Energy consumption of data centers worldwide

How will the Internet become green?

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***Abstract*— The increasing digitalization of the economy and society is leading to a dynamic increase in the amount of data that is processed and stored in data centers. Some scientific studies assume that this growth will also lead to a significant increase in the energy consumption of data centers worldwide. This article deals with the questions of whether and to what extent the energy consumption of data centers have increased in the past and what future developments can be expected. In addition, future challenges to sustainable data center operation will be analyzed. The article deals in particular with the topics of improving the energy efficiency of IT hardware and software, the use of regenerative electricity for the operation of data centers, and the use of waste heat from data centers.**

***Index Terms*— Data centers, energy consumption, waste heat, regenerative electricity, Bitcoin mining, energy efficiency, IT hard- and software**

I. Introduction

Video streaming, social media, big data, Bitcoin, artificial intelligence, and digitalization of business processes and production flows – these and other trends are leading to more and more data being stored and processed in data centers. Data center capacity is growing dynamically. The IT company Cisco assumes in its analyses that the worldwide computing capacities of data centers measured in workloads and computer instances will more than double between 2016 and 2021 (2.3 fold), the data storage capacities in the data centers will even grow by a factor of almost 4 to 2.6 ZB in the same period [1].

Whether this significant growth in computing and storage capacity will also be accompanied by an increase in energy consumption can hardly be predicted from today's perspective. However, most available analyses assume a more or less significant increase in energy consumption [2]–[14]. Yet the range of forecasts is very wide. While Andrae/Edler, for example, predict a 15-fold increase in the energy consumption of data centers worldwide between 2010 and 2030 [3], Shehabi et al. found that the energy consumption of data centers in the USA has stabilized in recent years due to increasing energy efficiency [4]. For more than 10 years, the authors themselves have been analyzing the development of the energy consumption of data centers with the help of a comprehensive structural model of data centers in Germany [9], [14]–[25]. For Germany, an increase of 25% in the energy consumption of data centers in the period from 2010 to 2017 has been calculated [27].

Against this background, the present contribution addresses the following questions:

- How did the energy consumption of data centers and their individual components develop in Germany between 2010 and 2017?
- What are the results of different studies on the development of the energy consumption of data centers in a global comparison?
- Which current trends influence the energy consumption of data centers?
- How can the energy consumption of data centers develop up to the year 2030? What forecasts are likely?
- What are the particular challenges for energy-efficient operation of data centers in the future?

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II. Methodology

This paper deals with the energy requirements of data centers, presenting the findings from various international studies and comparing them with the authors' own calculations. The calculations are carried out with the help of an extensive structural model of the data center landscape in Germany which was developed at the Borderstep Institute and is updated annually. In this model data centers are defined as all enclosed spatial units such as server cabinets, server rooms, building parts, or entire buildings in which at least three physical servers are installed. The energy requirements of stand-alone servers are also calculated. The development of the data center capacities is calculated in particular on the basis of the IT equipment (servers, storage, networks) in the data centers. The various size classes of the data centers in Germany are described in the model in terms of their equipment with different server types, storage systems, and network infrastructures. The model also takes into account the age structure of the servers and the energy requirements of the different server types in different operating states. In addition, the data center infrastructures such as air conditioning, power supply, UPS, etc. are modeled for different size and redundancy classes.

The following sources in particular were used for the calculations:

- Study “Entwicklung des IKT-bedingten Strombedarfs in Deutschland“ (Development of ICT-related electricity consumption in Germany) by Fraunhofer IZM and Borderstep on behalf of the Federal Ministry of Economics and Energy [26],
- Current and publicly available results of studies on the development of the data center market from various analyses [16], [17], [28]–[35],
- Data from the market research institute Techconsult on market development for servers, storage, and network components (eanalyzer) [36]–[38],
- Data from the market research institutes IDC and EITO on market development for servers, storage, and networks in Germany and Europe [39], [40],
- Scientific literature and manufacturer information on the development of energy consumption for servers, storage, and network products, and for advanced efficiency technologies for data centers.

A detailed description of the model has already been provided in various publications. [9], [15], [25], [26], [41].

III. Development of the Energy Consumption of Data Centers in Germany

Using the structural model of data centers presented above, it was calculated that despite a significant improvement in the energy efficiency of data centers, their energy consumption in Germany increased by 25% between 2010 and 2017 (Figure 1). The increase was mainly due to an increase in the number and performance of IT components in the data centers. In 2017, around 2.37 million servers were in operation in Germany, 18% more than in 2010. The number of data centers equipped with IT hardware for data storage and network technology also increased significantly – the number of hard disks in Germany more than doubled between 2010 and 2017. As a result of this increase, the power consumption of IT components in data centers rose from 5.8 billion kWh in 2010 to 7.9 billion kWh in 2017. In contrast, the electricity consumption of the data center infrastructure rose only slightly due to the measures implemented to increase energy efficiency: from 4.7 billion kWh in 2010 to 5.3 billion kWh in 2017. The average PUE[1] value of data centers in Germany fell from 1.98 to 1.75[2] between 2010 and 2017. This corresponds to an average increase in data center infrastructure efficiency of 13% [27].

