (7.5%), expected growth (14%) and high growth (20%). The authors write that these growth rates were chosen based on expected improvements in energy efficiency of network devices, the growth in the number of installed devices, and the growth in network traffic, but the precise calculations for how they were derived are not provided. Andrae, 2019a/b/c/d[31,33,34,45] takes an alternative approach by calculating energy consumption per CPU (Central Processing Unit) instruction, then extrapolates based on an estimated number of global CPU instructions annually. The main limitation with both approaches is the strength of the correlation between these inputs and how that changes over time (Table 2).

Of the publications categorized as either bottom-up or a combination of bottom-up and extrapolation, most estimates are for the years before the publication date. Projections are limited to just a few years into the future. For example, Brown et al., 2007[21] provided estimates for 2006 and 2011, Hintemann, 2020[46] provided estimates for 2010-2018, and Masanet et al., 2020[3] provided estimates for 2010 and 2018-2023. In contrast, publications that take a baseline and then extrapolate are more likely to offer estimates further into the future. For example, Vereecken et al., 2010a[47] provides estimates for 2008 and 2020, Andrae & Edler, 2015[11] makes estimates for 2010, 2020 and 2030, and Liu et al., 2020[48] has a projection for 2030. Naturally, future projections must be based on some baseline estimate so it is perhaps not unexpected that extrapolations are for future years. Given how quickly technology changes, how far into the future those authors are willing to predict is what makes them stand out.

Questioning assumptions and comparison limitations

As discussed by Lei & Masanet, 2021[38], it is questionable whether extrapolation should be considered an independent method due to its reliance on other baseline estimates. Calculations that use extrapolations often fail to account for all the relevant parameters, particularly in regard to technology changes, when making projections far into the future. Furthermore, extrapolation erodes statistical confidence as analysis will inherently adopt biases, estimate errors, and scope limitations (geographical or temporal) into findings, compounding the potential for inaccuracies. This snowballed bias is a problem where publications rely on earlier estimates without critically assessing their assumptions and sources.

For example, Corcoran & Andrae, 2013[44] develops energy growth scenarios where energy consumption is correlated with network traffic. These scenarios are adopted and modified in Andrae & Edler, 2015[11] which is then used as a methodology by The Shift Project, 2019[13] (Figure 6). Despite the unavailability of most of the sources supporting the estimates published by The Shift Project, 2019[13], this report has been cited by a large number of mainstream media outlets[49–52]. In this case, the underlying link between network traffic and energy consumption is a key assumption from 2013 which flows through all citing publications, despite later research suggesting that growth in energy consumption is not linked to network traffic. Shehabi et al., 2016[9] discusses the disconnect between past energy growth and what is expected in the future (4% increase between 2014-2020), further reinforced in Shehabi et al., 2018[10]. Malmodin &

Lundén, 2016[53] specifically refutes the link between data traffic and energy consumption, followed up by the same authors in 2018[54]. As can be seen from Figure 6, only Shehabi et al., 2016[9] is referenced by The Shift Project, and this is in support of the notion that energy growth is likely.

This reliance on a small number of sources, most of which are now unavailable, limits the reliability of the conclusions. Andrae returns to the topic in 2019[45], but subsequent real-world data from telecoms network operators such as Telefonica[55] show that the spike in network traffic caused by the sudden shift to work from home during the Coronavirus pandemic did not result in a corresponding increase in network energy consumption. Using kilowatt hour per gigabyte of data transferred (kWh/GB) energy intensity averages has some use when allocating known energy consumption totals for reporting purposes, but is inappropriate for predictions of future consumption because there is no direct correlation between data volumes and energy consumption[56,57]. This is highlighted by the trend of falling network energy intensity that goes back to 2015, as highlighted by Koomey and Masanet, 2021[39].

Where informal publications are concerned, several publications used surveys, questionnaires, workshops, meetings and other types of stakeholder participation to gather data. For example, Bertoldi, 2010[58] was based on a survey of 142 data center operators in Europe, and the Bio by Deloitte[59–65] reports also included input from project participants. This has the advantage of being able to include the real-world experience of operators to help validate literature reviews and equipment testing. The challenge is presenting the input data in a way that can be reproduced or considered reliable. Furthermore, individual responses may be anonymized, such as in Bertoldi, 2010[58], or reproduced without citing the original source, such as in the Bio by Deloitte Task 4 report[62].

Overall, the differences in methodology make it difficult to compare all estimates and drawing sound statistical relationships and measures has proven practically infeasible. For example, Koomey, 2007a[66] and Koomey, 2007b[67] both exclude storage and networking components, Somavat, Jadhav & Namboodiri, 2010[68] takes the US total from Brown et al., 2007[21] then doubles it on the assumption that the US represents half the global total, Andrae & Edler, 2015[11] excludes internal data center networks, instead including them as part of global networking as a whole, and Masanet et al., 2020[3] excludes Bitcoin whereas Montevecchi et al., 2020[69] includes it. These publications should therefore be compared with caution and this is why Figure 2, Figure 4 and Figure 5 represent the wide range of estimates across publications and should not be used as an analysis or projection of data center energy values themselves. Future research could examine the methodologies and system boundaries in more detail.

Data quality

Very little has changed since Koomey, 2007a[66] noted that information about data center floor area, power density, equipment shipments, and installed base statistics were anecdotal, limited, and privately held by commercial organizations. As can be seen from Table S1, almost every publication has a problem with missing data. That is not to say the data were unavailable at the time, but it is now unavailable when revisited today which makes it difficult to reproduce the original work, a core scientific need for validation. This is often because web links are not permanent and the web pages used as references are no longer available (a particular problem when Cisco is cited). The problem is compounded by how there are few available sources of market data which are generally only available from private/commercial reports or databases.

From the publications analyzed, industry analyst firm IDC was cited by 43%. This was most commonly related to the shipment and installed base statistics for server, storage and network equipment used in bottom-up assessments. Gartner was another such source, cited in 13% of publications. Figure 7 highlights an example of how three highly cited papers rely on IDC both explicitly in their list of references, but also implicitly because of how they cite each other. The flow of references shows Malmodin & Lundén, 2018a[54] cites Shehabi et al., 2016[9] which cites Van Heddeghem et al., 2014[70]. They all individually cite IDC market data sources to inform their own calculations, but are also relying on IDC indirectly. For example, Malmodin & Lundén, 2018a[54] cites IDC and Shehabi et al., 2016[9], which itself cites IDC. Figure 7 demonstrates how otherwise independent estimates use linked sources, sometimes unexpectedly, which suggests a future research opportunity to track every source back to the original publications. Once again, although we assume these sources were available when originally published, they cannot be fully reproduced today because the sources are no longer available.

For network traffic analysis, the most commonly used source was the networking company, Cisco. The Cisco annual “Global Cloud Index” and “Visual Networking Index”, amongst other Cisco sources, was cited by 30% of publications. In some instances, these historical documents remain available directly from Cisco’s website, or have been uploaded to other sites by third-parties. However, in most cases the original source is no longer available and Cisco redirects the old links to the latest data release. This makes it impossible to review the original data inputs relied upon by these publications.

Recurring data sourcing issues

The use of these sources presents a challenge for researchers. It is important that key data sources remain available for future reference and to ensure calculations can be reproduced. We acknowledge that it may be possible to obtain the original data by contacting the publication authors, but that is not a reliable method of reproducing research results. All data should ideally be open and publicly available for anyone, but this was not a widely used *modus operandi* in older studies. However, researchers are limited by the licensing terms surrounding the republication of original data, particularly in the case of private, paid-for reports. The lack of alternative sources means researchers often have no choice but to rely on these sources.

Common problems revealed in this review include sources listed without explaining where or how they are used, citations of now non-existent sources, assumptions without explanation, and model parameters without values. The most reliable publications analyzed in this review list all assumptions, are precise in attributing data to the relevant source, publish all parameters and values, and assess the reliability of their own sources e.g. using peer-reviewed calculations rather than numbers taken from mainstream news articles. We also note that our assessment of 'reliability' also injects a level of subjectivity when categorizing previous studies, but care was taken to do so only where methodologies were clearly lacking in the provenance and analysis needed for confidence in presented findings.

Almost all data centers are operated by private companies, and equipment manufacturers are all private firms. As noted by Koomey & Masanet, 2021[39], one way to improve the situation is for these organizations to regularly release more detailed data. Google and Microsoft are relative leaders in this regard because they both publish detailed top-level statistics. For example, Google's annual environmental report[71] includes time series metrics for energy consumption and renewable energy purchases, and they also publish PUE values every quarter for the data centers they own[72]. Microsoft publishes similar time series environmental data, with regional breakdowns, in its annual report[73]. Other major data center owners are not as transparent. Amazon only reports a single number for carbon emissions[74] which aggregates all their operations and so makes it difficult to break out data centers from ecommerce logistics.

The major hyperscale cloud providers have now all released calculators (Amazon[75], Google[76], Microsoft[77]) that allow their customers to examine the carbon footprint of their own workloads. This transparency is important because migrating IT workloads to the cloud outsources the operational emissions of running that infrastructure to the cloud provider[78]. These calculators will provide the details needed for users of cloud computing to better understand their environmental footprint.

Greater push for transparency

These improvements cover the major hyperscale cloud providers, but there are many more data centers around the world[4]. The larger data center owners report environmental metrics, such as Digital Realty[79] (291 data centers globally, as of 31 December 2020) and Equinix[80] (227 data centers globally, as of 31 December 2020), but only 33% of 539 respondents to the Uptime Institute 2021 data center survey reported that they track IT or data center carbon emissions[42]. However, the survey also shows that 82% track IT or data center power consumption so there is a disconnect between reporting energy consumption, a major cost of data center operations, and the environmental impact of that energy usage.

As data center energy consumption continues to be a topic of interest, government organizations may either mandate greater transparency or may task national statistics agencies to collect the data. Indeed, this is what the Irish Central Statistics Office has done with its January 2022 release of data center electricity consumption collected from metered data received from the Electricity Supply Board (ESB Networks)[81]. Intended to be updated annually, this will provide an accurate estimate for data center energy consumption in Ireland, a major data center hub for hyperscale cloud providers, and will hopefully provide a good example for other countries to follow. As these figures provide "actual" numbers, they will provide a useful comparison to validate estimates from bottom-up models. In the meantime, our recommendations for researchers (below) describe alternative steps to validate estimates.

Inputting this data into top-down assessment methodologies has the advantage that "actual" energy consumption data is being used rather than a model, but this is difficult to rely on for future projections because it assumes there is a direct relationship between demand and energy consumption. Opportunity for error compounds as more factors are considered, such as energy efficiency improvements or whether and when new technologies are deployed. On the other hand, bottom-up methodologies are inherently uncertain because there is always a degree of estimation involved. Equipment energy consumption values measured in lab conditions, such as those provided in the SPECpower database used by many of the publications analyzed, do not necessarily represent the diversity of real world applications, and there is potential for commercial interests limiting the full scope of data. As discussed by Van Heddeghem et al., 2014[70] (see below), the SPECpower database is biased towards more energy efficient servers. Shipment and installed base values rely on accurate reporting from manufacturers and must make assumptions about future market trends.

Technological change

Over the timescale of this review, a new type of data center - hyperscale - went from being mentioned but excluded as insignificant in Koomey, 2007a[66], to accounting for more than 40% of the entire 2020 server installed base in Shehabi et al., 2018[10]. At the end of 2021, of the 700 hyperscale facilities that were in operation, 49% were in the US[5]. This US focus has been suggested as a reason why data center energy consumption continues to rise in regions outside of the US because the US has benefitted from the improved efficiencies of these facilities[46,82].

The rise of cryptocurrency is another trend that affects energy estimates. From 2008 when the initial Bitcoin whitepaper was published[83], the energy consumption of proof-of-work crypto technologies has become a highly debated topic[84–86]. For example, on 15 July 2022 Digiconomist[87] estimated 132.05 TWh of annualized Bitcoin energy consumption whereas the Cambridge Bitcoin Electricity Consumption Index[88] estimated 80.92 TWh (although it also suggested a theoretical upper bound of 135.61 TWh, very similar to Digiconomist). Both of these tools provide real time estimates which can be calculated due to the open nature of the Bitcoin protocol. The asset price is an important factor which changes rapidly and determines the level of mining activity[89], which impacts energy consumption and results in these wide range of estimates. There are also many hundreds of other blockchain technologies to consider[90,91], although Bitcoin makes up 2/3 of cryptocurrency related energy demand[92].

