Seminar Report

Environmental Key Performance Indicators for Data Centers

Tim van den Berg

MatrNr: 00000000

Email: tim.vandenberg@stud.uni-goettingen.de

Supervisor: Laura Endter

Georg-August-Universität Göttingen
Institute of Computer Science

Summer Semester 2022

Contents

List of Abbreviations

ADP Abiotic Resource Depletion Potential

DCIE Data Center Infrastructure Efficiency

DCIRE Data Center Infrastructure Resource Efficiency

Flop/s Floating Point Operations per Second

GWP Global Warming Potential

HDD Hard Disk Drive

HPC High-Performance Computing

ICT Information and Communication Technology

KEA Cumulative Energy Expediture

KPI4DCE Key Performance Indicators for Data Center Efficiency

PUE Power Usage Effectiveness

SSD Solid State Drive

UNFCCC United Nations Framework Convention on Climate Change

IO Input/Output

ITRE IT Resource Efficiency

1 Introduction

1.1 Climate Crisis and Data Centers

There is overwhelming evidence, that the Climate Crisis is man made and real. The effects influence the lives of humans all around the world. Extreme weather phenomena are a risk to societies and economies around the globe[Mas+18].

The United Nations Framework Convention on Climate Change (UNFCCC) is a regular meeting of nation states regarding the Climate Crisis, that introduces international treaties to solve and manage the Climate Crisis. In the 2015 Paris Agreement 196 members of the UNFCCC committed to limit the Global Warming to 1.5 °C compared to the pre-industrial mean temperature[UNF]. To reach this goal, the green house gas emissions need to be cut by roughly 45 % until 2030 compared to 2010 and reach net zero around 2050[Mas+18].

IT-services like streaming services (i.e. YouTube, Netflix), cloud storage solutions (i.e. Dropbox, Google Drive) and many other applications (i.e. social networks, communication services, Multiplayer Games) do not run on local machines, but on servers that are located in data centers all around the world. Due to the increasing usage these IT-services by mankind, data centers are responsible for a substantial and growing amount of energy consumption of mankind. However, it is not easy to derive an exact number. In 2017 Michael Oghia wrote an essay titled "Shedding light on how much energy the internet and Information and Communication Technology (ICT) consume" where he compares different sources on the energy consumption of the ICT sector[Ogh17]. Summarizing, one can probably say that the internet and ICT uses 5 to 10 percent of the total energy consumption of mankind.

In a 2015 study by Huawei Technologies Sweden the predicted green house gas emissions of the ICT Sector could contribute 23% of the total green house gas emissions in 2030 in the worst case scenario. Furthermore, data center electricity usage is predicted to increase in the future (see Figure 1)[AE15]. Please note, that all sources stated above are from before the Covid-19 Pandemic, which probably increased the use of ICT by a significant amount.