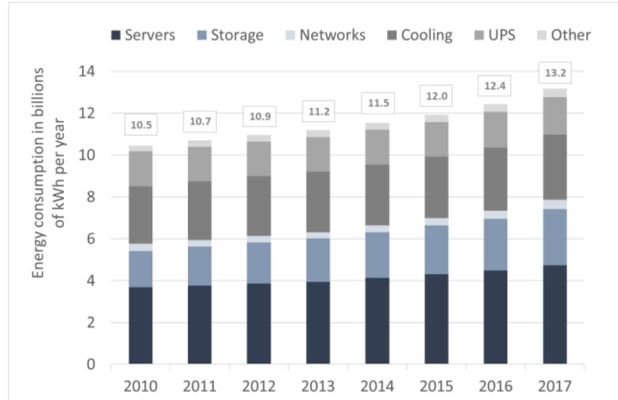

Fig. 1. Energy consumption of servers and data centers in Germany in the years 2010 to 2017 (Source: Borderstep)

Significant further improvements in the efficiency of data center infrastructures can be expected in the future. Newly built larger data centers today often realize PUE values of 1.3 and lower [27], [33].[3]

Growth in the data center market is driven primarily by the cloud market (Figure 2). Large international cloud providers in particular are currently building up resources in Germany and are thus meeting the requirements of German companies to enable the storage and processing of their data in Germany. International cloud companies often use the support of colocation providers, thereby driving the colocation market at the same time. The share of colocation data centers in the IT area of all data centers in Germany again increased significantly in 2017 and will be 32% in 2017 [27].

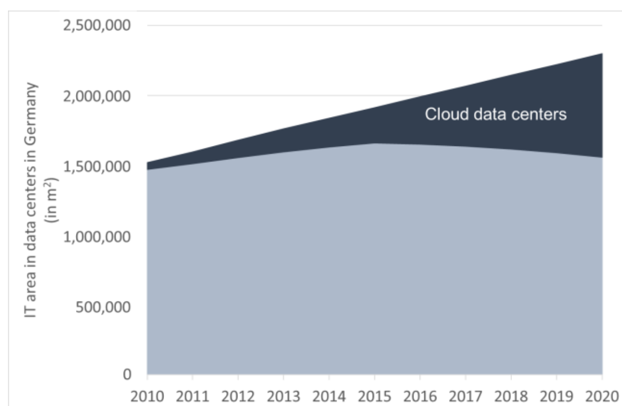

Fig. 2. Development of the IT area of data centers in Germany with the share of cloud data centers in the years 2010 to 2017 and forecast to 2020 (Source: Borderstep)

From a regional perspective, the greater Frankfurt area and thus the federal state of Hesse in particular are benefiting from

[1] The Power Usage Effectiveness (PUE) value indicates the ratio of the total energy consumption of a year to the annual energy consumption of the IT department of the data center.

[2] The stand-alone servers, which are normally operated without their own air conditioning, are not included in the calculation of these values. Taking stand-alone servers into account, the average PUE value in Germany improved from 1.82 in 2010 to 1.58 in 2017.

[3] The PUE is an indicator often used to assess the energy efficiency of data centre infrastructures. The advantage of PUE is that it is easy to determine. However, the interdependencies between the energy demand of IT and the energy demand of the entire data center are very complex. If, for example, the energy consumption of IT is reduced, the PUE can worsen, even though the total energy consumption of the data center decreases significantly.

the growth of the data center market. This applies in particular to the colocation data center segment [34]. In 2017, there was a total IT area of 550,000 m^2 in the data centers in Hesse, 250,000 m^2 of which was in colocation data centers. As a result, the capacities in the colocation data centers – measured by the IT space in Hesse between 2010 and 2017 – have increased by 60% (Figure 3). In terms of the available IT connection resources, capacities even increased by 100%. [34].

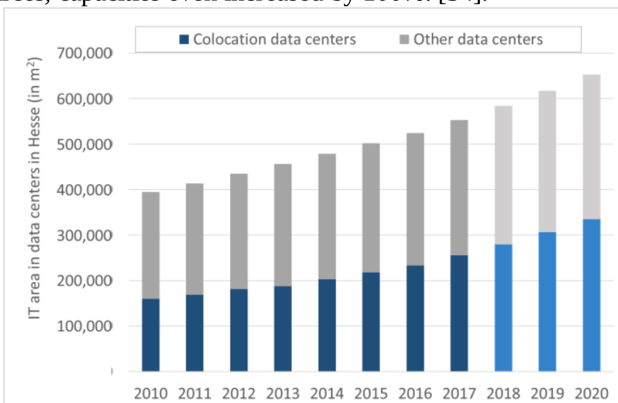

Fig. 3. Development of data center capacities (IT area in m^2) in Hesse in the years 2010 to 2017 and forecast to 2020 (Source: Borderstep)

Despite the dynamic development in the data center market in Germany, it is possible that it will become less important in international comparison as a data center location. Especially in the rapidly growing segment of hyperscale data centers, which are very large, significantly more capacity is being built worldwide, also elsewhere in Europe, for example, the Netherlands, Ireland and Scandinavia. [33], [34].