Simple bans on cryptocurrency mining activities have been shown to cause displacement to more carbon intensive regions[93], so regulators should be careful to model the effects of their policies. The ability to do so depends on accurate data, so publications should be clear about whether (and which) cryptocurrencies are included in the definition of a data center, or not. For example, this is a major difference when comparing the estimates published by Masanet et al., 2020[3] (does not include crypto mining) and Borderstep, e.g., in Hintemann, 2020[46] (does include crypto mining).

Examining key assumptions is important, particularly when it comes to growth and technology change. For example, Van Heddeghem et al., 2014[70] examined the "SPECpower ssj2008" benchmark data[94] to consider whether server power consumption had continued to grow based on the trends discussed for 2000-2005 in Koomey, 2011[26]. They reviewed entries for servers tested between 2008-2012 (393 entries) and grouped them by power consumption and type. Different types were shown to change the reported power per server - volume server power consumption was decreasing by 3% per year whereas mid-range servers were growing by 6% per year. Van Heddeghem et al., 2014[70] highlighted that the SPECpower database is biased towards more energy efficient servers, but because volume servers were the largest group by power consumption, they concluded that energy consumption did not increase between 2005-2012. As such, the original power values from Koomey, 2011[26] were used. Improvements in energy efficiency may also have minimal impact on the energy consumption from cryptocurrency mining[90]. This highlights how using a single value for "energy efficiency improvement" hides nuance and can result in large errors over long periods of time.

Our review also found instances where assumptions are used without explanation, or with potentially unreliable sources. For example, Andrae, 2019a[34] follows Andrae & Edler, 2015[11], but with modified "electricity intensity improvements and data traffic growth" that are not explained. Another example is Andrae & Edler, 2015[11] which caps efficiency improvements at 5% from 2022 because of expected challenges as Moore's Law efficiency gains slow down[95–97]. However, the choice of 5% is not explained and the sources used are online magazine articles which are not peer-reviewed. It is difficult to assess the credibility of these assumptions without more information on why they were selected.

An alternative approach to bottom-up calculations from shipment and installed-base statistics was developed in Andrae, 2019a/b/c/d[31,33,34,45]. Here, estimates for the energy per individual CPU instruction are suggested and then extrapolated to an estimated total number of annual, global number of CPU instructions. Although future efficiency improvements can be included in the calculations, the tech industry has shown it is repeatedly able to introduce unexpected innovations. For example, Apple announced its the M1 Max ARM chip in 2021 which has been benchmarked to have a 2.5-3 times greater performance per watt with single-threaded applications and 4-6 times greater performance per watt for multi-threaded operations compared to an equivalent Intel i9-11980HK[98]. The introduction of these types of "next generation" technologies raises the question of how to account for unprecedented or unpredictable improvements in efficiency and performance, particularly when making projections far into the future.

These are just a few examples of major technology changes that have arisen in the timeline of this review, all of which were hard to predict and would have invalidated assumptions made just a few years prior; these rapid advances are common in the technology sector. On one hand, proof-of-work blockchain mining requires a significant amount of energy, but on the other hand, many IT workloads have moved from inefficient enterprise data centers to more efficient hyperscale cloud systems. The smartphone has become an important computing device with more energy efficient processors compared to desktop computers, but questions remain about the power profile of new 5G cellular networks[99]. Will power consumption remain decoupled from demand[10] or will the challenges of keeping up with Moore's Law predictions become too great[97]?

Recommendations

Data center energy estimates are used by three main stakeholder groups - end-users who make use of data center energy estimates e.g. journalists writing about data center renewable energy pledges; the research community e.g. academics developing energy consumption models; and policy-makers or regulators within the energy sector e.g. grid operators planning future energy system infrastructure projects. In this section, we make recommendations for each group so they can either work towards more reliable estimates or better understand how to interpret the estimates already available.

Recommendations for end-users

For end-users looking to make use of data center energy estimates, we suggest asking three questions before relying on any research or published estimates (Figure 8):

1. How old is the publication and how up to date are the key sources? Is the publication considering recent data sources for key parameters like equipment energy consumption and installed base? If published more than a few years ago, it is unlikely to be able to provide robust estimates for data center energy consumption today. The same applies to future projections - estimates more than a few years into the future, especially if they are many times higher than estimated consumption values today, are unlikely to be reliable.
2. What is the basis for the estimates? Historical top-down and bottom-up estimates are likely to be more accurate because they are usually based on "actual" values, such as measured energy consumption. Projections using extrapolation methods carry higher risk of inaccuracy because they tend to have wider estimate ranges (Figure 5), particularly far into the future. The assumed relationship between demand and energy consumption is a major cause of this despite more recent research questioning the assumption of correlation between network traffic and energy in situations other than allocational reporting. The basis for extrapolations should be subjected to detailed scrutiny.
3. Are key sources and calculations available? Non-experts do not necessarily need to examine the sources in detail. A lack of transparency about inputs and calculations can be used as a simple heuristic. If sources are unavailable and it is unclear how the data center energy estimates have been calculated (even after asking the authors), the estimate should not be relied upon.

Recommendations for the research community

We start by endorsing the recommendations made by Koomey & Masanet, 2021[39] which apply equally to data center energy estimates as well as networks and the internet. Open data sharing is the core of good scientific practice, but our review has shown that many estimates are unreliable due to the difficulty accessing and assessing the source materials they rely on.

As such, data center energy researchers should more actively pursue the 15 FAIR guiding data principles[100] to ensure that data provenance in their research is Findable, Accessible, Interoperable, and Reusable. These fundamental principles speak to many of the issues that we have highlighted in our review and a methodical approach that incorporates more open, accessible, and reusable data and methods will vastly improve the credibility that can be placed on data center energy estimations and in particular, the context in which they should be understood and used.

From a research perspective, improvements can be made in several areas (Figure 9):

Define System Boundaries

Firstly, system boundaries should be stated clearly. Without precisely defining what is included within each estimate, calculations cannot be compared or validated. This is important not just for other researchers attempting to analyze trends, but also for lay readers trying to understand how results differ. Although it is commonly understood that data centers consist of servers, storage, networks, and infrastructure components, whether networks include internal and external connectivity, how to categorize cloud computing, and whether bitcoin mining counts as a data center, are all characteristics that make a difference to the results. Good examples of well defined system boundaries were found in Van Heddeghem et al., 2014[70] and Malmodin & Lundén, 2018a[54]. In Van Heddeghem et al., 2014[70], the scope is clearly described in the first figure and the key components of the calculations are listed. Excluded components that might otherwise be expected to be included, such as TVs and mobile phones, are highlighted. In Malmodin & Lundén, 2018a[54], a visual diagram featuring illustrations of each of the included components is prominent.

Transparent & Parameterized Models

Secondly, models should be described in detail. In categorizing the sources in Table S1, we encountered many cases where sources are simply listed without explaining which values were used as inputs. Sometimes this was made clear in supplemental information, such as in Excel workbooks, however we recommend all models are parameterized with the sources and values used for each variable clearly stated. This is particularly important for key inputs, such as growth rates, which should include an explanation for how the rate was calculated. Good examples of clearly described and parameterized models were found in Masanet et al., 2011[29] and Shehabi et al., 2018[10] which explains the calculations, the input values used, and their sources. In multiple cases, previously published models were referred to without further explanation. This is an acceptable approach where new data is input into existing models, however in several publications the earlier model was published in a different language. These were excluded from our review (Note S1) but were relied on in several instances by publications that were included (indicated in purple in Table S1). Whilst we are not suggesting that publications should only ever be in English, sufficient explanation to fully understand and reproduce the model is needed where source languages differ.

Reproducible Models

Our third recommendation is that researchers should aim to make it easy to re-run all calculations and output the results as stated in the manuscript. We found several cases where results are presented only in graphical form making it difficult to read exact numbers from the graphs. Results should be stated in captions or tables and published alongside the source code used to generate the figures. A good example of this is the supplemental information published alongside Masanet et al., 2020[3]. Task 4 from Bio by Deloitte[62] also provided all data used as part of the assessment, however it lacked source references which makes it difficult to rely on.

Input data should be included in the final published version where licenses allow, but at least made available as part of the peer-review process. Where private sources are used, citations should make it possible to locate the exact source document used. In several publications analyzed, generic references were used for commercial products without defining product or report IDs, date ranges, or document titles. This makes it difficult to locate specific sources.

Critically Assess Sources

Next, both researchers and readers should conduct their own assessment of source reliability. Understanding the basis for calculations is important before using a source. What is the year the results apply to? Is growth assumed to be linear? How far out into the future are the predictions? Are the assumptions used for assessing systems in the past still relevant today? A good example of this type of assessment can be found in Hintemann, 2020[46] where the results under discussion are compared to other contradictory publications. This highlights factors such as the relevance of cryptocurrency energy consumption for inclusion within the system boundary and how regional growth may have local effects that are not represented in global statistics.

Source Longevity

Finally, researchers and publishers should consider how to cite web links. The unreliability of web links is a known phenomenon where links break ("link rot") or are redirected to different destinations ("content drift"). Estimates of the average lifetime of a link vary, but a study of the New York Times website showed 53% of articles had at least one broken link and 25% of all links were inaccessible[101]. Our review revealed that 11% of the sources we analyzed had broken links. Where possible, publications should be cited with a permanent DOI, but this is unlikely to be possible for most web pages. Instead, researchers could consider using an archive service that will snapshot the specified content as a permanent reference. The effectiveness of this approach has been examined in the past[102], although of the two services recommended, WebCite and Internet Archive, only the latter remains operational for new submissions. An archive service which collects a snapshot of all references may be something publishers should consider offering to authors.

Recommendations for policy-makers/regulators

In the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report[103], digitization is highlighted as an important contributor to the path to decarbonization, but the report also notes that the gains made from moving to digital services can be reduced by the growth in demand caused by the use of digital devices. This is similar to the conclusions reached by the Royal Society a few years earlier[104], who discussed the need to increase accountability by improving access to data about energy consumption.

Aside from the relevancy to achieving future net-zero goals, the lack of accurate information about data center energy consumption and how that will grow is already having an impact. In 2019, the Municipality of Amsterdam halted construction of new data centers because of their high energy consumption and high load on the electricity grid[105]. The authorities in Amsterdam have now set rules for data center construction which include annual power budgets (67MVA), a power ceiling (670MVA until 2030), and Power Usage Effectiveness requirements (which must be 1.2 or below)[106]. Exemptions are provided for small data centers (less than 5MVA).

More recently, new housing projects in London were reported by The Economist as at risk of delay due to the high load being placed on the electricity grid by data centers competing for connection capacity[107]. Following this article, we submitted a Freedom of Information Request (FOI) to the Greater London Authority (GLA) which revealed that the distribution network operator, Scottish & Southern Electricity Networks (SSEN), has received unexpected connection requests from data centers and battery operators[16]. SSEN reports that this is equivalent to the demand from tens of thousands of homes and that as a result, housing developers in West London are now unable to get grid connections until the late 2020s. The FOI request also revealed similar requests to the UK electricity transmission network operated by National Grid Electricity Transmission (NGET), also from data centers and battery operators who want direct connections. In this case, upgrades to support those requests will not be complete until 2029. The opens questions about what data SSEN and NGET are using to plan their infrastructure upgrades, how they are engaging with their customers and whether this has been affected by the lack of accurate data from, and/or lack of engagement with, data center operators.

Whatever the cause, the challenges faced by the cities of Amsterdam and London are examples where the rapid growth of IT is mixing with the much slower lead times of electricity infrastructure. The solution to cap demand introduced by Amsterdam is able to provide certainty so that the grid operator can deliver appropriate infrastructure upgrades, but it also places constraints on the ability for IT providers to grow their services within the region. When demand outpaces supply, prices will inevitably rise, potentially having an impact on the ability for people in lower income brackets to benefit from access to digital services. Regulators should be careful to consider these types of unintended consequences particularly given past interventions in areas like Bitcoin mining have resulted in demand being redirected to regions with higher carbon intensity[93].

A better understanding of the digital supply chain is likely to grow in importance as disclosure requirements become more widespread. Many of the publications in our review rely upon private sources, particularly for equipment shipments and installed-base statistics. In the absence of the IT industry publishing data voluntarily, regulators should consider mandatory disclosure requirements. For manufacturers, this should focus on equipment lifecycle analysis to understand the power requirements for servers, networking and storage equipment. For data center operators, this should cover energy consumption metrics, sources of energy and grid mix. The climate impact of electricity consumption depends on the proportion of clean energy, so making this data available in a timely manner is important.