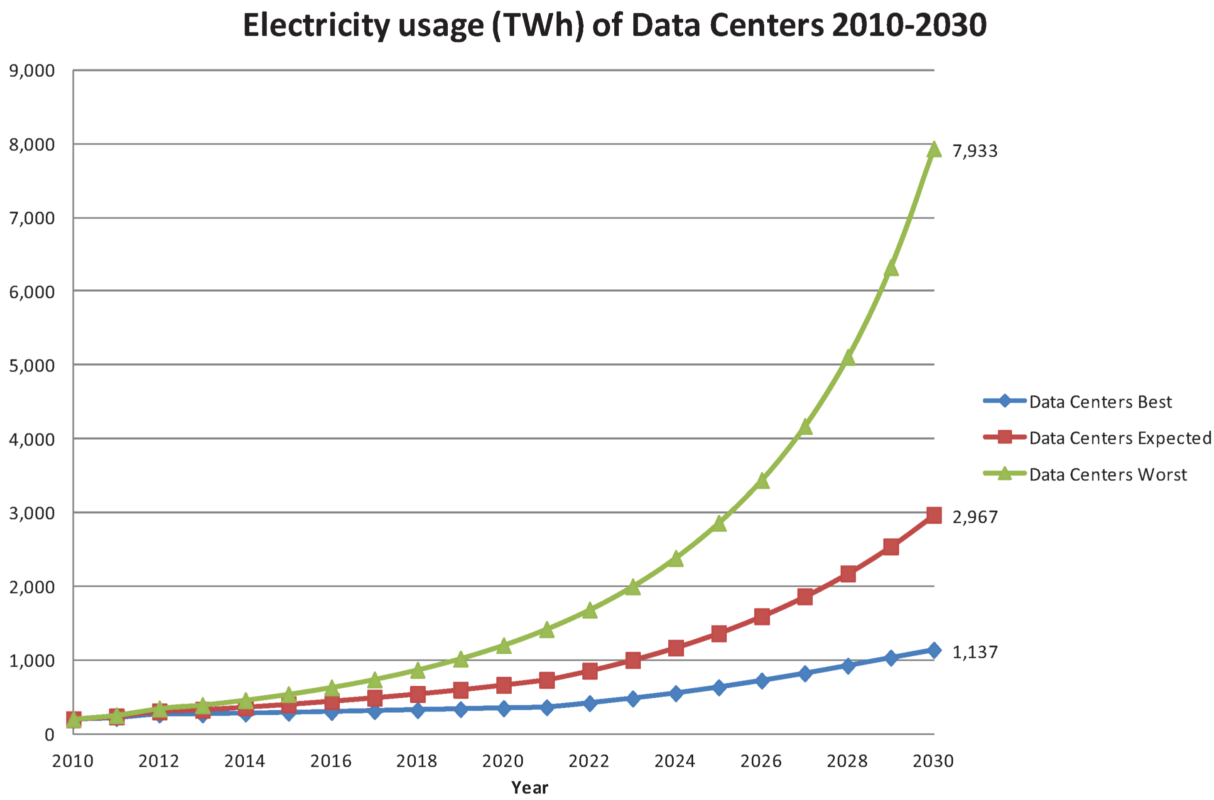

Figure 1: Predicted Electricity Usage in TWh of data centers from 2010 to 2030. Copied from [AE15]. The data center usage was measured using data traffic between data centers and between data centers and Consumers. The authors state, that the worst case scenario probably will not happen, due to the economic laws. Furthermore, note, that the study is from 2015, so the Covid-19 pandemic is not included. The key takeaway here is, that the electricity usage of data centers will increase, even if they get more efficient, because the demand for their services increase faster.

Due to the substantial amount of energy consumed by data centers, efficient data centers would decrease the total green house gas emissions. Therefore, "green" data centers are an important lever to get to net-zero green house gas emissions and to fulfill the Paris Agreement.

1.2 Performance Indicators for data centers

As seen above, it is important to reduce the green house gas emissions of data centers and make them more efficient. To do this, one first has to be able to access the current state of the data center. Therefore, Performance Indicators are needed to measure the current state and the progress of a data center. In order to develop such ecological Performance indicators, some hurdles must be overcome.
The Performance Indicator needs to be comparable, but data centers are very different. Therefore, it has to measure the performance at the physical IT infrastructure level. This becomes clear immediately, when thinking of possible Performance Indicators, which are not measured at the infrastructure level: *Number of concurrent Virtual Machines*, *Number of happy customers* or *Number of supported Software Versions* just make sense in certain

scenarios and are not generalizable.
Moreover, the definition of performance varies between use cases. Even when measuring performance at the physical infrastructure level, depending on the use case, different performance dimensions are relevant. When the use case is bleeding edge high performance computing, computational performance is key. However, computational performance does not really matter if the use case is largely storage related. This factor is also represented by the wide variety of leader boards, where data centers compete on different performance dimensions against each other. The TOP500 list ranks the civil supercomputers by computational performance in Floating Point Operations per Second (Flop/s), i.e. computational operations per second[TOP22b], the IO500 list uses an IO benchmark suite to rank systems in terms of IO performance[IO522] and the Green500 ranks systems by their energy efficiency in Flop/s/Watt.
Furthermore, performance was traditionally seen from an economical perspective, whereas nowadays customers are requesting green data centers that represent their ecological values. For ecological performance, efficiency is the performance indicator of choice. In theory the performance indicator creates competition to get more efficient data centers and IT processes, because a more efficient data center will potentially generate more profit. Efficiency is also the key idea behind the most abundant performance indicator, the Power Usage Effectiveness (PUE). What PUE is and why this does not necessarily mean that it is a good ecological performance indicator will be discussed in the next subsection.

1.2.1 Power Usage Effectiveness

The efficiency of a data center is often measured using the Power Usage Effectiveness (PUE) performance indicator[Bra+13], which is defined as

$$\text{PUE} = \frac{\text{total Facility Energy Usage}}{\text{IT Equipment Energy Usage}} \tag{1}$$

The total Facility Energy Usage describes the Energy Usage of the entire data center. This includes the IT Equipment Energy Usage, the energy used by the building (like heating and light) and the energy used for the cooling of the Servers. A perfectly efficient data center would have a PUE of 1, because all energy would be used by the IT Equipment and no energy would be used for anything else. In practice the PUE will be slightly higher than 1, because servers need to be cooled, buildings are heated and humans need light to work in a data center.
However, the PUE has some weak spots: It does not show the total energy usage, because it is a ratio and not a discrete value. This makes it very hard to compare different systems with each other, it is much harder to run smaller data centers as efficient as large data centers as more energy is used for the IT infrastructure and the size of the data center is not apparent from the PUE.
Moreover, the granularity of the PUE is not fine enough to pinpoint specific problems in a data center, e.g. with just one number it is very hard to see where the data center is inefficient, one can just see that another data center is more efficient.
Furthermore, the PUE sets the wrong incentives. Replacing old inefficient IT Hardware leads to a worse PUE if the Infrastructure can not keep up, even if the data center uses less energy in total to do the same amount of work.
As large amounts of energy of a data center can be used for cooling, the PUE depends

heavily on the site location which prevents comparability between data centers, e.g. in warmer climates, more energy is used for cooling which results in a worse PUE.
Furthermore, the PUE is misused for marketing purposes[New15].
Finally, Brady et al. (2013)[Bra+13] found that the PUE does not lead to more efficient IT processes.
Nevertheless, the PUE is one of the most widely used performance indicators for data centers[Biz+21]. It is difficult to understand why this is the case, given all the disadvantages listed above. The most obvious reason is its simplicity. With just one value, one has a parameter to rank different data centers against each other without being an expert in data center efficiency. Furthermore, it is easy to calculate for a data center as the data needed is mostly available anyway. Probably the biggest reason for its prevalence is, that every data center uses it. It is a good marketing tool as everybody can understand what it means.
The PUE was established by the Green Grid organization[Gri22a], which is an industry consortium including a few of the largest ICT companies (AMD, HP, IBM, Intel, Microsoft, Nvidia, Cisco, Dell, Google)[Gri22b]. Therefore, the PUE probably had a lot of traction and was established quickly. The Green Grid consortium is an "advocate for the optimization of energy and resource efficiency of data center ecosystems which enable a low carbon economy"[Gri22c]. This was probably also the reason for the creation of the PUE. However, to create an ecological performance indicator, one has to take the type of resources that are used into account. What this means and why this disqualifies the PUE as a good ecological performance indicator for data centers will be discussed in the next subsection.