Operators of hyperscale data centers shy away from Germany as a business location primarily because of the high electricity costs and the sometimes lengthy approval processes. The increasing shortage of skilled personnel for data centers in Germany is also becoming an increasingly disadvantageous location factor [33]. Rapidly growing applications such as Bitcoin mining [6] cannot be operated in Germany at break-even due to the high electricity prices.

IV. Energy consumption of data centers in Europe and worldwide

Several scientific studies examine the energy consumption of data centers. In the following, the results of selected and well-known studies are briefly presented and compared.

The results of a 2015 paper by Andrae/Edler [3] have achieved a relatively high level of attention in the discussion about the energy consumption of data centers [13], [14], [42]–[44]. This is certainly due to the fact that Andrae/Edler forecast a strong increase in energy consumption. In the "expected" scenario, according to their calculations, the energy consumption of data centers worldwide will increase by a factor of 15 from approx. 200 billion kWh/a in 2010 to almost 3,000 billion kWh/a by 2030. Even in the "best" scenario, an increase by a factor of almost 6 to 1,337 billion kWh/a is calculated. In the "worst" scenario, the energy consumption of data centers will increase by a factor of 40 to 7,933 billion kWh by 2030 [3].

At the beginning of 2019, Andrae published an update of its calculations and forecasts, which deviates significantly from the values from 2015. For the year 2030, "only" an increase in the energy demand of data centers worldwide to 1,929 billion kWh/a is expected. For the year 2018 it assumes 211 billion kWh/a - in contrast to 539 billion kWh/a in the estimate from the year 2015 [45].

A publication by Belkhir and Elmeligi [14] also assumes a very significant increase in the energy requirements of data centers. Based on a calculation by Vereecken et al. [46], they assume a worldwide energy demand for data centres of 275 billion kWh/a in 2009 and anticipate an annual growth rate of 10% by 2020. This growth rate was determined by the market research company Technavio [47]. This results in an energy demand of 659 billion kWh/a for data centers worldwide in 2018.

Malmodin/Lunden calculate worldwide energy consumption of data centers to be 240 billion kWh in 2015 [44]; according to van Heddegdem et al. no less than 270 billion kWh were needed in 2012 [48]. Bitterlin assumes that data centers worldwide required 416 billion kWh of energy in 2015 [12].

According to a Borderstep Institute estimate, worldwide energy consumption of server data centers increased by about 30% to 287 billion kWh between 2010 and 2015 [9]. This increase accelerated once again in the last two years. A current TEMPRO project estimate concludes that between 2015 and 2017 the energy consumption of data centers worldwide increased by approx. 20% to 350 billion kWh (Figure 4). Increasing digitalization and the sometimes very high energy demand of new applications such as Bitcoin mining were identified as reasons for this accelerated growth in energy consumption [27]. Even though there is little reliable information on the energy consumption of Bitcoin mining to date, it can be assumed that the worldwide annual energy consumption of this application increased by more than 30 billion kWh between the beginning of 2017 and the end of 2018 [6], [49].

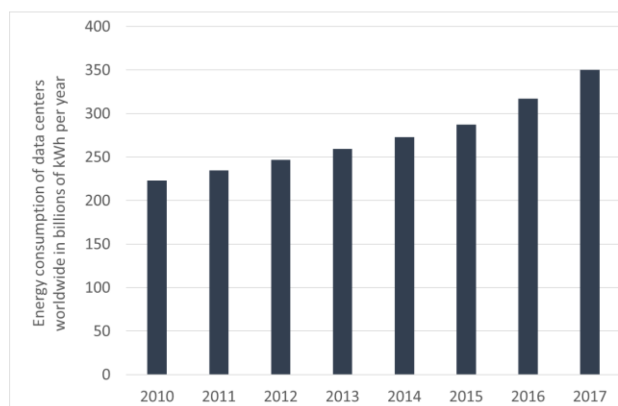

Fig. 4. Energy consumption of servers and data centers worldwide in the years 2010 to 2017 (Source: Borderstep)

The different assessments of the development of the energy consumption of data centers are also reflected in regional analyses. For the USA, Shehabi et al. calculated that the energy consumption of data centers has hardly increased since 2010;

they calculate energy consumption of 70 billion kWh in 2014, compared to approx. 67 billion kWh in 2010. The small increase in the USA is due to a general improvement in the energy efficiency of IT systems and infrastructure with lower PUE values. In addition, there has been a significant shift in computing power to particularly efficient hyperscale data centers with PUE values below 1.2 [4], [10].