Of course, this assumes legitimate organizations exist to report their metrics, which is not always the case if cryptocurrency mining is made illegal[108]. Absolute values are useful for localized demand planning and conversion into carbon emission equivalents, but energy intensity is more useful for comparisons between organizations and understanding efficiency improvements over time. Care should be taken when choosing these metrics to accurately represent the application being measured. For example, kWh per gigabyte (GB) of data has historically been used to measure network energy intensity[109], but kWh per hour of video streamed has been shown to be a more accurate measurement for that specific application[57]. PUE is often used in the context of data center efficiency, but it correlates poorly with energy usage and can be manipulated by increasing IT load[110]. Another example is cloud emissions calculators now available from the major cloud providers. We assume that these use underlying energy consumption data to calculate the carbon dioxide equivalents they publish, but the methodologies are still unclear. Exposing the energy data would be helpful for comparing the energy efficiency of cloud services because emissions statistics vary spatially and temporally, and can be affected by offsets or other emissions reduction mechanisms.

Conclusions

The level of interest in data center energy consumption has grown almost as much as the growth in the usage of IT itself. Having started with a small number of reports within a tight-knit academic community, there is now regular mainstream reporting of the environmental impact of computing. The industry operators themselves have also become more engaged in recent years, with high profile renewable energy projects forming a key part of the marketing message for the major cloud providers even if some of the transparency pledges have yet to be realized.

Whilst significant progress has been made in the development of modeling methodologies for assessing data center energy consumption, there remain major challenges impacting the reliability of those calculations. Problems with source accessibility and reproducibility of results may seem like concerns only relevant to academics analyzing the results in depth, but they ultimately have an impact on the credibility of publications relied on by a range of stakeholders. Unexpected demand is already causing problems for grid operators in Amsterdam and London which is driving responses such as Amsterdam setting quotas on data center power requirements and the Irish Statistics Office publishing energy consumption data from direct meter measurements.

From policy-makers to software engineers, it is important that there is an accurate understanding of the environmental impact of computing. That is difficult when energy estimates range by an order of magnitude - meeting future global IT energy demand of ~200 TWh is a completely different task compared to ~8,000 TWh. Estimates of surprisingly large future energy consumption always generate controversy, but there is a risk of relying on faulty calculations. At the very least, many calculations cannot be reliably reproduced and users of data center energy consumption estimates should be highly cautious of any publications basing their results on extrapolation-based approaches.

Our analysis has revealed several opportunities to improve data center energy research methodologies. For academic researchers, the recommendations above consist primarily of changes to basic scientific methods - clearly defining boundaries, publishing transparent and reproducible models, and considering the applicability of sources. In particular, the use of private reports from IDC and data from Cisco that regularly disappear from the web damage the reproducibility and reliability of estimates that rely on them. The problem is that there are no alternatives to these sources, yet developing more consistent and robust calculations relies upon transparent data that can withstand inevitable future scrutiny.

For industry, improving the quality and availability of data - that related to IT equipment shipment, installed base, network traffic, and power consumption - is the next step. The business incentives were initially related to positive press coverage, but are now a combination of competitive tensions as customers start to consider environmental concerns in their procurement processes. If the likes of IDC and Cisco cannot (or will not) release their data freely, the IT companies running large networks and data centers should do it instead. And if they fail to step up, regulators should force the issue through additional disclosure requirements.

The key takeaway of our review is that the onus is on us, researchers in the scientific community, to ensure that critical points and procedures of data provenance are transparently demonstrated within publications and research. End-users of our information, referring to lay people who rely on official dissemination of data center information, can not be expected to be the stakeholders that need to get to the source.

Supplemental information

Table S1 - List of references and sources analyzed

Data center energy estimates analyzed in this review. For each reference, the source material supporting the calculation for each of the system boundary components - servers, storage, network, infrastructure - are indicated along with the source of market information e.g., server shipments, installed base, growth projections. Sources in orange with prefixes indicating: Could not be found [NF] e.g., a web search could not locate the original document; Broken link [BL] e.g., the web address specified no longer works; Specific source or methodology not specified [NS] e.g., the citation is not specific enough or not specified at all; private/commercial [PC] e.g., the source data was provided privately or requires payment to access; or the data comes from the referenced source itself (internal data source, such as interviews conducted as part of the project). Sources in purple do not match the inclusion criteria for this review (see Note S1). Color choices from Color Brewer 2.0, found here: https://colorbrewer2.org/#type=diverging&scheme=PuOr&n=3

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
Koomey, 2007a[66]	- [PC] Cohen, Lloyd, and Stephen L. Josselyn. 2007. Market Analysis: U.S. and Worldwide Server Installed Base 2006-2010 Forecast, IDC. - [PC] IDC: Total installed base of servers by server class, historical and projected, for the U.S. and the	- [NS] Server energy data based on measured data, on-line server configuration calculators estimates from manufacturer specification sheets. Where unavailable, estimates made based on maximum measured use or	N/A	N/A	- Greenberg et al., 2006[111] - Malone & Belady, 2006[37] (Only covers server, cooling and auxiliaries associated with server power.)

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	World, 1996 to 2010. - [PC] IDC: Total shipments of servers by server class, historical and projected, for the U.S. and the World, 1996 to 2010. - [PC] IDC: Installed base of servers by model and manufacturer, for the U.S. and the World, 1998 to 2003. - [PC] IDC: Shipments of servers by model and manufacturer, for the U.S. and the World, 1996 to 2005.	rated input power supply, multiplied by factors from industry experience. - [NS] "Server lifetime estimates are based on reviews of server service contracts and other survey data"			
Brown et al., 2007[21]	- [PC] IDC Worldwide Installed Base Forecast, 2007-2010. - [PC] Bailey, M., M. Eastwood, T Grieser, L. Borovick, V.	Koomey, 2007a[66]	[PC] Personal communication with experts.	[PC] Personal communication with experts.	- Koomey, 2007a[66] - [NF] Working Group Notes from the EPA Technical Workshop on Energy Efficient Servers and Datacenters.

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	Turner, and R.C. Gray. 2007. Special Study: Data Center of the Future. New York, NY: IDC. IDC #06C4799.				Santa Clara, CA: U.S. Environmental Protection Agency (agenda found online, but not the notes)
Koomey, 2007b[67]	- Koomey, 2007a[66] - [PC] IDC Worldwide Server Tracker, 2Q07 (via personal communication with IDC).	Koomey, 2007a[66]	N/A	N/A	Koomey, 2007a[66] (Only covers server, cooling and auxiliaries (C&A) associated with server power.)
Bio Intelligence Service, 2008[112]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Fichter, 2007[113]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Fichter, 2007[113]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Fichter, 2007[113]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Fichter, 2007[113]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Fichter, 2007[113]
Koomey, 2008[114]	- Brown et al., 2007[21] - [PC] Cohen L and Josselyn S L 2007 Market Analysis: US and WorldwideServer Installed Base 2006-2010 Forecast IDC. Draft report, January. - [PC] Bailey, M., M. Eastwood, T Grieser, L.	- Koomey, 2007a[66] - Koomey, 2007b[67]	Brown et al., 2007[21]	Brown et al., 2007[21]	- Greenberg et al., 2006[111] - Belady & Malone, 2007[115]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	Borovick, V. Turner, and R.C. Gray. 2007. Special Study: Data Center of the Future. New York, NY: IDC. IDC #06C4799.				
Pickavet et al., 2008[116]	Koomey, 2007a[66]	Koomey, 2007a[66]	Koomey, 2007a[66]	Koomey, 2007a[66]	Koomey, 2007a[66]
Somavat, Jadhav & Namboodiri, 2010[68]	- Koomey, 2007a[66] - [BL] Gartner: Data Centres Account for 23% of Global ICT CO2 Emissions," November 5, 2007	Brown et al., 2007[21]	Brown et al., 2007[21]	Brown et al., 2007[21]	Brown et al., 2007[21]
Malmodin et al., 2010[40]	[PC] IDC "Virtualization 2.0: The next phase in customer adoption. Doc #204904, December 2006"	- Brown et al., 2007[21] - Koomey, 2007a[66] - Koomey, 2007b[67]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Koomey, 2007b[67]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Koomey, 2007b[67]	- Brown et al., 2007[21] - Koomey, 2007a[66] - Koomey, 2007b[67]
Bertoldi, 2010[58]	[NS] Survey of 142 EU Code of Conduct participants.	[NS] Survey of 142 EU Code of Conduct participants.	[NS] Survey of 142 EU Code of Conduct participants.	[NS] Survey of 142 EU Code of Conduct participants.	[NS] Survey of 142 EU Code of Conduct participants.
Vereecken et al., 2010a[47]	Pickavet et al., 2008[116]	Pickavet et al., 2008[116]	Pickavet et al., 2008[116]	Pickavet et al., 2008[116]	Pickavet et al., 2008[116]
Koomey, 2011[26]	- [PC] Bailey, M.,	- Brown et al.,	- Brown et al.,	- Brown et al.,	- Brown et al.,

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	M. Eastwood, T Grieser, L. Borovick, V. Turner, and R.C. Gray. 2007. Special Study: Data Center of the Future. New York, NY: IDC. IDC #06C4799. - Koomey, 2008[114] - [PC] IDC "January 2010 installed base/shipments forecast" and "15 March 2011 IDC shipments forecast", both via personal communication with IDC.	2007[21] - Koomey, 2008[114]	2007[21] - Koomey, 2008[114]	2007[21] - Koomey, 2008[114]	2007[21] - Koomey, 2008[114]
Masanet et al., 2011[29]	- [PC] Bailey, M., M. Eastwood, T Grieser, L. Borovick, V. Turner, and R.C. Gray. 2007. Special Study: Data Center of the Future. New York, NY: IDC. IDC #06C4799. - [PC] IDC's Worldwide	- [NF] Advanced Micro Devices, Power and Cooling in the Data Center, Santa Clara, CA, 34246C, 2006 - Koomey, 2007a[66] - Koomey, 2007b[67] - Brown et al., 2007[21] - Koomey, 2008[114] - Energy Star,	- Brown et al., 2007[21] - Battles et al., 2007[117] - [PC] Personal communication.	- Koomey, 2007a[66] - Koomey, 2007b[67] - Brown et al., 2007[21] - Koomey, 2008[114] - [PC] Personal communication.	- Greenberg et al., 2006[111] - Koomey, 2007a[66] - Koomey, 2007b[67] - Brown et al., 2007[21] - Belady et al., 2008[118] - Koomey, 2008[114]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	Installed Base Forecast 2007-2010, 2009	2009 - [PC] Personal communication.			
Global e-Sustainability Initiative aisbl & The Boston Consulting Group, Inc, 2012[119]	- Koomey, 2011[26] - [NS] "Cisco"	- CERN, 2008[120] - Malmodin et al., 2010[40] - Koomey, 2011[26] - [NS] "AT&T" - [NS] "BCG Experience" - [NS] "Expert interview"	- Malmodin et al., 2010[40] - Koomey, 2011[26]	- Malmodin et al., 2010[40] - Koomey, 2011[26] - [NS] "Cisco"	- Malmodin et al., 2010[40] - Koomey, 2011[26] - Carbon Disclosure Project, 2011[121] - [NS] "Google Data" - [NS] "AT&T" - [NS] "BCG Experience" - [NS] Expert interview
Corcoran & Andrae, 2013[44]	- Pickavet et al., 2008[116] - Koomey, 2011[26] - Corcoran, 2012[122] - [BL] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012–2017 - [BL] Cisco Global Cloud Index: Forecast and Methodology, 2011–2016	- Pickavet et al., 2008[116] - Koomey, 2011[26] - Corcoran, 2012[122]	- Pickavet et al., 2008[116] - Koomey, 2011[26] - Corcoran, 2012[122]	- Cucchietti, Griffa & Radice, 2007[123] - Pickavet et al., 2008[116] - Verizon Communications, 2010[124] - Koomey, 2011[26] - Corcoran, 2012[122] - Lambert et al., 2012[125] - CEET, 2013[126] - Coroama et al., 2013[127] - [BL] Eco-efficiency Indicator for	- Pickavet et al., 2008[116] - Koomey, 2011[26] - Corcoran, 2012[122]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
				Telecom_Italia_S.P.A. (TI). - Telecom Italia, 2012[128]	
Van Heddeghem et al., 2014[70]	- IDC, 2012[129] - IDC, 2013[130]	Koomey, 2011[26]	Koomey, 2011[26]	Koomey, 2011[26]	- [BL] Energy Star, Performance ratings technical methodology for data center, energy star, 2010. - [NF] Uptime Institute, 2011 data center industry survey - Koomey, 2011[26]
Liua et al., 2014[131]	- [NS] IDC - [NF] Schäppi, Bernd et al.; Energy efficient servers in Europe, Energy consumption, saving potentials and measures to support market development for energy efficient solutions, Wien 2009 - Kaskade, 2011[132]	- [NF] Schäppi, Bernd et.al; Energy efficient servers in Europe, Energy consumption, saving potentials and measures to support market development for energy efficient solutions, Wien 2009 - Bozman & Broderick, 2010[133] - Stansberry & Kudritzki, 2012[134]	SNIA, 2011[135]	[BL] NetApp White Paper “Reducing Data Centre Power Consumption Through Efficient Storage”, July 2009	- Koomey, 2011[26] - Stansberry & Kudritzki, 2012[134] - [PC] Expert opinion