1.2.2 Ecological Performance Indicators for data centers

As hinted on before, with an ecological performance indicator one wants to measure the Resource Efficiency of a data center. However, it is important to also consider the impact of these resources on the environment. The PUE, presented in chapter 1.2.1 does not differentiate between different kinds of resources. It just uses the combined Energy in Watts as a measurement. This is not sufficient to measure the resource efficiency of a data center, as it does make a difference which kind of energy is used, i.g. green electricity does emit a lot less green house gases than electricity produced with hard coal.
This is a problem that the Green500 list has also. The Green500 list ranks civil Supercomputers by Flop/s/Watt. Compared to the TOP500, the Green500 takes the electricity usage into account, but does not differentiates between different kinds of resources[TOP22a]. This does not mean that a performance indicator like the Green500 list is not good. It has other use cases, e.g. one can see which kind of architectures are most efficient in terms of energy usage in real world scenarios and if one wants to buy new hardware, this is an important information.
Besides the Green500 list, there are multiple benchmarks that try to provide insights into the ecological performance of parts of and the whole data center. However, according to Schödwell et al. (2018)[Sch+18] there is no "gold standard" in the industry as these benchmarks fall short in different ways. Many of these benchmarks are analysed in detail by Schödwell et al. (2018)[Sch+18], but this will not be a part of this report as it would go beyond its scope.
To be able to communicate to the customer how good a data center is doing, performance indicators like the PUE can be used directly. However, as seen before, their simplicity is curse and blessing. An alternative is to use environmental certificates. They can combine

different benchmarks and performance indicators to certify a data center. The most important environmental certificate in Germany is the Blue Angel, that will be introduced in the next section.

1.3 The Blue Angel for Data Centers

Since 1978, the "Blue Angel" is an environmental certificate that is owned and managed by the German Environmental Agencies (*Umweltbundesamt* and *Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit*). The Blue Angel is a member of the *Global Ecolabeling Network*, which is a network of different environmental certificates from all around the world[Net]. There are many different Blue Angel certificates. Interesting from a data center perspective are *DE-UZ 161 Energy-Efficient Data Center Operation*[Eng15] and *DE-UZ 214 Climate Friendly Colocation Data Centers*[Ang20]. However, due to their age, a new "Blue Angel for Data Centers" will combine DE-UZ 161 and 214. It is currently in development and will be published in spring of 2023[Eng]. Until then, one can give personal opinions on the different benchmarks and thresholds used on the website or in a meeting of the comity for the new Blue Angle for Data Centers and industry representatives, that is open to the public[Eng].
The Blue Angel has relevance for data center operators, because it can be required to get government contracts and is requested increasingly by customers of data centers, as industry representatives reported during a meeting of the comity for the new Blue Angel for Data Centers[Eng].

1.4 Goals of this report

After this introduction to the field of (environmental) performance indicators for data centers in chapter 1, a new suite of performance indicators by Schödwell et al. (2018)[Sch+18] will be presented in chapter 2 and tested in chapter 3 on the HPC system Emmy. Finally, the usability of the new performance indicators will be evaluated and this report will be summarized in the last chapter. This report should be a introduction to the topic of environmental performance indicators and the new performance indicators by [Sch+18]. It is out of scope to summarize the entire 261 pages report by [Sch+18]. All opinions and conclusions reached in this seminar report should be taken with a grain of salt, as the author had never heard of the topic before taking this seminar and is certainly no expert in the field.

2 Key Performance Indicators for Data Center Efficiency (KPI4DCE)

The final report *Kennzahlen und Indikatoren für die Beurteilung der Ressourceneffizienz von Rechenzentren und Prüfung der praktischen Anwendbarkeit* (English: *Key figures and indicators for assessing the resource efficiency of data centers and testing their practical applicability*) of the Key Performance Indicators for Data Center Efficiency (KPI4DCE) project of the German Environmental Agency, published in 2018 tries to solve some of the problems described in the Introduction (Chapter 1)[Sch+18]. A system of key figures to measure resource efficiency of data centers was developed and tested on three data

centers. The developed system will be called the KPI4DCE method in the following. Furthermore, existing performance indicators were analyzed and evaluated, however, this will not be part of this report as it would go beyond its scope.
As calculating the resource efficiency of a data center is the goal of the KPI4DCE method, the next section will examine natural resources.

2.1 Natural Resources

Two general strategies can be applied to measure the environmental impact of a data center:

1. Midpoint-Methods consider the potential environmental impact on specific classes of activity (e.g. water usage, land usage, ozone depletion potential).[Sch+18]

2. Endpoint-Methods consider the potential damage to protective goods (e.g. biodiversity, human health). Here, the potential environmental impact is quantified by aggregation and weighting factors.

The KPI4DCE method uses Midpoint-Methods as according to the authors the weighting in Endpoint-Methods is not scientifically justified, but depends on attitude and political intentions.
The Midpoint-Methods chosen forKPI4DCE method use four measures or dimensions for the consumption of natural resources: water consumption, abiotic depletion potential, cumulative energy expenditure and global warming potential, that will be explained in the following sections.