If one compares the development of the energy consumption of the data centers in the USA calculated by Shehabi et al. with the development in Germany calculated by Borderstep, it is striking that energy consumption in Germany seems to increase significantly more strongly, although the increases in the server inventories are comparable. The basic structure of Shehabi et al.'s model is comparable to that of the Borderstep Institute. Therefore, it was possible to carry out a detailed comparison of the different model parameters. The differences in the developments can essentially be attributed to two factors. On the one hand, there are hardly any hyperscale data centers in Germany – therefore, computing power has hardly shifted to this particularly efficient type of data center. Secondly, the assumptions in the models differ with regard to the average development of the maximum power consumption of a server at full load. While Shehabi et al. assume that maximum power consumption is constant [4], the Borderstep model assumes an increase in maximum power consumption due to a significant increase in the average amount of RAMs and multiprocessor systems. These assumptions are also confirmed for Europe by other studies [7], [11]. Whether the differences in the model assumptions are justified by the real differences in the USA and Europe or Germany is yet to be verified by further investigations.

The results of various studies on the energy consumption of data centers in Europe are relatively similar. The Ecodesign Preparatory Study on Enterprise Servers and Data Equipment determines energy consumption of 78 billion kWh for data centers in Europe by 2015 [11]. Prakash et al. calculate energy consumption of 52 billion kWh for 2011 and forecast an increase to 70 billion kWh by 2020 [7]. According to estimates by Borderstep, energy consumption of data centers in Western Europe also rose significantly between 2010 and 2017. Based on data on the development of workloads and server numbers in data centers of the IT company Cisco [30], [31], the authors assume that energy consumption has increased from 56 billion kWh in 2010 by a good 30% to 73 billion kWh in 2017 [27].

In summary, the various studies on the development of the energy consumption of data centers do not provide a uniform picture. While some studies, e.g. Andrae/Edler, assume a very strong increase, other studies assume low to moderate growth in the last ten years.

However, the energy efficiency of the data center infrastructure and thus the PUE values have improved significantly in recent years, and the share of IT components in the energy consumption of the data centers has thus increased.

V. Discussion: How will the energy consumption of data centers develop in the future?

As the results presented in the previous section show, there are great uncertainties in determining the energy consumption of data centers worldwide even for the current point in time. Forecasts beyond 2020 are even more difficult due to the unclear development of technologies and the extent to which data centers and the services they provide will be used in the future [4], [10]. In particular, the possible end of the efficiency advances made to date, and thus the end of Moore's Law, could lead to a significant increase in energy consumption in the future. Andrae/Edler, for example, have modeled an end to Moore's Law in their calculations by 2022 and thus also an end to the significant increases in data center efficiency [3]. This is a major reason for the very significant increase in energy consumption in their scenarios. It can be discussed if and when Moores Law will end. It is clear that technical development is approaching the physical limits of conventional CMOS silicon technology. The structures currently consist of only a few atomic layers. Leading companies such as Intel and AMD expect Moore's law to come to an end around 2023 [50]. However, alternative materials and 3D architectures will presumably contribute to further increases in performance and reliability despite the small structures. An abrupt end to improvements in the energy efficiency of computing operations is unlikely.

Assuming a continuation of Moore's Law, the Andrae/Edler model yields much more moderate increases. Another reason for the significant increases in energy consumption in the model is the assumption that the performance of data centers is determined by the IT traffic between the user and the data center. According to Cisco forecasts, this increases by 23% annually [3], [51]. If the assumption of increasing data center performance is modified in such a way that the number of workloads and compute instances is chosen as the measure, the calculated increase in energy consumption in the model would be lower. According to Cisco, the number of workloads and compute instances is currently growing at an average annual rate of 18.6% [1].

To illustrate the differences between the different analyses, figure 5 shows various forecasts of the energy consumption of data centers worldwide through 2030. Studies have been selected which allow the presentation of the development up to the year 2030. Beside the investigations of Andrae/Edler [3], Andrae [45] and Belkhir/Elmeligi [14] a “best case” is presented. This development would occur using the Andrae/Edler model if Moore's Law continued and moderate growth rates in data center performance were assumed. Furthermore, according to Borderstep's calculations, the trend in the development of the worldwide energy consumption of data centers between 2010 and 2017 will continue through 2030.