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
		- [BL] Arnclan Computer Services 2011 - When is the right time to replace servers? - Standard Performance Evaluation Corporation, n.d.[94] ("from 2008 until now", assumed to be 2014)			
Malmodin et al., 2014[43]	- [NS] TeliaSonera. 2008. Annual reporting. - [BL] PTS (The Swedish Post and Telecom Agency). The Swedish Telecommunications Market 2007, 2008 (PTS-ER-2008:15), 2009 (PTS-ER-2009:21), 2010 (PTS-ER-2010:13), 2011 (PTS-ER-2011:15).	Koomey, 2011[26]	Koomey, 2011[26]	- Donovan, 2009[136] - Koomey, 2011[26]	Koomey, 2011[26]
Whitehead et al., 2014[137]	- Koomey, 2011[26]	Koomey, 2011[26]	Koomey, 2011[26]	Koomey, 2011[26]	Koomey, 2011[26]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	- Masanet et al., 2011[29] - [NF] DCD Industry census 2012: energy DatacenterDynamics Focus, 3 (26) (2012) - [BL] DCD Special market report: data centers in the United Kingdom (2011)				
Whitney & Delforge, 2014[138]	- Brown et al., 2007[21] - [BL] Mirko Lorenz, How Many Servers Worldwide?, Vision Cloud, August 2011 - Koomey, 2011[26] - Masanet et al., 2011[29] - Global e-Sustainability Initiative aisbl & The Boston Consulting Group, Inc, 2012[119] - [PC] Expert interview	- Koomey, 2011[26] - Masanet et al., 2011[29] - Standard Performance Evaluation Corporation, n.d.[94]	- Koomey, 2011[26] - Masanet et al., 2011[29]	- Koomey, 2011[26] - Masanet et al., 2011[29]	- Koomey, 2011[26] - Masanet et al., 2011[29] - Bennett & Delforge, 2012[139]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
Andrae & Edler, 2015[11]	Cisco, 2013[140]	- Tucker, Hinton & Ayre, 2012[141] - Time Magazine[95] - Corcoran & Andrae, 2013[44] - Hachman, 2015[96]	- Tucker, Hinton & Ayre, 2012[141] - Time Magazine[95] - Corcoran & Andrae, 2013[44] - Hachman, 2015[96]	N/A - excluded from the data center energy system boundary.	- Tucker, Hinton & Ayre, 2012[141] - Time Magazine[95] - Corcoran & Andrae, 2013[44] - Hachman, 2015[96]
Bio by Deloitte, 2015[59–65] (Tasks from the same study separated into 7 individual reports. Final report published as Berwald et al., 2016[142])	- [NS] "Market data provided by DIGITALEUROPE through the consultation process" (from Task 2[60]) - [NS] Average equipment lifetime from DIGITALEUROPE (from Task 3[61]) - [NS] "IDC quarterly public press releases" (from Task 2[60]) - [NS] "Gartner quarterly public press releases" (from Task 2[60]) - IDC, 2010[143] (from Task 2[60]) - PRODCOM, 2012[144] (from Task 2[60]) - [PC] Gartner – Market Definitions and Methodology:	- [BL] The Green Grid Whitepaper No 19 "Using virtualisation to improve data centre efficiency", 2009 (from Task 3[61]) - [NS] "Anecdotal information" about server utilisation (from Task 3[61]) - [NS] "DIGITALEUROPE provided specific data regarding different server utilization profiles" (from Task 3[61]) - [NS] SPEC "An averaged power consumption value based on available SERT data" (from Task 3[61])	- [BL] Seagate (from Task 4[62]) - [BL] Enterprise Storage Forum (from Task 4[62]) - [BL] Fujitsu (from Task 4[62]) - [BL] HGST (2013) 12Gb/s SAS: Key Considerations For Your Next Storage Generation (from Task 4[62])	Discussed in Task 4[62] but no sources provided.	- Google[72] (from Task 6[64]) - Uptime Institute, 2014[145] (from Task 6[64]) Task 7[65] provides PUE assumptions for each scenario, but does not provide sources for them.

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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IEA, 2017[162]	[BL] Cisco Global Cloud Index: Forecast and Methodology, 2015-2020, 2016	Shehabi et al., 2016[9]	Shehabi et al., 2016[9]	Shehabi et al., 2016[9]	Shehabi et al., 2016[9]
Malmodin & Lundén, 2018a[54]	- Malmodin et al., 2010[40] - Malmodin, Bergmark & Lundén, 2013[28] - Malmodin & Lundén, 2016[53]	- Malmodin et al., 2010[40] - Koomey, 2011[26] - Malmodin, Bergmark & Lundén, 2013[28]	- Malmodin et al., 2010[40] - Koomey, 2011[26] - Malmodin, Bergmark & Lundén, 2013[28]	- Malmodin et al., 2010[40] - Koomey, 2011[26] - Malmodin, Bergmark & Lundén, 2013[28]	- Malmodin et al., 2010[40] - Koomey, 2011[26] - Malmodin, Bergmark & Lundén, 2013[28]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Andrae, 2019b[33]	- Hilbert & López, 2011[179] - Xu, 2014[180] - Andrae & Edler, 2015[11]	- Xu, 2014[180] - Van Heddeghem et al., 2014[70] - Andrae & Edler, 2015[11] - Ionescu, 2017[181] - Bashroush, 2018[182] - [NF] Presentation "J.L. Summers. 2018. From ZettaBytes to zeptoJoules – can digital demand outstrip the physical limits? Presentation held at RISE SICS Open House Kista, Sweden 19 April 2018"	N/A	Andrae & Edler, 2015[11]	N/A
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Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
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Montevecchi et al., 2020[69]	- Hintemann, Fichter & Schlitt, 2014[147] - Fichter & Hintemann, 2014[172] - Stobbe et al., 2015[24] - [BL] Cisco Global Cloud Index: Forecast and Methodology 2014-2019, 2015	- Van Heddeghem et al., 2014[70] - Fichter & Hintemann, 2014[172] - Stobbe et al., 2015[24] - Andrae & Edler, 2015[11] - Bio by Deloitte, 2015[59–65] - Koomey & Taylor, 2015[202]	- Van Heddeghem et al., 2014[70] - Fichter & Hintemann, 2014[172] - Stobbe et al., 2015[24] - Andrae & Edler, 2015[11] - Bio by Deloitte, 2015[59–65] - Koomey & Taylor, 2015[202]	- Van Heddeghem et al., 2014[70] - Fichter & Hintemann, 2014[172] - Stobbe et al., 2015[24] - Andrae & Edler, 2015[11] - Bio by Deloitte, 2015[59–65] - Koomey & Taylor, 2015[202]	- Van Heddeghem et al., 2014[70] - Fichter & Hintemann, 2014[172] - Stobbe et al., 2015[24] - Andrae & Edler, 2015[11] - Bio by Deloitte, 2015[59–65] - Koomey & Taylor, 2015[202]

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	- Hintemann, 2015[148] - Shehabi et al., 2016[9] - [BL] Cisco Global Cloud Index: Forecast and Methodology 2015-2020, 2016 - Hintemann, 2017a[169] - CBRE, 2017[167] - Hintemann, 2018[201] - Belkhir & Elmeligi, 2018[27] - CBRE, 2018[168] - Hintemann & Clausen, 2018a[170] - Hintemann & Clausen, 2018b[171] - [NF] M. Howard-Healy, "Co-location Market Quarterly (CMQ) brief - Vortrag auf dem BroadGroup's Knowledge Brunch in Frankfurt Broadgroup, 2018	- Shehabi et al., 2016[9] - Avgerinou, Bertoldi & Castellazzi, 2017[161] - Shehabi et al., 2018[10] - Hintemann, 2018[201] - Belkhir & Elmeligi, 2018[27] - The Shift Project, 2019[13] - Andrae, 2019a[34] - Andrae, 2019d[45] - Andrae, 2019e[203] - Digiconomist, n.d.[87] (source has no date but cited as 2019) - IEA, 2019[204] - Rauchs et al., 2019[205] - Hintemann & Hinterholzer, 2019[82] - [NS] Manufacturer information on the power requirements of servers, storage and network products	- Shehabi et al., 2016[9] - Avgerinou, Bertoldi & Castellazzi, 2017[161] - Shehabi et al., 2018[10] - Hintemann, 2018[201] - Belkhir & Elmeligi, 2018[27] - The Shift Project, 2019[13] - Andrae, 2019a[34] - Andrae, 2019d[45] - Andrae, 2019e[203] - Digiconomist, n.d.[87] (source has no date but cited as 2019) - IEA, 2019[204] - Rauchs et al., 2019[205] - Hintemann & Hinterholzer, 2019[82] - [NS] Manufacturer information on the power requirements of servers, storage and network products	- Shehabi et al., 2016[9] - Avgerinou, Bertoldi & Castellazzi, 2017[161] - Shehabi et al., 2018[10] - Hintemann, 2018[201] - Belkhir & Elmeligi, 2018[27] - The Shift Project, 2019[13] - Andrae, 2019a[34] - Andrae, 2019d[45] - Andrae, 2019e[203] - Digiconomist, n.d.[87] (source has no date but cited as 2019) - IEA, 2019[204] - Rauchs et al., 2019[205] - Hintemann & Hinterholzer, 2019[82] - [NS] Manufacturer information on the power requirements of servers, storage and network products	- Shehabi et al., 2016[9] - Avgerinou, Bertoldi & Castellazzi, 2017[161] - Shehabi et al., 2018[10] - Hintemann, 2018[201] - Belkhir & Elmeligi, 2018[27] - The Shift Project, 2019[13] - Andrae, 2019a[34] - Andrae, 2019d[45] - Andrae, 2019e[203] - Digiconomist, n.d.[87] (source has no date but cited as 2019) - IEA, 2019[204] - Rauchs et al., 2019[205] - Hintemann & Hinterholzer, 2019[82] - [NS] Manufacturer information on the power requirements of servers, storage and network products

Reference	Market sources	Server sources	Storage sources	Network sources	Infrastructure sources
	- Malmodin & Lundén, 2018a[54] - Hintemann & Hinterholzer, 2019[82] - Andrae, 2019d[45] - Masanet et al., 2020[3] - [PC] Techconsult - [PC] EITO/IDC				- [PC] Expert interviews
Liu et al., 2020[48]	- Cisco, 2013[206] - Cisco, 2016b[207]	- Dagher, Marcellin & Neifeld, 2007[208] - Corcoran & Andrae, 2013[44] - Andrae & Edler, 2015[11] - Hachman, 2015[96]	- Dagher, Marcellin & Neifeld, 2007[208] - Corcoran & Andrae, 2013[44] - Andrae & Edler, 2015[11] - Hachman, 2015[96]	- Dagher, Marcellin & Neifeld, 2007[208] - Corcoran & Andrae, 2013[44] - Andrae & Edler, 2015[11] - Hachman, 2015[96]	- Dagher, Marcellin & Neifeld, 2007[208] - Corcoran & Andrae, 2013[44] - Andrae & Edler, 2015[11] - Hachman, 2015[96] - Avgerinou, Bertoldi & Castellazzi, 2017[161] - Yole Développement, 2017[209]
Koot & Wijnhoven, 2021[210]	- Cisco, 2013[206] - Kückelhaus, Macaulay & Chung, 2015[211] - NL Times, 2018[212] - Masanet et al., 2020[3] - Cisco, 2020[213]	- Cisco, 2013[206] - Shehabi et al., 2018[10] - Masanet et al., 2020[3] - Shalf, 2020[214]	- Cisco, 2013[206] - Shehabi et al., 2016[9] - Shehabi et al., 2018[10] - Masanet et al., 2020[3]	- Cisco, 2013[206] - Shehabi et al., 2016[9] - Aslan et al., 2018[109] - Masanet et al., 2020[3]	Barroso, Clidaras & Hölzle, 2013[30]

Table S2 - Individual data center energy estimates

Table S2 lists all individual data center energy estimates extracted from each of the papers analyzed in Table S1.