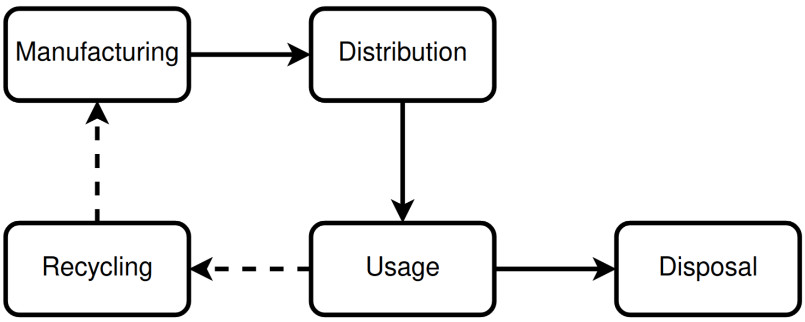

Figure 2: Stages of the product life cycle.

These dimensions are measured or estimated over the entire life cycle of the data center and then normalized to one year. The life cycle of a product in general consists of different stages, that can also be used to describe the life cycle of a data center and its components. The four phases depicted in Figure 2 are: manufacturing, distribution, use and disposal phase. In the manufacturing phase, for example the building that will host the IT equipment is constructed. This does also include the production of cement and steel for the building. The distribution phase includes all resources used for transporting the goods to the data center. The use phase is the largest portion of time in the life of the data center, it describes the resources used during the operation time of the data center or a specific component. The disposal phase includes resources used at the end of the life (e.g. disposal, scraping, recycling) of components of the data center or a component.

The ideal would be a circular economy where the disposal phase is replaced by a recycling phase. Recycling happens already with some parts of a data center (crushed concrete can be reused as rubble, steel and copper can be melted in), but there is still a long way to go. However, this goes beyond the scope of this seminar report. The life cycle of the components of the data center are viewed separately and the resources used by the different components are then summed up per life cycle stage to get the overall numbers. Of course in the context of a data center one has to estimate and extrapolate many values, as the resource efficiency is most of the time during the use phase of the data center and many of its components.

The next sections will explain the dimensions for the consumption of natural resources used by the KPI4DCE method in more detail.

2.1.1 Water Consumption

The water usage of the data center is measured in cubic meters of water per year (m^3/a). Water is used primarily for cooling the IT hardware in data centers. Water can be a critical resource in locations with water shortage and high temperatures. If the temperatures outside are low, nearly no water is used, because the cooling circuit is closed and the water is manly used to transport heat. However, if it is very warm outside evaporation cooling can be used, which looses the evaporating water and leads to its consumption.
As with the following Resources, the water consumption is measured over the entire life cycle, e.g. the Water Consumption of the manufacturing phase is divided by the number of years the component is used and added to the water consumption value of the respective component.
This dimension does only describe the impact on the availability of water, it does not include other factors related to water like water pollution. The ILCD method (v1.0.10, August 2016) is used to access this dimension.

2.1.2 Abiotic Resource Depletion Potential

The Abiotic Resource Depletion Potential (ADP) describes the usage of raw materials of the data center. The unit of the ADP is kilogram antimony equivalents per year ($\frac{kg\ Sb_{eq}}{a}$). This dimension is a focus of the report and a calculation tool was implemented in Microsoft Excel. The report states that the ADP is standardized in ISO 14040 but should be adapted to also fit data centers[Sch+18]. The KPI4DCE method uses the ILCD method (v1.0.10, August 2016), that combines 43 raw materials of the CML method, 16 additional rare earths and 19 raw materials, that include fossil fuels. The method used here just takes into account the geological availability of the raw materials, this could change in the following years to also include anthropogenic and social economic availability[Sch+18].
The usage of raw materials is a problem of IT Hardware, as many so called "rare earths" are used to produce it and the recycling of it is not solved in a sustainable economic and ecologic way.

2.1.3 Cumulative Energy Expenditure

The Cumulative Energy Expediture (KEA) (from German "Kumulativer Energieaufwand") is the amount of energy used in mega Joule per year (MJ/a). Renewable and non-renewable energy is treated equally.

2.1.4 Global Warming Potential

The Global Warming Potential (GWP) measures the emission of greenhouse gasses per year. This is measured in kg CO_2 equivalents per year ($\frac{kg\ CO_{2\ eq}}{a}$). Similar to the ADP, the greenhouse gasses are multiplied by specific factors, that set them in relation to the global warming potential of CO_2 and then summed up. The method used is from IPCC 2013 [Myh+13]. The GWP depends heavily on the used electricity mixture, which will be seen in chapter 3. Giegrich et al. (2012) [Gie+12] found that there is a 89 % correlation between the GWP and the KEA. However, this study is from 2012 and with increasing use of renewable energy, this correlation should decrease in my opinion.

2.2 Data Center Infrastructure Resource Efficiency (DCIRE)

The KPI4DCE method differentiates between the *Data Center Infrastructure Resource Efficiency* (DCIRE) and the *IT Resource Efficiency* (ITRE). This is due to the often separated management structures of these areas and the need to include colocation data centers. In colocation data centers, different customers can rent server space to put in their own server racks. Due to this mode of operation, the equations for colocation data centers are different as they cannot access all information of the customers hardware, as well as are not responsible for it. These equations are not part of this report, but can be found in Schödwell et al.(2018)[Sch+18, p. 97].
The DCIRE is adapted from the *Data Center Infrastructure Efficiency (DCIE)*[Fon14], which is the reciprocal of the PUE. The DCIE gives the ratio of energy used by the data center for IT Infrastructure compared to all the energy used (including cooling, lights, heating, etc.). The DCIE has the same advantages and disadvantages as the PUE which is described in detail in chapter 1.2.1.