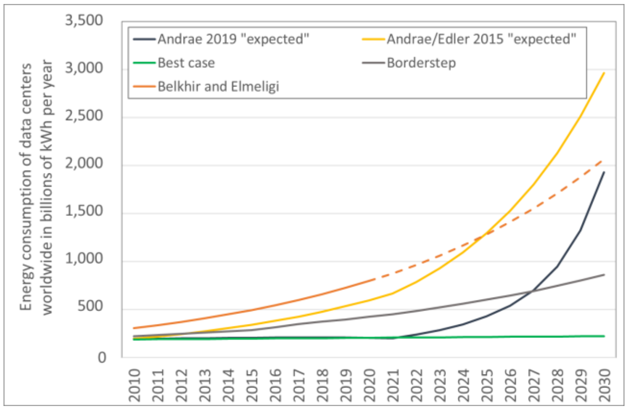

Fig. 5. Energy consumption of servers and data centers worldwide – forecasts to 2030

A comparison of the various forecasts shows that the possible future development of the energy consumption of data centers has a wide range. In the "best case" the energy consumption of data centers can remain largely constant. If Moore's Law ends and the performance of the data centers increases significantly, annual energy consumption may increase to almost 3,000 billion kWh/a (Andrae/Edler 2015 "expected"). Andrae 2019 and Belkhir/Elmeligi expect an energy consumption of approx. 2000 billion kWh/a for 2030. If the current developments determined by Borderstep continue, the energy consumption of data centers will double by 2030 compared to today.

However, the analysis of the development makes one thing clear: energy-efficient operation of data centers will continue to be of great importance in the future. However, the challenges are changing. This will be discussed in the following section.

VI. Future Challenges: Energy-efficient IT Hardware and Software, Use of Waste Heat and Renewable Energies

As shown above, the PUE values of data centers are improving continuously. As a result, the share of the data center infrastructure in the energy consumption of data centers is becoming smaller. In the future, efforts to improve the energy efficiency of data centers will have to focus even more on IT components. Further improvements to IT hardware, energy-efficient software, and efficient software deployment models such as virtualization and container technology offer opportunities for optimization. Completely new technologies such as neuromorphic processors or the use of artificial intelligence to improve efficiency in data centers also offer high potential [18].

Even if all possible future improvements in the efficiency of IT components and infrastructure are taken into account: almost everywhere, the electricity used in data centers is converted into heat and then released into the environment – mostly using additional energy for ventilation and cooling. The example of Sweden in particular shows that it is possible to use the waste heat from data centers under appropriate conditions [52], [53]. In view of the increasing energy consumption of data centers, the topic of waste heat utilization will play a central role in the future [18]. Innovative new solutions must be implemented here. This applies to both classic air-cooled and new innovative liquid-cooled IT systems. In Germany and presumably in other countries too, however, the framework conditions must change in order to promote the use of waste heat in data centers. So far, electricity prices in Germany have been so high that the operation of heat pumps that can raise the waste heat level of data centers to a usable level is uneconomical. Often it is economically more favorable to burn oil or gas for heat generation instead of using existing waste heat.

Another future challenge for environmentally friendly data center operation is the supply of electricity generated largely from renewable sources because the supply of continuously available electricity generated from hydropower or biomass is limited. This means that intelligent use of fluctuating wind and solar power in data centers is becoming increasingly important. Here, too, there are promising technological approaches [18], [54], [55].

VII. Summary and Conclusion

This paper discusses the development of the energy consumption of data centers, and the results of various studies are presented. Although the various studies presented assume greater or smaller increases in energy consumption of data centers in recent years, estimates of both the absolute amount of energy consumed and the increases in energy consumption differ significantly.

The forecasts for the development of future energy consumption of data centers differ even further. The article briefly presents and discusses possible scenarios for the energy consumption of data centers worldwide through 2030, ranging from keeping energy consumption constant to an increase by a factor of 40.

All the uncertainty and variation of the forecasts notwithstanding, a further significant increase in the energy consumption of data centers seems likely. Improving energy efficiency will therefore continue to be of great importance. The focus here will be more on improving the energy efficiency of IT components in the future, as significant improvements in infrastructure such as cooling and uninterruptible power supply have already been achieved in the past. Measures that do not directly affect the energy efficiency of data centers, such as the use of waste heat and operation with (fluctuating) regenerative energy, will also become increasingly important in the future.

With a view to the future, it can be assumed that the focus of sustainable data center operation will shift from the sole consideration of energy requirements to other sustainability categories. Initial approaches, e.g. for the consideration of the 17 Sustainable Development Goals of the UN, already exist today [56].

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References

[1] Cisco, “Cisco Global Cloud Index: Forecast and Methodology 2016-2021,” 2018 [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.pdf. [Accessed: 07-Feb-2018]

[2] G. A. Brady, “Energy Efficiency in Data Centres and the Barriers to Further Improvements: An Interdisciplinary Investigation,” The University of Leeds, Leeds, 2016 [Online]. Available: http://etheses.whiterose.ac.uk/12359/1/Gemma%20Brady%20PhD%20Thesis%20(1).pdf. [Accessed: 15-Apr-2018]

[3] A. S. G. Andrae and T. Edler, “On Global Electricity Usage of Communication Technology: Trends to 2030,” Challenges, vol. 6, no. 1, pp. 117–157, Apr. 2015.