Table S3 - Data center scope publications and data provenance

Table S3 groups all the data center energy publications and cited sources for analysis.

Note S1 - References excluded from review

- Fichter, 2007[113] - presentation in German.
- Hintemann, Fichter & Stobbe, 2010[149] - report in German.
- Hintemann & Clausen, 2014[146] - report in German.
- European Commission Pan-European Data Centre Alliance (PEDCA), 2015[215] - no methodology or sources provided.
- Stobbe et al., 2015[24] - report in German.
- Hintemann, 2017a[169] - presentation in German.
- Hintemann, 2017b[192] - report in German.
- Yole Développement, 2017[209] - no calculations, sources or methodology provided.
- Hintemann, 2018[201] - report in German.
- Hintemann & Clausen, 2018a[170] - report in German.
- Hintemann & Clausen, 2018b[171] - report in German.
- Bashroush, 2018[216] - based on analysis of 350 public sector data centers. Sources, methodology not provided.
- Bashroush & Lawrence, 2020[217] - no calculations, sources or methodology provided.

Note S2 - Literature search keywords

The following terms were used as part of the literature search described in the Review methodology. Where necessary, British English alternatives such as “data centre” were also used:

Data center energy, data center power, data center energy consumption, data center energy use, IT energy consumption, green IT, data center emissions, IT emissions, cloud energy consumption, review of data center energy estimates, environmental footprint of data centers, environmental impact of data centers, energy efficiency of data centers.

Note S3 - Detailed methodology notes

In addition to the literature search described in the Review methodology section, a reverse citation search was also used for each publication. Where a peer-reviewed paper referred to another publication, we included that additional publication even if it did not show up in the original search. For example, Andrae, 2019a[34] and Andrae, 2019b[33] were reviewed even though they had not been formally published because they were referenced in Andrae, 2019c[31] (which was peer-reviewed).

In some cases, earlier reports were subsequently published in peer-reviewed journals. In those instances, the later publication was cited unless there were major deviations from the earlier works. For example Lannoo, 2013[218] was later published as Van Heddeghem et al., 2014[70] with only minor modifications, so we only included the latter. Bertoldi et al., 2017[160] was later published in modified form as Avgerinou et al., 2017[161], but as they each provide separate calculations both were included.

Estimates were required to provide a minimum level of detail about sources and/or input values to calculate the estimate, whether in the main text or as part of any supplemental information. For example, Yole Développement, 2017[209] provides estimates but does not explain calculations or sources, so was excluded. Bordage, 2019[219] was excluded because it does not provide input values or a methodology for the data center energy calculations. News articles such as Bawden, 2016[220] were also excluded unless the sources or calculations were provided - quotes from experts or unnamed studies were not sufficient for inclusion. We found that news articles tended to cite a recently published source, such as Donovan, 2019[221] reporting on The Shift Project, 2019[13], and the latter was included in this review.

Estimates provided from “surveys” were included if at least the survey parameters were provided e.g., details about participants. Surveys without methodological information were excluded. This was difficult to determine in some cases, such as Bertoldi, 2010[58] which was included because it provided a more detailed breakdown of the survey results (dataset size, type of data center, average floor size, average electricity consumption, etc.) compared to European Commission Pan-European Data Centre Alliance (PEDCA), 2015[215] which was excluded because it did not include sufficient information about the underlying survey data.

Estimates for a subset of data centers, such as those owned by a specific organization, operated by a certain industry, grouped by industry body membership (such as those from Uptime Institute surveys), or grouped with other energy users, were excluded. For example Cook et al., 2014[222] and Baniata et al., 2021[223] provide estimates only for specific companies, Obringer et al., 2021[12] covers only “the internet” i.e. networks, Fehske et al., 2011[224] only includes data centers related to mobile network communications, Kishita et al., 2016[225] groups data centers with other buildings (labeled as “Other”), and Dayarathna et al., 2016[226] is a review of data center modeling techniques and does not perform any new calculations. These publications were all excluded.

Some publications make multiple projections based on different assumptions, such as how much energy efficiency will change, each of which are represented by a particular scenario name and year. The methodology type was categorized for each publication based on the methodology as described within each publication. Where possible, a single methodology was assigned e.g., “Extrapolation” or “Bottom-up”, but in several cases multiple categories were used.

Sources were assessed to fit into one or more categories and the most appropriate category was selected based on how that source was used in the publication. In some cases this was not clear, so careful judgment was used to apply the source to the most relevant category or categories. For example, Van Heddeghem et al., 2014[70] was cited as the source for “Data Centers - Historical Compound Aggregated Growth Rate (CAGR) of electricity (TWh)” in Andrae, 2019d[45], which does not fit into a single category. In this case, the source was considered to fall into the servers, storage, network, and infrastructure categories because it considers the whole data center. Another example is Pickavet et al., 2008[116] which relied on Koomey, 2007a[66] alone for all five categories (thus, five individual publication-source mappings were drawn) in their published work.

For effective visualization of the key source mappings, appropriate groupings were established to demonstrate core data provenances (Table S3). Data sources, through various industry reports and database citations such as IDC, Cisco, and Gartner, were grouped as one because publications often cited updated reports and databases which utilized very similar methods in their republication of information over the years. Careful consideration was given to these groupings whereby categorizations were made for the most common data type and reliability. Referring to the IDC grouping again as an example, this overall data group was classed as “PC” (private/commercial) with “Various” data type classification as no one data type dominated this grouping (see Table S1 for ungrouped details). In Figure 6 and Figure 7, years used for data sources are tied to the year of publication and not the year in which the data encompass. Grouped sources with no single or clearly defined year were not included in reported descriptive statistics.

It is important to note that although publications and sources were thoroughly classified to represent an accurate as possible assessment of data provenance, some understandable nuances need to be considered. For instance, a source that has been classed as "Data with source" for its data type can be also listed as “NF” (not found) if the report or database name is known despite the link to the publication/data being absent. Some citations are listed as “NF” but their categorization of publication type as “Report” were made based on justified assumptions as per the publishing body/author. Categorizing sources as “NS” implies that either the methods or the sources’ data provenance is unclear or poorly justified, injecting a level of subjectivity (though carefully measured) into our assessment. A classification of “Data without source” implies that the exact source of the data is unknown, for example, a Cisco mapped source (not tied to a report or database) was classified under this category whereas a source labeled "Cisco, 2015" (a report) was entered as “Data with source”. Sources determined to be “Reports” represented two main types of industry/consultant reports as well as instances where the author self-published a report, as is the case with Koomey, 2007a[66] and 2007b[67]. These methodological nuances do not alter the key findings and takeaways in our review, but should be taken into consideration for further context and replicability.

Citation count was used to filter the most important publications in Figure 7. This was determined by the citation count indicator in Google Scholar as of January, 2022. For most publications, there was an exact match and the citation count was used directly. For those that did not match exactly or had multiple entries, such as Whitney & Delforge, 2014[138], the citation count of all the results on the first page were summed to produce the citation count.

Figure legends

Figure 1: A flowchart summarizing the review inclusion criteria. From the literature search, a publication was assessed to determine whether it contained original calculations, whether it covered a whole geographical region (or was a global estimate), whether the sources and input values were provided, and whether it contained values for use-stage energy consumption. If so, the scenarios, estimates, and sources were extracted and analyzed.

Figure 2: Global data center energy estimates for 2010, 2020 and 2030 as ranges (in TWh) plotted by the year the estimate applies to (estimate year). This figure demonstrates the wide range of estimates across publications and should not be used as an analysis or projection of data center energy values themselves - caution should be used when comparing estimates due to a wide range of methods and system boundaries. n = number of estimates. Excludes 5 estimates > 2,000 TWh with a range of 2,000 TWh to 8,253 TWh to allow for effective scaling of the visualization. All estimates can be found in Table S2. Code used to perform calculations and generate visualization is available on Figshare.

Figure 3: Breakdown of key source (grouped) categorization. Orange color indicates source publications that could not be found with the reasons shown, as described in Table 1 and listed in Table S1. Although we assume these sources were available when originally published, we are highlighting those that are unavailable now, therefore undermining the replicability of the estimate today. Blue and teal colors show a breakdown of main source types. Blue and teal sources may also appear in the percentage calculation for missing sources (orange). See Table S3 for a full list of each source and how it is categorized.

Figure 4: Global data center energy estimates for 2010, 2020 and 2030 as ranges (in TWh) plotted by the year the estimate applies to (estimate year) and grouped by methodological classification. This figure demonstrates the wide range of estimates across publications and highlights how the estimates vary by methodology. It should not be used as an analysis or projection of data center energy values themselves - caution should be used when comparing estimates due to a wide range of methods and system boundaries. n = number of estimates. Excludes 5 estimates > 2,000 TWh with a range of 2,000 TWh to 8,253 TWh to allow for effective scaling of the visualization. All estimates can be found in Table S2. Code used to perform calculations and generate visualization is available on Figshare.

Figure 5: Global data center energy estimates for 2010-2030 as ranges (in TWh) plotted by the year to which the estimate applies (estimate year). Number above each box indicates the estimate count. Excludes 5 estimates > 2,000 TWh with a range of 2,000 TWh to 8,253 TWh to

allow for effective scaling of the visualization. All estimates can be found in Table S2. Code used to perform calculations and generate visualization is available on Figshare. **Top:** All estimates grouped by estimate year. **Bottom:** The same estimates, but also grouped by methodology type. The comparison highlights the wide ranges generated by extrapolation-based methods.

Figure 6: Sankey diagram showing the flow of citations between Corcoran & Andrae, 2013[44], Andrae & Edler, 2015[11], and The Shift Project, 2019[13]. Each of these publications has at least one missing source (indicated in orange), with the sources used by The Shift Project, 2019[13] such as Gartner, IDC, and Statista almost entirely unavailable or insufficiently referenced so as to locate the original source. Although we assume these sources were available when originally published, they are now unavailable which undermines the replicability of the estimate today. See Table S1 for the full list of publications, sources, and reasons for sources that could not be found. Code used to generate visualization is available on Figshare.

Figure 7: Sankey diagram showing the flow of citations between three highly cited publications - Malmodin & Lundén, 2018a[54] cites Shehabi et al., 2016[9] which cites Van Heddeghem et al., 2014[70]. Sources in orange indicate that source could not be found. This diagram highlights how publications can be undermined by unavailable sources further down the chain, such as the use of non-public data from IDC in both Malmodin & Lundén, 2018a and Shehabi et al., 2016. Colored nodes on the right (for end publications) indicate citation count from Google Scholar (green >= 100, yellow >= 500). See Table S1 for the full list of publications, sources, and reasons for sources that could not be found. Code used to generate visualization is available on Figshare.

Figure 8: Questions for determining data center energy estimate reliability. In order for end-users to critically assess the value of data center publications, estimates, and data, these three guiding questions should be a starting point when determining the level of confidence that should be placed in calculations and energy consumption findings.

Figure 9: Recommended methodology flow for data center energy analysis. Key stages of analysis are highlighted, starting from a clearly defined system boundary. If Stage 5 has not been adequately fulfilled, we recommend that authors remove troublesome sources and rerun our suggested flow from Stage 2 to ensure validated inputs are fed into methods.

Tables

Table 1: Publication classifications used to analyze source availability in Table S1 and S3.

Publication Classification	Criteria and Examples

EL	Existing link and accessible through a reasonable method e.g., via a working web link, published in an open access journal, published in a closed-access journal but with subscription access generally available through a public or academic library.
NF	Could not be found, e.g., a web search could not locate the original document.
BL	Broken link, e.g., the web address specified no longer works.
NS	Specific source or methodology not specified, e.g., the citation is not specific enough or not specified at all.
PC	Private/commercial, e.g., the source data were provided privately or requires payment to access, or the data were collected as part of the publication methodology, but kept private (internal data source).

Table 2: Characteristics of the three main approaches to assessing data center energy - bottom-up, top-down, extrapolation.