$$\text{DCIE} = \frac{1}{\text{PUE}} = \frac{\text{IT Equipment Energy}}{\text{total Facility Energy}} \tag{2}$$

Since the focus lies on resources and energy is just one of them, the DCIRE is defined in the KPI4DCE method as:

$$\text{DCIRE} = \frac{\text{IT Resource Usage}}{\text{Facility Resource Usage}} \tag{3}$$

In contrast to the DCIE, the DCIRE uses resources instead of energy used by the data center. Therefore, the DCIRE gives the ratio of resources used by the data center for IT Infrastructure compared to all resources used by the entire data center. The perfect score would be 1 (or 100 %, depending on the representation), where all of the resources would be used for the IT equipment and the rest of the data center (building, cooling, heating) would not use any resources. The worst score would be 0, but this would not be a data center then.
The DCIRE is calculated over the whole life cycle of the data center resp. its components and then normalized to one year. The DCIRE can be calculated using the different resources shown in chapter 2.1, this will be seen later on a practical example. Due to the possible loss of transparency and objectivity no aggregation rule is defined. This means, that one will get a DCIRE value for each natural resource dimension. This has the drawback, that the simplicity and elegance of a single value that can be used by the customer for fast and uncomplicated business decisions is lost (as seen with the PUE in chapter 1.2.1).

2.3 IT Resource Efficiency (ITRE)

As with the DCIRE, the ITRE is measured over the entire life cycle of the hardware and then normalized to one year. In general, the ITRE measures the resource efficiency of the IT equipment of the data center. The KPI4DCE method defines the ITRE as

$$\text{IT Resource Efficiency} = \frac{\text{IT Performance (Output)}}{\text{Consumption of Natural Resources (Input)}} \tag{4}$$

IT Performance and *Consumption of Natural Resources* are measured in multiple dimensions. The dimensions of the *Consumption of Natural Resources* were already presented in chapter 2.1, the dimensions of IT Performance will be defined and explained in the following sections. As with the DCIRE this leads to many ITRE values and no aggregation rule was defined due to the possible loss of transparency and objectivity. This again leads to many very transparent and objective performance indicators, but due to their number it is more difficult for the data center to use them in PR and the customer probably misses the simplicity of a PUE.
The resource efficiency can be calculated for the entire data center, but also for subsystems or specific pieces of hardware, if the respective measurements are available. This is very convenient as a possible customer could use this method to compare different data centers and a data center operator can use this method to compare different hardware stacks.
Different ITRE values for the HPC System Emmy will be calculated in chapter

2.4 IT Performance

The KPI4DCE method uses three IT performance dimensions: computation, data storage and data transmission. As seen in chapter 1.2, different data centers have different tasks and therefore a different focus. While one data center will focus on computation, other data centers focus on data storage. Therefore, it is important to measure these dimensions separately. The three dimensions will be presented in the following sections.

2.4.1 Computational Performance

The computation dimension is very relevant for computation focused systems like High-Performance Computing (HPC) systems. Here, the KPI4DCE method uses the SPECint_rate multiplied by the actual CPU utilization.

$$\text{Computational performance} = \text{SPECint\_rate} \times \text{CPU utilization} \tag{5}$$

The SPECint_rate is a benchmark by the *Standard Performance Evaluation Cooperation* and the version from 2006 is used by the KPI4DCE method, which is retired by now as there is a newer version[SPE06]. The SPECint_rate measures the computational throughput of a computer, e.g. how many tasks a system can solve in a certain time. Multiplying the benchmark with the average CPU utilization gives a real world number and not an artificial value, which is important as the KPI4DCE method tries to provide performance indicators for the ecological impact of real data centers. The unit is SPECint_rate operations per year.

2.4.2 Data Storage Performance

In the storage dimension, the number of read/write operations per year, the data throughput of the read/write operations per year and the overall used storage volume are used by the KPI4DCE method. These values are treated separately, to maintain transparency and objectivity. Storage media other than Solid State Drive (SSD)s and Hard Disk Drive (HDD)s are discarded in the report. This is because magnetic Tapes and optical media (e.g. Blue Ray) do not allow immediate data access. They are therefore mostly used for archiving, have a small market share and the electricity usage in the use phase is negligible compared to SSDs and HDDs[Sch+18].

2.4.3 Data Transmission Performance

To obtain the Data Transmission Performance, the amount of data transmitted between the data center and the outside world is measured. One could also measure the transfer rater and latency within a data center, but this would be very difficult and unfeasible. This is an important measurement for data centers, that do have a lot of data traffic, i.e. a data center hosting a streaming provider.

2.5 Practical Examples from the Report

In the KPI4DCE methods report [Sch+18], three example data centers are used to test the usability of the method. The authors were able to show, that the method works and that it provides insight. The results of these calculations will be presented in the following section.

2.5.1 Example Data Centers

In the report three different data centers (DC1, DC2, DC3) were evaluated and compared according to the KPI4DCE method[Sch+18]. All three data centers are in availability class 3 (EN 50600). Further information on the data centers can be found in table 1 and in Schödwell et al. (2018)[Sch+18, p. 156 et seq]. The authors used the open source software from OpenLCA of the Berlin company GreenDelta to calculate the following values[Del22].

Table 1: Basic information about the three example data centers. Adapted and translated from [Sch+18, p. 156 and 259]. An Managed Service Provider (MSP) is a data center, that takes care of the outsourced IT of another company.