[4] A. Shehabi et al., “United States Data Center Energy Usage Report,” Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, LBNL-1005775, 2016 [Online]. Available: https://eta.lbl.gov/sites/all/files/publications/lbnl-1005775_v2.pdf. [Accessed: 19-Feb-2018]

[5] J. Koomey, “Growth in data center electricity use 2005 to 2010,” Rep. Anal. Press Complet. Req. N. Y. Times, 2011 [Online]. Available: http://www.missioncriticalmagazine.com/ext/resources/MC/Home/Files/PDFs/Koomey_Data_Center.pdf. [Accessed: 22-Jul-2014]

[6] A. de Vries, “Bitcoin’s Growing Energy Problem,” Joule, vol. 2, no. 5, pp. 801–805, 2018.

[7] S. Prakash, Y. Baron, L. Ran, M. Proske, and A. Schlösser, “Study on the practical application of the new framework methodology for measuring the environmental impact of ICT - cost/benefit analysis,” European Commission, Brussels, Studie, 2014.

[8] M. Avgerinou, P. Bertoldi, and L. Castellazzi, “Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency,” energies, Sep. 2017.

[9] R. Hintemann and J. Clausen, “Green Cloud? The current and future development of energy consumption by data centers, networks and end-user devices,” in Proceedings of ICT for Sustainability 2016, Amsterdam, The Netherlands, 2016 [Online]. Available: http://www.atlantis-press.com/php/pub.php?publication=ict4s-16. [Accessed: 05-Sep-2016]

[10] A. Shehabi, S. J. Smith, E. Masanet, and J. G. Koomey, “Data center growth in the United States: decoupling the demand for services from electricity use,” Environ. Res. Lett., vol. 13, no. 12, 2018 [Online]. Available: http://iopscience.iop.org/article/10.1088/1748-9326/aaec9c. [Accessed: 02-Jan-2019]

[11] Bio by Deloitte and Fraunhofer IZM, Ecodesign Preparatory Study on Enterprise Servers and Data Equipment. Brussels, 2016 [Online]. Available: https://publications.europa.eu/en/publication-detail/-/publication/6ec8bbe6-b8f7-11e5-8d3c-01aa75ed71a1. [Accessed: 22-Jan-2018]

[12] T. Bawden, “Global warming: Data centres to consume three times as much energy in next decade, experts warn,” The Independent, Jan. 2016 [Online]. Available: http://www.independent.co.uk/environment/global-warming-data-centres-to-consume-three-times-as-much-energy-in-next-decade-experts-warn-a6830086.html. [Accessed: 28-May-2018]

[13] N. Jones, “How to stop data centres from gobbling up the world’s electricity - The energy-efficiency drive at the information factories that serve us Facebook, Google and Bitcoin.,” nature, Sep. 2018 [Online]. Available: https://www.nature.com/articles/d41586-018-06610-y?WT.ec_id=NATURE-20180913&utm_source=nature_etoc&utm_medium=email&utm_campaign=20180913&spMailingID=57356737&spUserID=MTQyOTQwOTY4MDcS1&spJobID=1481695484&spReportId=MTQ4MTY5NTQ4NAS2. [Accessed: 15-Sep-2018]

[14] L. Belkhir and A. Elmeligi, “Assessing ICT global emissions footprint: Trends to 2040 & recommendations,” J. Clean. Prod., vol. 177, pp. 448–463, 2018.

[15] K. Fichter and R. Hintemann, “Beyond Energy: Material Stocks in Data Centers, Taking Resource Efficiency into account in Green IT Strategies for Data Centers,” J. Ind. Ecol., no. im Erscheinen, 2014.

[16] R. Hintemann, “Consolidation, Colocation, Virtualization, and Cloud Computing – The Impact of the Changing Structure of Data Centers on Total Electricity Demand,” in ICT Innovations for Sustainability. Advances in Intelligent Systems and Computing, L. M. Hilty and B. Aebischer, Eds. Berlin, Heidelberg: Springer, 2014.

[17] R. Hintemann, K. Fichter, and D. Schlitt, “Adaptive computing and server virtualization in German data centers - Potentials for increasing energy efficiency today an in 2020,” in Proceedings of the 28th Conference on Environmental Informatics - Informatics for Environmental Protection, Sustainable Development and Risk Management, Oldenburg, 2014, pp. 477–484 [Online]. Available: http://enviroinfo.eu/sites/default/files/pdfs/vol8514/0477.pdf. [Accessed: 25-Jan-2015]

[18] R. Hintemann and S. Hinterholzer, “Technology radars for energy-efficient data centers: A transdisciplinary approach to technology identification, analysis and evaluation,” in Sustainable Technologies. World Congress. 2018. (WCST 2018), Cambridge, 2018 [Online]. Available: https://www.researchgate.net/publication/330359801_Technology_radars_for_energy-efficient_data_centers_A_transdisciplinary_approach_to_technology_identification_analysis_and_evaluation. [Accessed: 24-Jan-2019]