	Bottom-up	Top-down	Extrapolation
Key inputs	● Equipment specifications e.g. server power draw. ● Data center infrastructure characteristics e.g. PUE. ● Installed base / equipment shipment values.	● Government or organization measurements e.g. total data volume and total operator energy consumption.	● Baseline year value (from bottom-up or top-down models). ● Growth rate (which may factor in energy efficiency improvements and growth in data volumes or customer numbers).
Assumptions for future growth	● Future equipment shipment values. ● Future equipment trends e.g. power density, GPUs, liquid	● Relationship between demand and energy consumption, usually data volume. ● Future customer	● Relationship between demand and energy consumption, usually data volume.

	cooling. • Energy efficiency improvements e.g., PUE improvements or server power draw improvements.	growth e.g., number of internet provider customers. • Energy efficiency improvements (usually broad because of the lack of specific breakdowns such as PUE or server power).	• Energy efficiency improvements e.g., PUE improvements or server power draw improvements.
Main limitations	• Availability of installed base and server equipment values. • Ability to project trends in equipment type and energy efficiency improvements more than a few years into the future.	• Accuracy and availability of organization data. • Ability to project future trends in energy efficiency. • Correlation between inputs e.g. data consumption per customer.	• Correlation between inputs e.g. energy consumption per unit of data. • Ability to project future trends in energy efficiency.
Examples	• Malmodin et al., 2010[40] • Masanet et al., 2020[3] = 205 TWh global historical estimate for 2018.	Malmodin et al., 2014[43] = 238 TWh global historical estimate for 2010.	• Corcoran & Andrae, 2013[44] = 281 TWh global baseline for 2012 with projections ranging from 349 - 485 TWh for 2015. • Andrae & Edler, 2015[11] = projections ranging from 1137 TWh - 7993 TWh for 2030.

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Author contributions

Conceptualization: D.M.; Methodology: D.M. and M.A.; Software: D.M.; Data Curation: D.M. and M.A.; Formal Analysis: D.M. and M.A.; Writing - Original Draft: D.M.; Writing - Review & Editing: D.M. and M.A.; Visualization: D.M. and M.A.

Declaration of interests

D.M. has a financial interest in StackPath, LLC, an edge computing company, and was engaged by Uptime Institute as a Research Affiliate from December 2020 to November 2021. The authors declare no further competing interests.

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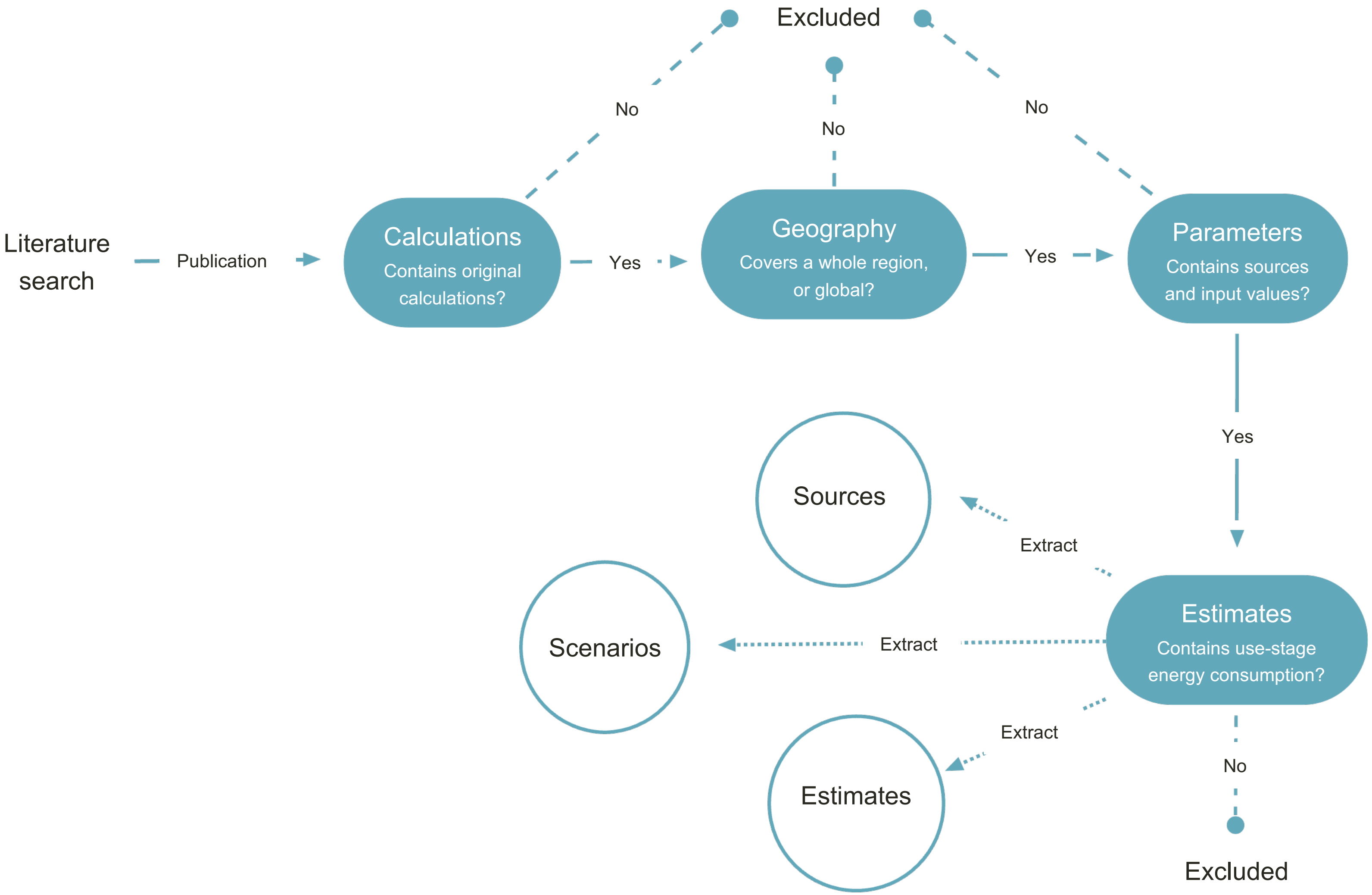
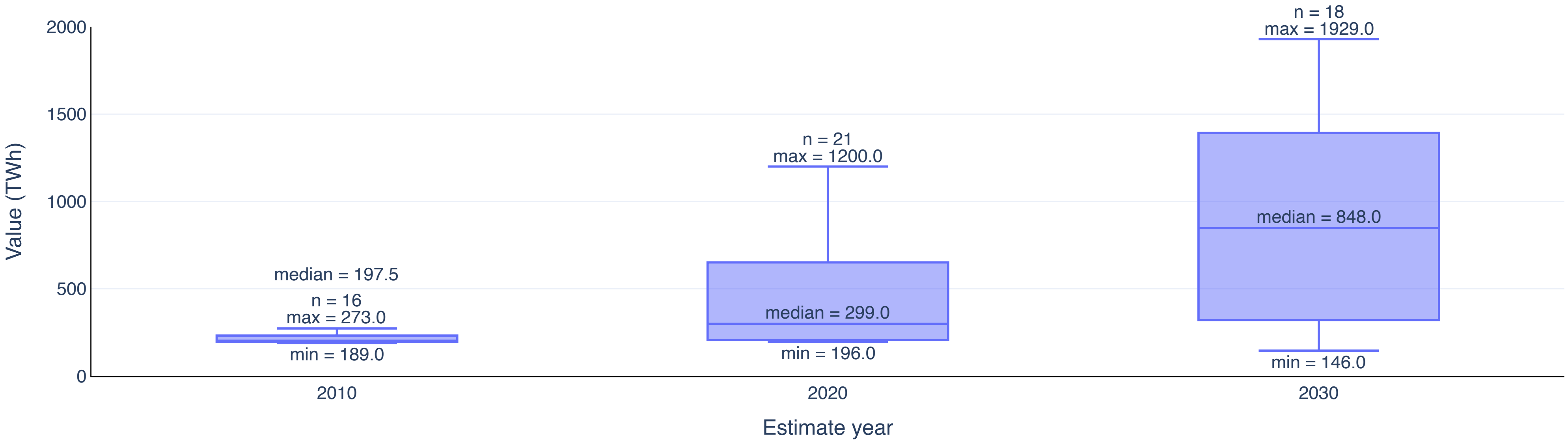

Excluded
No
No
No
Literature search
Publication
Calculations
Contains original calculations?
Yes
Geography
Covers a whole region, or global?
Yes
Parameters
Contains sources and input values?
Yes
Sources
Extract
Scenarios
Extract
Estimates
Contains use-stage energy consumption?
Extract
Estimates
No
Excluded



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1000
500
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Value (TWh)
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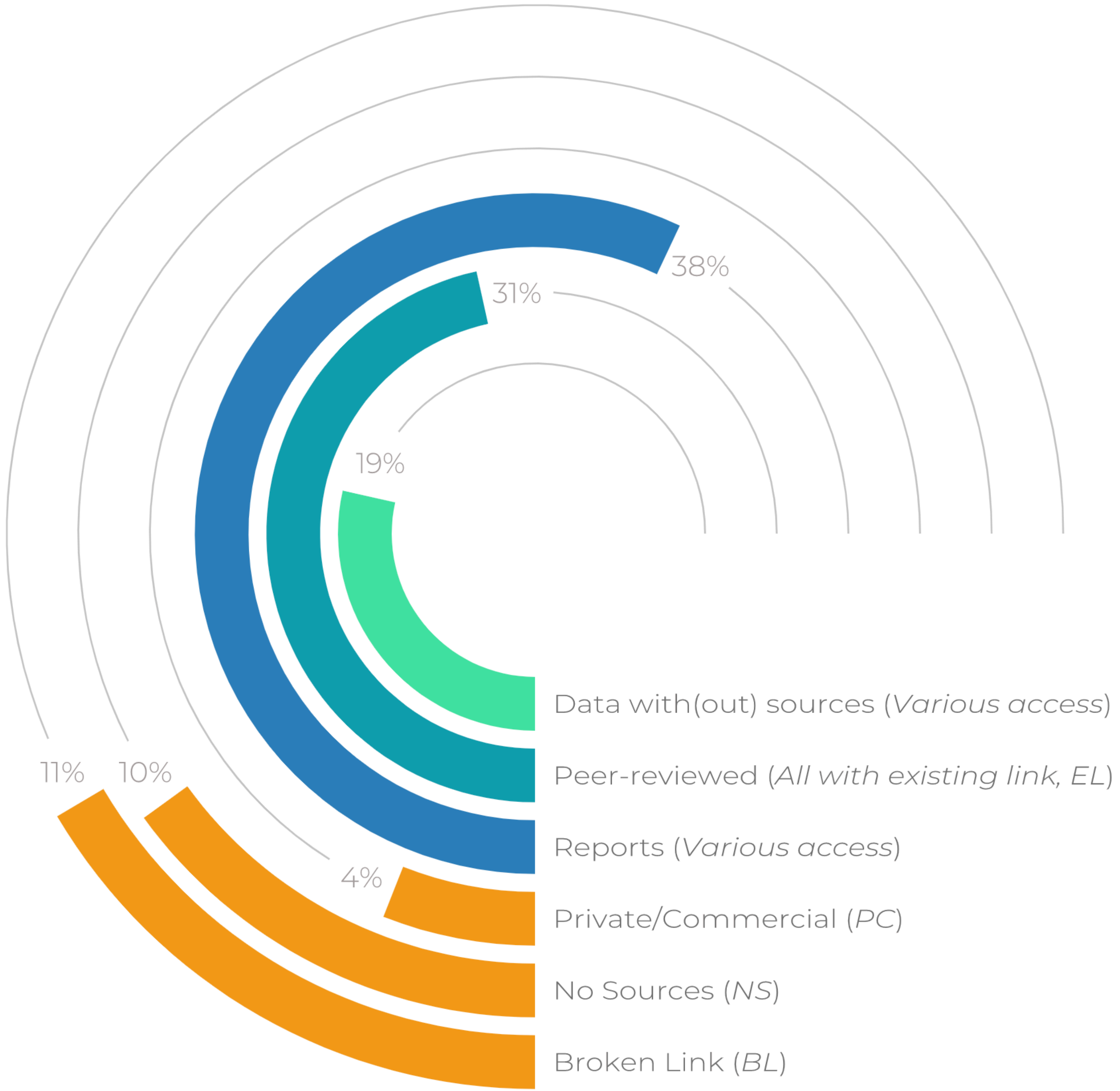
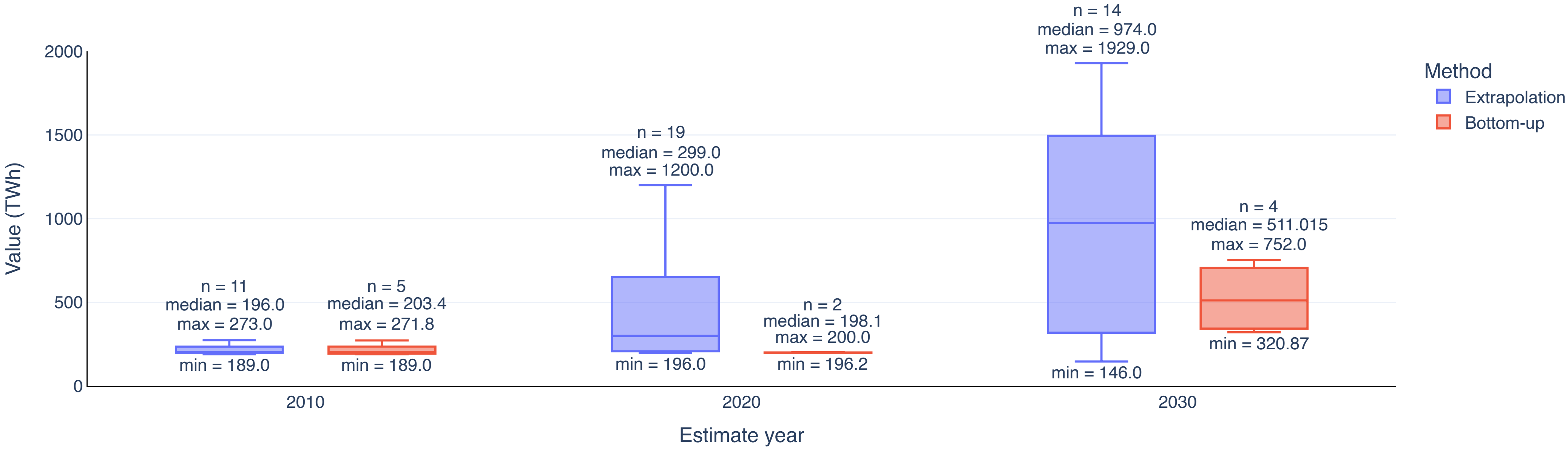
max = 273.0
median = 197.5
min = 189.0
n = 21
max = 1200.0
median = 299.0
min = 196.0
n = 18
max = 1929.0
median = 848.0
min = 146.0
2010
2020
2030
Estimate year