Data Center	DC1	DC2	DC3
Business	municipal IT service provider	web hoster	IT consulting
	MSP + Colocation	MSP	MSP
max. power supply	750 kW	83 kW	192 kW
electricity usage	902,282 kWh	49,939 kWh	716,203 kWh

The resource efficiencies and the DCIRE values calculated were visualized using bar charts and will be discussed in the following section.

2.5.2 Results of the practical Examples from the Report

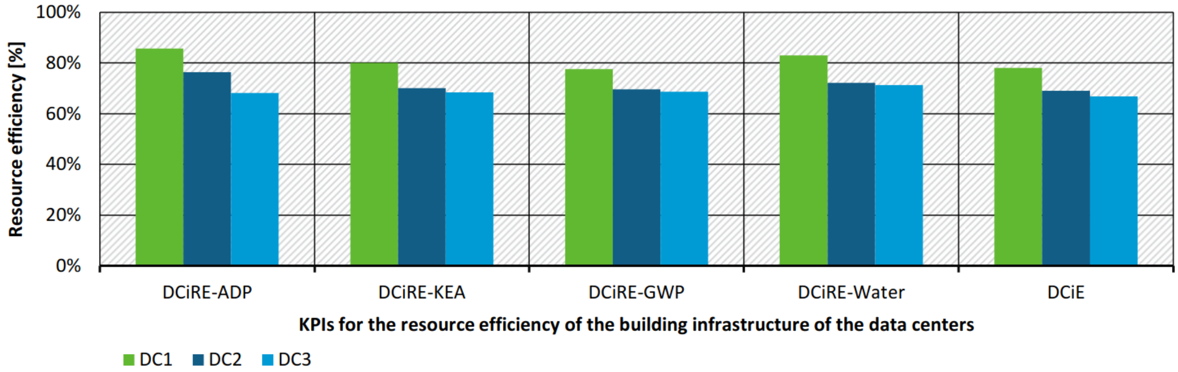

Figure 3: DCIRE and DCIE for the three data centers regarding the different resource dimensions, copied from [Sch+18]. data center 1 (green) is most efficient.

In Figure 3 the different DCIRE values for the data center are shown. One can generally see, that DC1 is more resource efficient in terms of the DCIRE than the other two data centers, e.g. more of the resources are spend on IT Hardware and its usage in comparison to the rest of the data center like heating and cooling. None of the three data centers have adiabatic cooling. Therefore, the DCIRE using water and Energy consumption (KEA) are fairly similar. A data center with adiabatic cooling would have a lower DCIRE value regarding water consumption and a higher value for energy consumption, e.g. adiabatic cooling uses evaporates water to use less energy.

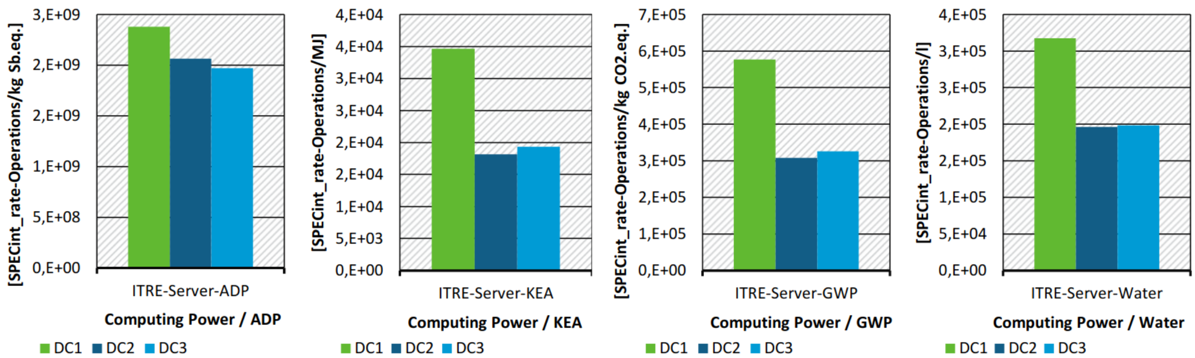

Figure 4: Resource Efficiencies using Computing Power as IT Performance, copied from [Sch+18].

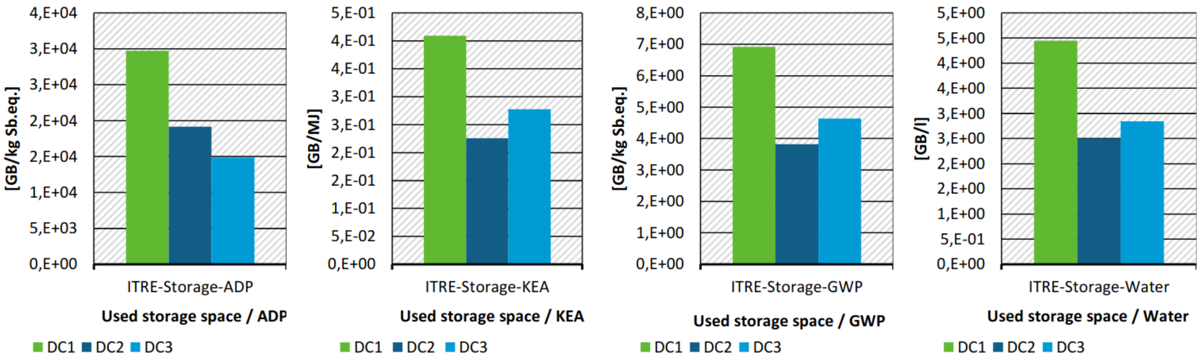

Figure 5: Resource Efficiencies using used storage space as IT Performance, copied from [Sch+18].