[19] K. Fichter, S. Beucker, J. Clausen, and R. Hintemann, “Green IT: Zukünftige Herausforderungen und Chancen,” Umweltbundesamt, Dessau, 2009 [Online]. Available: http://www.umweltbundesamt.de/publikationen/green-it-zukuenftige-herausforderungen-chancen. [Accessed: 05-Jun-2014]

[20] BITKOM, “Leitfaden Energieeffizienz in Rechenzentren. Ein Leitfaden zur Planung, zur Modernisierung und zum Betrieb von Rechenzentren.,” Berlin, 2008 [Online]. Available: http://www.bitkom.org/de/themen/54930_53432.aspx. [Accessed: 09-Jul-2014]

[21] BITKOM, “Energieeffizienz-Analysen in Rechenzentren. Messverfahren und Checkliste zur Durchführung.,” Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e.V (BITKOM), Berlin, Leitfaden 3, 2008 [Online]. Available:

http://www.bitkom.org/files/documents/Energieeffizienz-Analysen_in_RZ_web.pdf. [Accessed: 09-Jul-2014]
[22] R. Hintemann and K. Fichter, "Energy consumption and quantities of materials in German data centers," in Electronics Goes Green 2012+ (EGG), 2012, 2012, pp. 1–6.
[23] R. Hintemann, "Energy Consumption of Data Centers in 2014," Borderstep Institut für Innovation und Nachhaltigkeit, Berlin, 2015.
[24] R. Hintemann, "Energy consumption of data centers continues to increase – 2015 update," Borderstep Institut für Innovation und Nachhaltigkeit, Berlin, 2015 [Online]. Available: www.borderstep.de/publikationen
[25] R. Hintemann, S. Beucker, J. Clausen, L. Stobbe, M. Proske, and N. F. Nissen, "Energy efficiency of data centers - A system-oriented analysis of current development trends," in EGG 2016+ Proceedings, Berlin, 2016.
[26] L. Stobbe, R. Hintemann, M. Proske, J. Clausen, H. Zedel, and S. Beucker, "Entwicklung des IKT-bedingten Strombedarfs in Deutschland - Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie," Fraunhofer IZM und Borderstep Institut, Berlin, 2015 [Online]. Available: http://www.bmwi.de/BMWi/Redaktion/PDF/E/entwicklung-des-ikt-bedingten-strombedarfs-in-deutschland-abschlussbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf
[27] R. Hintemann, "Boom führt zu deutlich steigendem Energiebedarf der Rechenzentren in Deutschland im Jahr 2017," Borderstep Institut für Innovation und Nachhaltigkeit, Berlin, 2018.
[28] CBRE, "Nachgefragte Leistung europäischer Rechenzentren übersteigt erneut 100 MW-Wert," Nachgefragte Leistung europäischer Rechenzentren übersteigt erneut 100 MW-Wert, 21-Mar-2018. [Online]. Available: http://news.cbre.de/nachgefragte-leistung-europaischer-rechenzentren-ubersteigt-erneut-100-mw-wert. [Accessed: 04-Apr-2018]
[29] CBRE Global Corporate Services, "European Data Centres Market Review. Q4 2016," London, 2017 [Online]. Available: https://www.cbre.de/de-de/research/European-Data-Centres-MarketView-Q4-2016. [Accessed: 10-Jun-2017]
[30] Cisco, "Cisco Global Cloud Index: Forecast and Methodology 2014-2019," 2015 [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/Cloud_Index_White_Paper.pdf
[31] Cisco, "Cisco Global Cloud Index: Forecast and Methodology 2015-2020," 2016 [Online]. Available: https://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.pdf. [Accessed: 10-Oct-2017]
[32] R. Hintemann, "Energieeffizienz und Rechenzentren in Deutschland – weltweit führend oder längst abgehängt?," Netzwerk energieeffiziente Rechenzentren - NeRZ, Berlin, 2017 [Online]. Available: https://www.borderstep.de/wp-content/uploads/2017/07/NeRZ-Studie-Rechenzentrumsmarkt-30-06-2017.pdf. [Accessed: 25-Oct-2017]
[33] R. Hintemann and J. Clausen, "Bedeutung digitaler Infrastrukturen in Deutschland. Sozioökonomische Chancen und Herausforderungen für Rechenzentren im internationalen Wettbewerb. Berlin. Verfügbar unter," Berlin, 2018 [Online]. Available: https://www.eco.de/wp-content/uploads/dlm_uploads/2018/06/DI_Studie.pdf. [Accessed: 14-Jun-2018]
[34] R. Hintemann and J. Clausen, "Potenzial von Energieeffizienztechnologien bei Colocation Rechenzentren in Hessen," Borderstep Institut für Innovation und Nachhaltigkeit, Berlin, 2018 [Online]. Available: https://www.digitalstrategie-hessen.de/rechenzentren. [Accessed: 26-Apr-2018]
[35] M. Howard-Healy, "Co-location Market Quarterly (CMQ) brief - Vortrag auf dem BroadGroup's Knowledge Brunch in Frankfurt," Broadgroup, 2018.
[36] Techconsult, "Daten des eanalyzers," 2014. [Online]. Available: www.eanalyzer.biz
[37] Techconsult, "Daten des eanalyzers," 2015. [Online]. Available: www.eanalyzer.biz
[38] Techconsult, "Daten des eanalyzers," 2016. [Online]. Available: www.eanalyzer.biz
[39] EITO/IDC, "EITO Costumized Report for Borderstep.," EITO/IDC, Berlin, 2014.
[40] IDC, "Server Market and Enterprise Storage Systems By Country 2014-2017," 2018.
[41] R. Hintemann, K. Fichter, and L. Stobbe, "Materialbestand der Rechenzentren in Deutschland-Eine Bestandsaufnahme zur Ermittlung von Ressourcen-und Energieeinsatz," Stud. Im Rahm. UFO-Plan-Vorh. "Produktbezogene Ansätze Inf.-Kommun. "Förderkennzeichen 370 893 302 Beauftr. Vom Umweltbundesamt, 2010.
[42] J. Pohl and M. Finkbeiner, "Digitalisation for sustainability? Challenges in environmental assessment of digital services," Inform. 2017, 2017.
[43] J. Malmodin and D. Lundén, "The energy and carbon footprint of the ICT and E&M sector in Sweden 1990-2015 and beyond," Pap. Publ. Present. ICT Sustain. ICT4S Amst. Neth., pp. 30–31, 2016.
[44] J. Malmodin and D. Lundén, "The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015," Sustainability, vol. 10, no. 9, p. 3027, 2018.
[45] A. S. G. Andrae, "Projecting the chiaroscuro of the electricity use of communication and computing from 2018 to 2030," 2019.
[46] "Vereecken: Energy efficiency in thin client solutions - Google Scholar." [Online]. Available: https://scholar.google.com/scholar_lookup?title=Energy%20efficiency%20in%20thin%20client%20solutions&author=W.%20Vereecken&publication_year=2009. [Accessed: 15-Apr-2019]
[47] Technavio, "Global Data Center Market 2015-2019," 2015.
[48] W. Van Heddeghem, S. Lambert, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Trends in worldwide ICT electricity consumption from 2007 to 2012," Comput. Commun., vol. 50, pp. 64–76, 2014.
[49] Digiconomist, "Bitcoin Energy Consumption Index," Digiconomist, 2019. [Online]. Available: https://digiconomist.net/bitcoin-energy-consumption. [Accessed: 12-Apr-2019]
[50] M. Peckham, "The Collapse of Moore's Law: Physicist Says It's Already Happening," Time [Online]. Available: http://techland.time.com/2012/05/01/the-collapse-of-moores-law-physicist-says-its-already-happening/. [Accessed: 15-Apr-2019]
[51] Cisco, "Cisco Global Cloud Index: Forecast and Methodology 2013-2018," 2014.
[52] U. Ostler, "Server-Hitze für 10.000 warme Stuben - Ein weiteres Datacenter mit Anschluss ans Fernwärmenetz – in Stockholm," DataCenter Insider, 18-Sep-2017 [Online]. Available: https://www.datacenter-insider.de/ein-weiteres-