38%
31%
19%
11%
10%
4%
Data with(out) sources (*Various access*)
Peer-reviewed (*All with existing link, EL*)
Reports (*Various access*)
Private/Commercial (*PC*)
No Sources (*NS*)
Broken Link (*BL*)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median = 203.4
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min = 189.0
n = 19
median = 299.0
max = 1200.0
min = 196.0
n = 2
median = 198.1
max = 200.0
min = 196.2
n = 14
median = 974.0
max = 1929.0
min = 146.0
n = 4
median = 511.015
max = 752.0
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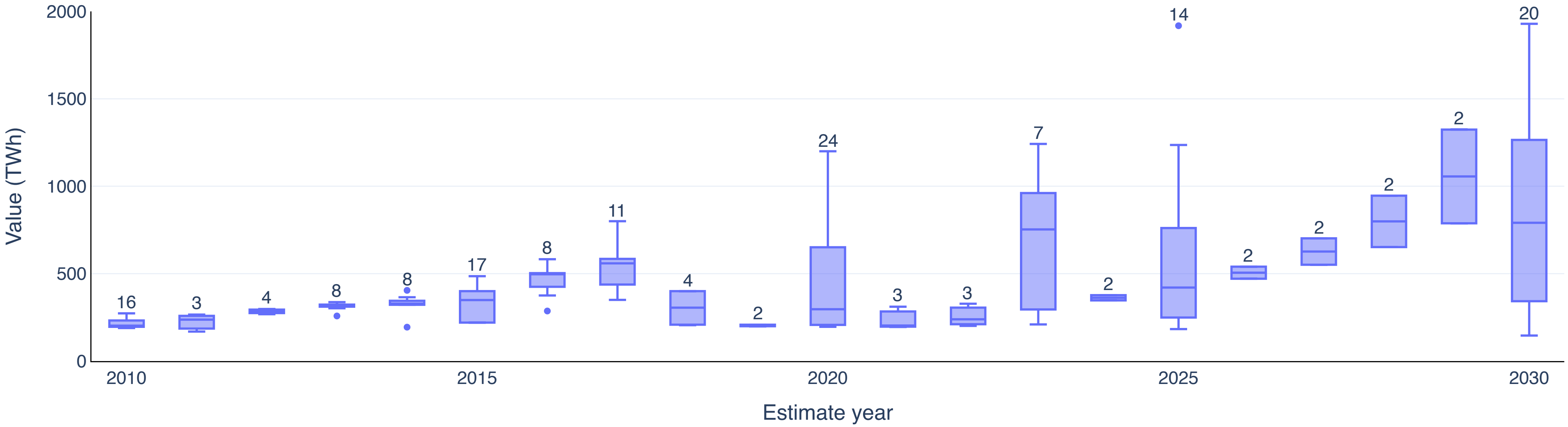
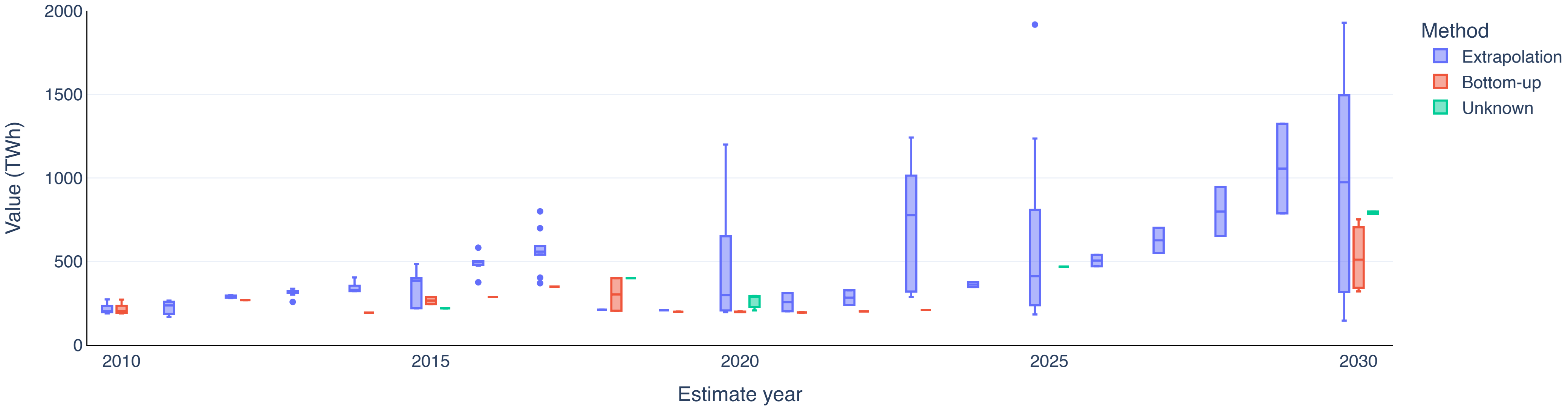
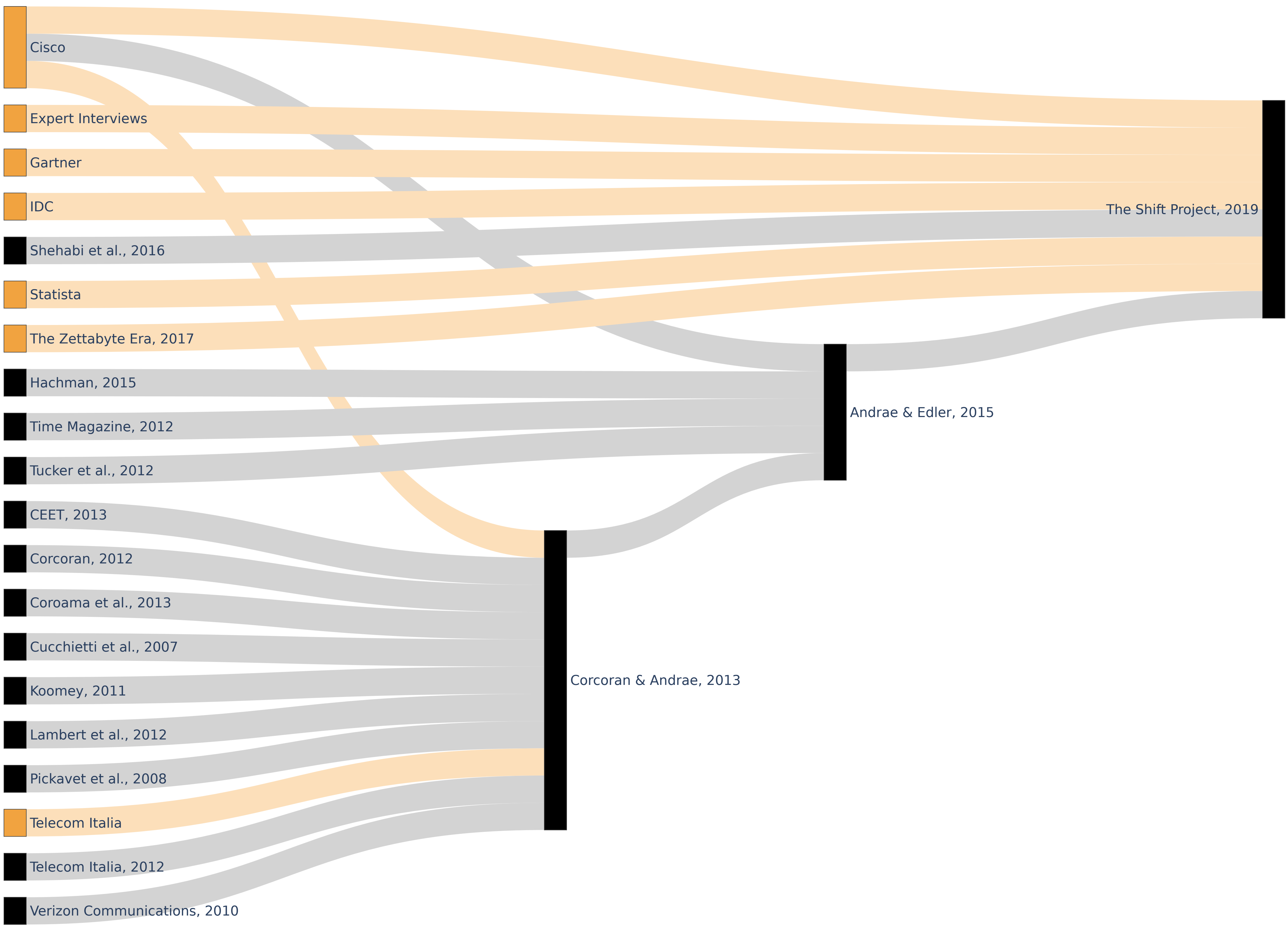
2010
2020
2030
Estimate year
Method
Extrapolation
Bottom-up