In Figure 4 and 5 one can see the Resource Efficiencies of the IT systems of the three data centers. In Figure 4 the computing power is used as the performance measurement, whilst in Figure 5 the used storage space is used as the performance measurement. In both cases, one can see, that DC1 is more efficient than the other two. DC1 seems to use much more efficient hardware than the other two data centers, as one can see a lot more calculation and storage for the same amount of energy, greenhouse gas emissions and water. Regarding the ADP, the data centers are more similar, especially regarding the computational resource efficiency. However, as a possible customer, given prices and other factors are the same, one should choose DC1 over the other two due to its higher resource efficiencies.

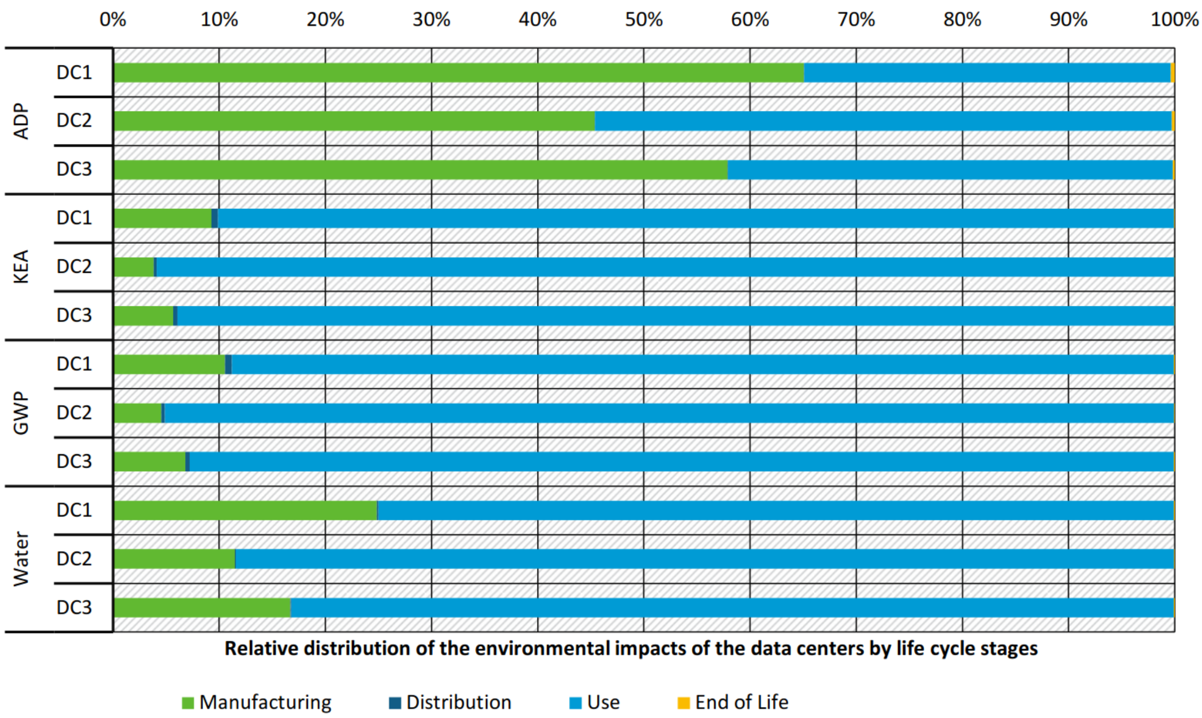

Figure 6: Relative distribution of the environmental impacts over the life cycle stages, copied from [Sch+18]. Distribution and End of Life (disposal phase) are vanishingly small compared to the use phase and the Manufacturing. The manufacturing phase is dominating the ADP, while the other resources are primarily used in the usage phase.

In Figure 6 one can see the distribution of the environmental impacts over the life cycle stages. Distribution and End of Life (disposal phase) are vanishingly small compared to the use phase and the manufacturing phase. The manufacturing phase is very important for the ADP ($\approx 45\% - 65\%$), while the other resources are primarily used in the usage phase ($\approx 75\% - 95\%$).

Summarizing, the authors claim, that the test on the three example data centers was a success. The greatest challenge was to get the required data. In many cases, the data was not available and had to be estimated. Therefore, it is not clear how trustworthy the results are. However, since the goal of these practical examples was to test and demonstrate the method, this does not matter from my point of view. The authors state, that "the calculated values of the KPIs may give a first clue in what range future benchmarks probably could be established."[Sch+18, p. 44]. This can indeed be true and remains to be seen. Furthermore, the authors hint at some methods, that could improve their estimation of the ADP and that should have been published by now.
Moreover, the authors state, that an inherent problem of the method is, that all IT load is considered good. This means, that one could in theory optimize for the benchmark, i.e. filling up storage with junk files to optimize the used storage space parameter. However, this is a problem of all similar performance indicators.
To validate their tests and to get a bit of hands on experience on this topic, the KPI4DCE method was used to calculate some resource efficiencies for the HPC system Emmy, this is shown in chapter 3.

3 Resource Efficiency of "Emmy"

The HPC system Emmy started in 2020 on rank 47 of the TOP500 list and currently holds rank 91. The 120 000 core and 500 Tb RAM machine produces 5.95 PFlop/s in the LINPACK Performance Benchmark [TOP22c][GWD20]. Emmys PUE is with 1.03 very good, e.g. Googles Data Centers have a PUE of 1.1[Goo22], while the Boden Type Data Center from Sweden, which is a research project on low PUE Data Centers, achieved a PUE smaller 1.02[One22].
In the following, a selection of Resource Efficiency indicators will be calculated for Emmy in order to use the KPI4DCE method described above. Due to the limited scope and time frame of this seminar report, only the use phase of the infrastructure and a selection of performance indicators will be considered.