datacenter-mit-anschluss-ans-fernwaermenetz-in-stockholm-a-644074/. [Accessed: 10-Oct-2017]
[53] S. Reveman and U. Ostler, “Die Energie in deutschen Datacenter verpufft zu 100% - Rechenzentren jagen das Geld zum Fenster raus,” DataCenter Insider, 12-Jul-2016 [Online]. Available: http://www.datacenter-insider.de/die-energie-in-deutschen-datacenter-verpufft-zu-100-a-541729/. [Accessed: 12-Jul-2016]
[54] U. Ostler, “Windcloud 4.0 führt den Rechenzentrumsbetrieb in eine klimaneutrale Zukunft,” 18-Nov-2018. [Online]. Available: https://www.datacenter-insider.de/windcloud-40-fuehrt-den-rechenzentrumsbetrieb-in-eine-klimaneutrale-zukunft-a-778745/. [Accessed: 13-Dec-2018]
[55] A. Rüdiger and U. Ostler, “Das erste Rechenzentrum in einer Windmühle läuft und die Kundschaft ist happy,” 14-Sep-2018. [Online]. Available: https://www.datacenter-insider.de/das-erste-rechenzentrum-in-einer-windmuehle-laeuft-und-die-kundschaft-ist-happy-a-752383/. [Accessed: 13-Dec-2018]
[56] R. Hintemann, “Nachhaltige Rechenzentren: Viel mehr als nur Energieeffizienz,” Funkschau, Nov. 2018 [Online]. Available: https://www.funkschau.de/datacenter/artikel/159905/. [Accessed: 04-Jan-2019]