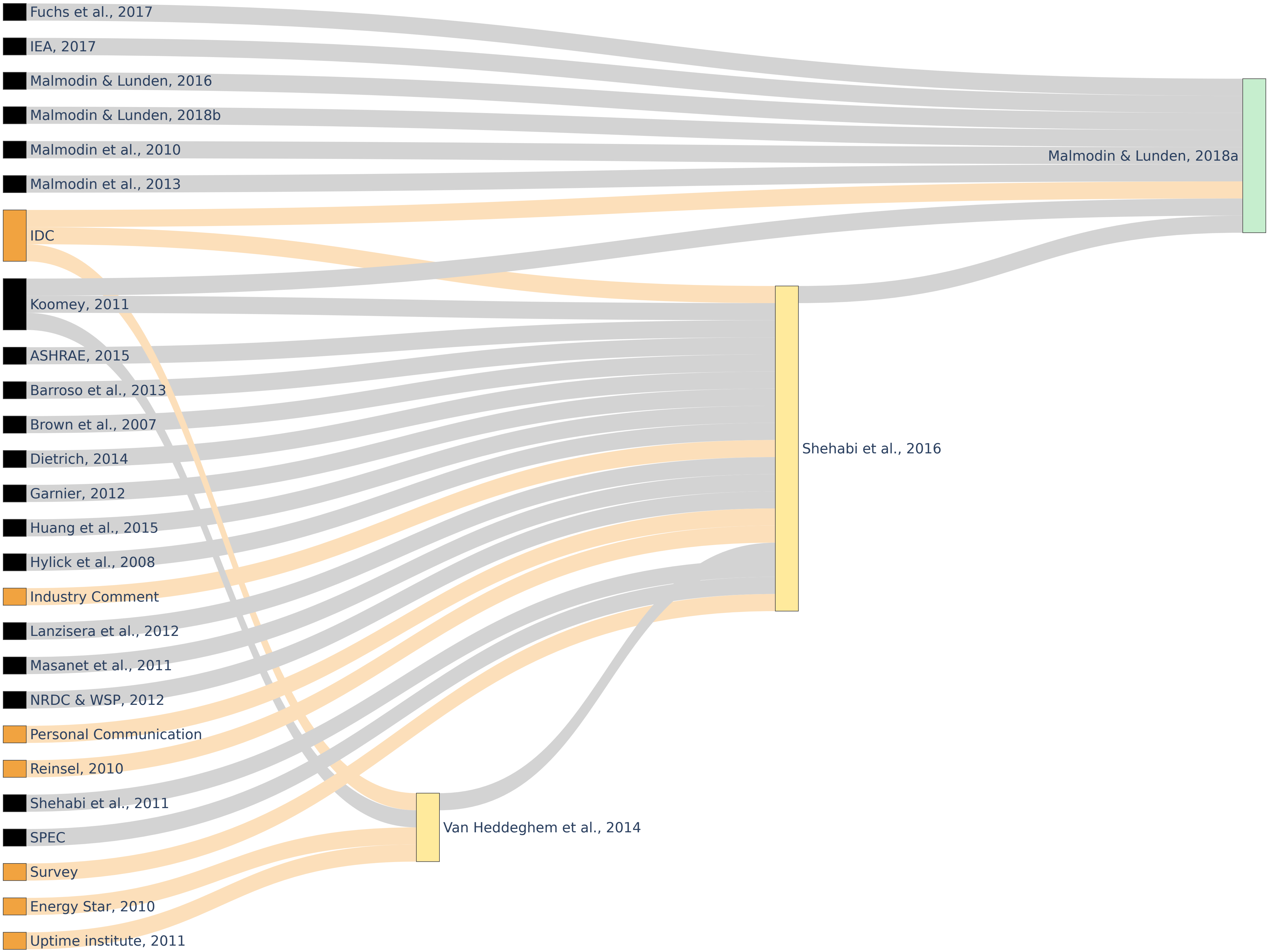


2000
1500
1000
500
0
Value (TWh)
16
3
4
8
8
17
8
11
4
2
24
3
3
7
2
14
2
2
2
2
20
2010
2015
2020
2025
2030
Estimate year



Value (TWh)
2000
1500
1000
500
0
2010
2015
2020
2025
2030
Estimate year
Method
Extrapolation
Bottom-up
Unknown


Cisco
Expert Interviews
Gartner
IDC
Shehabi et al., 2016
Statista
The Zettabyte Era, 2017
Hachman, 2015
Time Magazine, 2012
Tucker et al., 2012
CEET, 2013
Corcoran, 2012
Coroama et al., 2013
Cucchietti et al., 2007
Koomey, 2011
Lambert et al., 2012
Pickavet et al., 2008
Telecom Italia
Telecom Italia, 2012
Verizon Communications, 2010
The Shift Project, 2019
Andrae & Edler, 2015
Corcoran & Andrae, 2013


Fuchs et al., 2017
IEA, 2017
Malmodin & Lunden, 2016
Malmodin & Lunden, 2018b
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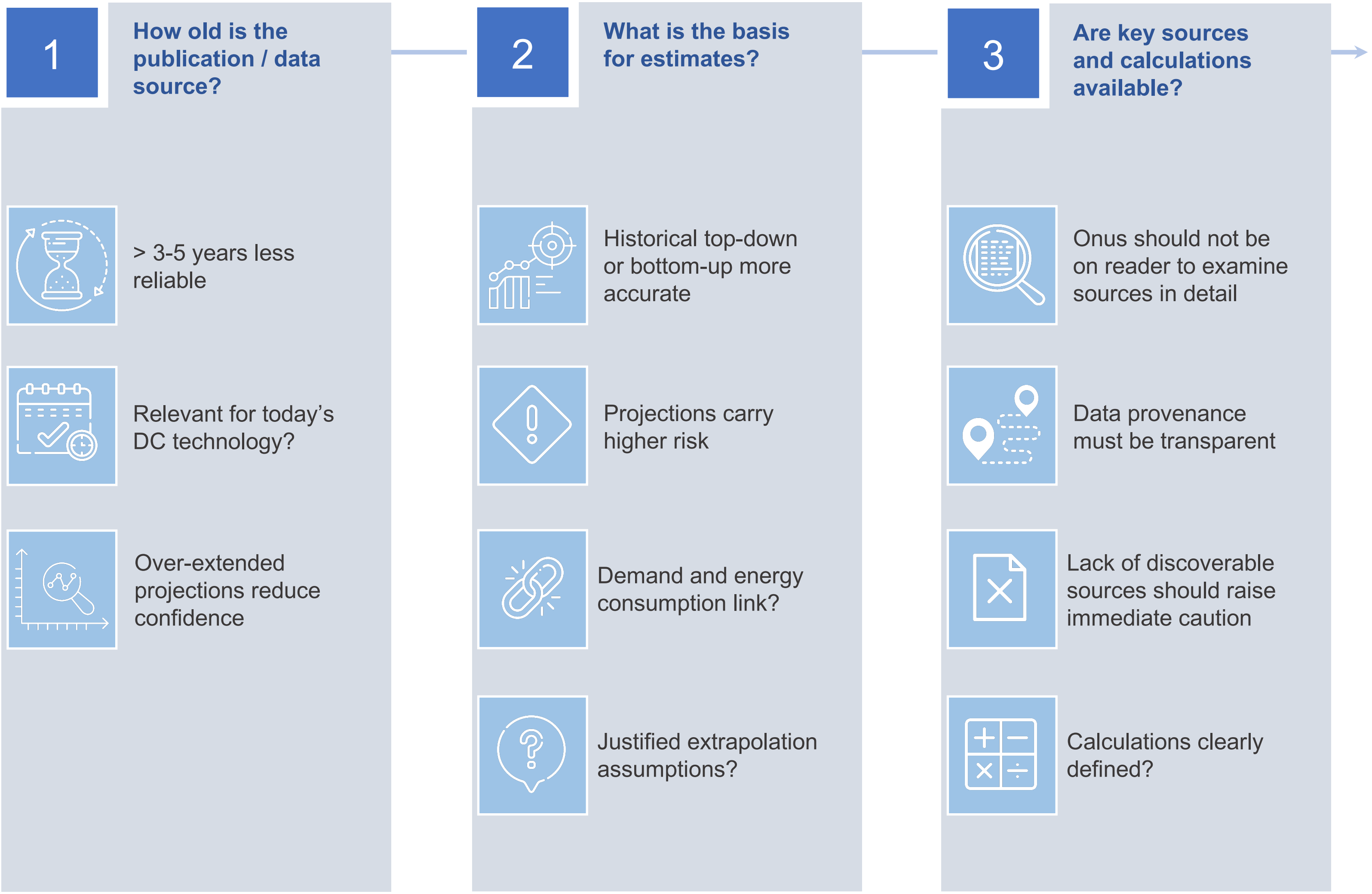
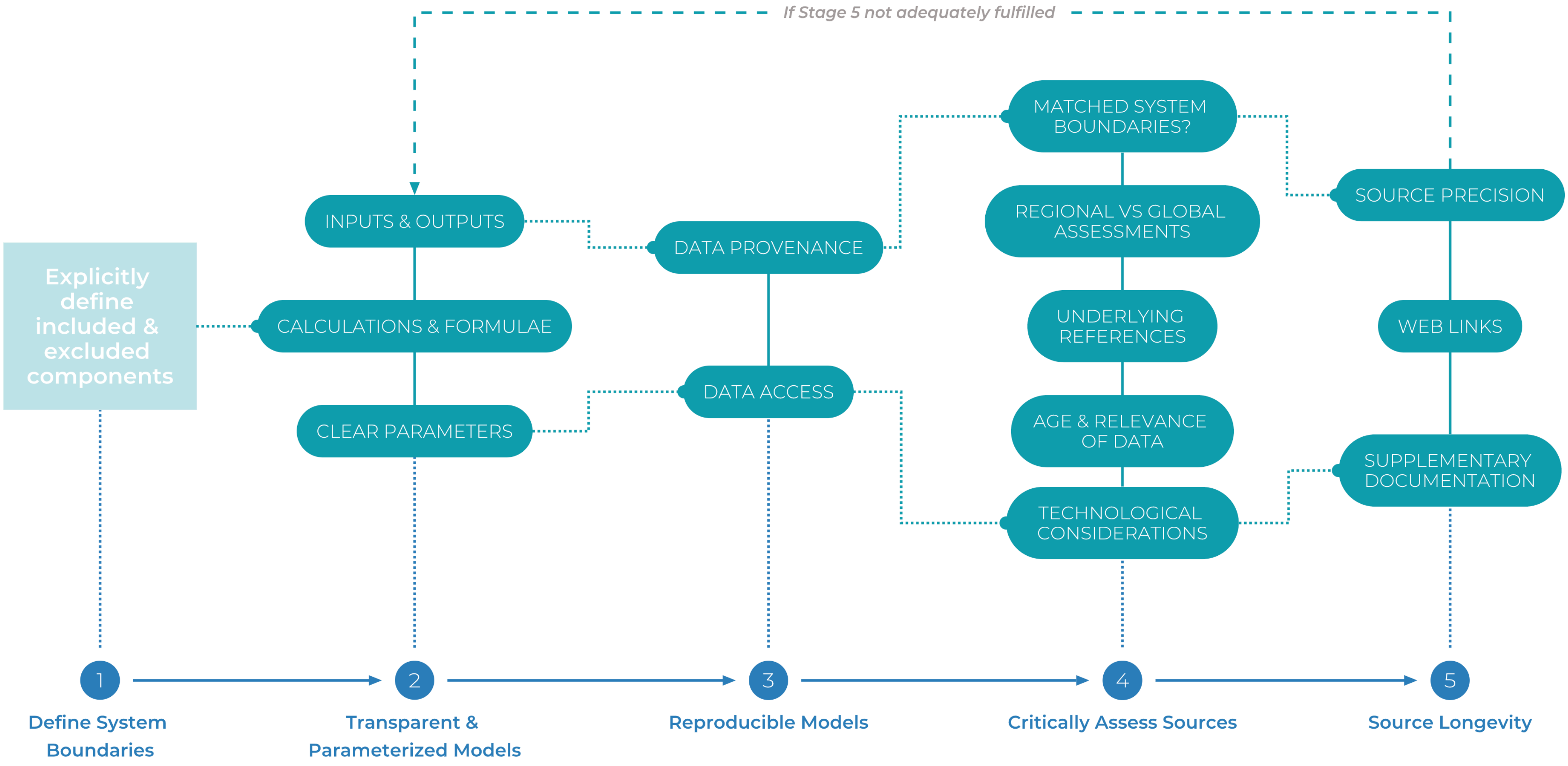
IDC
Koomey, 2011
ASHRAE, 2015
Barroso et al., 2013
Brown et al., 2007
Dietrich, 2014
Garnier, 2012
Huang et al., 2015
Hylick et al., 2008
Industry Comment
Lanzisera et al., 2012
Masanet et al., 2011
NRDC & WSP, 2012
Personal Communication
Reinsel, 2010
Shehabi et al., 2011
SPEC
Survey
Energy Star, 2010
Uptime institute, 2011
Malmodin & Lunden, 2018a
Shehabi et al., 2016
Van Heddeghem et al., 2014


1
How old is the publication / data source?
> 3-5 years less reliable
Relevant for today's DC technology?
Over-extended projections reduce confidence
2
What is the basis for estimates?
Historical top-down or bottom-up more accurate
Projections carry higher risk
Demand and energy consumption link?
Justified extrapolation assumptions?
3
Are key sources and calculations available?
Onus should not be on reader to examine sources in detail
Data provenance must be transparent
Lack of discoverable sources should raise immediate caution
Calculations clearly defined?



If Stage 5 not adequately fulfilled
Explicitly define included & excluded components
INPUTS & OUTPUTS
CALCULATIONS & FORMULAE
CLEAR PARAMETERS
DATA PROVENANCE
DATA ACCESS
MATCHED SYSTEM BOUNDARIES?
REGIONAL VS GLOBAL ASSESSMENTS
UNDERLYING REFERENCES
AGE & RELEVANCE OF DATA
TECHNOLOGICAL CONSIDERATIONS
SOURCE PRECISION
WEB LINKS
SUPPLEMENTARY DOCUMENTATION
1
Define System Boundaries
2
Transparent & Parameterized Models
3
Reproducible Models
4
Critically Assess Sources
5
Source Longevity