3.1 IT Performance

To calculate the resource efficiency, the IT performance has to be determined. As Emmy is an HPC system, the computation performance was used. In the KPI4DCE report, the SPECint_rate is requested to obtain the computation performance[Sch+18]. However, the SPECint_rate was not available for Emmy. According to the GWDG[1], running a SPECint_rate benchmark on the entire system costs approximately 25 000 €. As this is not in the budget of a seminar report, the already available LINPACK benchmark was used (5.95 PFlop/s). Sadly, that means the results will not be comparable with the example data centers from the report.

[1]Sebastian Krey provided this helpful information.

The CPU utilization was estimated by the electricity usage of Emmy. This is possible, because the power usage and CPU utilization in server CPUs have a linear relationship[Dar14]. According to the GDWG[2], in 2021 Emmy used on average 80 % of the electricity used at the LINPACK Peak.

$$\text{IT Performance} = 0.8 \times 5.95\ PFlop/s = 4.76\ PFlop/s \tag{6}$$

This IT performance value will be used later to calculate the resource efficiency values. However, first values for the consumption of natural resources must be calculated.

3.2 Consumption of Natural Resources

According to the GWDG[3], Emmy was running on a little bit more than 1 MW on average in 2021. To calculate the Consumption of Resources of the IT Equipment, one would normally multiply 1 MW with the PUE (1.03). This would lead to a Consumption of Resources of approximately 0.97 MW. However, since 1 MW is already a bit lower than the actual value and the actual value is unknown, it is assumed that 1 MW is the power the IT Equipment runs on. This simplifies further calculations.
In the following, the KEA and the GWP for 2021 is calculated. Furthermore, the GWP for 2022 is estimated, given that Emmy is used in 2022 as it was used in 2021, but uses green electricity in 2022.

3.2.1 Cumulative Energy Expenditure (KEA)

Knowing the average energy usage over a year, the KEA can easily be calculated by multiplying it with a year and doing some unit transformations:

$$\text{KEA} = 1\ MW \times 1\ a/a \approx 31\ 556\ 952\ MJ/a \approx 31.5\ TJ/a \tag{7}$$

In table 2, one can see the KEA of the three example data centers from [Sch+18] in comparison to Emmy. Emmy uses about three time as much energy as the example data center.

Table 2: Cumulative Energy Expenditure of Emmy in comparison to the example data centers from [Sch+18]. One can see, that Emmy uses about three times as much energy as DC1, the largest example data center. The Server, Storage, Network and Rest values are from [Sch+18, p. 257]. Use Phase values were estimated using Figure 6.

in MJ/a	**Server**	**Storage**	**Network**	**Rest**	**Combined**	**Use Phase**
Emmy	-	-	-	-	-	**31,556,952**
DC1	5,579,552	2,315,676	1,083,167	2,235,784	11,214,179	10,092,761
DC2	2,731,099	882,475	413,362	1,711,476	5,738,412	5,508,876
DC3	4,281,974	710,876	852,292	2,700,788	8,545,930	8,033,174

[2]Sebastian Krey provided this helpful information.
[3]Sebastian Krey provided this helpful information.

3.2.2 Global Warming Potential

Calculating the GWP is a bit more complicated.
Multiplying 1 MW with one year gives that Emmy used roughly 8.8 million kWh of electricity in 2021. This roughly corresponds to 2625 Lower Saxony households[Neh21].

2021
In 2021 Emmy sourced electricity from the university. The electricity mix emitted on average 0.287 kg CO_2 equivalents per kWh (Source: Facility Management). This gives

$$\text{GWP} = 8\ 760\ 000\ kWh \times 0.287\ kg\ CO_2/kWh = 2\ 514\ 120\ kg\ CO_2 \tag{8}$$

This corresponds to driving with a 2020 2 l VW Golf for approx. 12.5 million kilometers, which corresponds to about 300 times the earths circumference.

2022
In 2022 Emmy runs on 100% green electricity[GWD21]. It is assumed, that Emmy runs otherwise the same as in 2021.

The CO_2 footprint varies heavily between different forms of green electricity, depending on the used source (water, wind, sun...)[Smo]. In Germany the emissions of a specific electricity contract can be looked up in the "Herkunftsnachweisregister" (English: register of proof of origins) of the German Environmental Agency[Umwb]. For the purpose of this seminar report, the CO_2-Calculator of the German Environmental Agency was used[Umwa]. The CO_2-Calculator does not provide sources for the CO_2-Emissions of Green Electricity and did not respond to an email inquiry. However, due to the limited scope and consequences of this report, the CO_2-Calculator provides a first estimation. Nevertheless, for business decisions the correct data should be looked up in the "Herkunftsnachweisregister" by the GWDG. Using green electricity, the CO_2-Calculator approximated

$$\text{GWP}_{2022} \approx 233\ 940\ kg\ CO_2 \tag{9}$$

This is just 9.3% of the CO_2-Emissions from 2021, which is an impressive improvement. In Table 3 one can see the respective GWP values of the example data centers from [Sch+18]. Using the electricity mix of the University, Emmy emits around six times as much CO_2 equivalents than largest example data center DC1, whereas with green electricity Emmy emits less then the data centers.

Table 3: Green House Gas Emissions of Emmy in comparison to the example data centers from [Sch+18]. The Server, Storage, Network and Rest values are from [Sch+18, p. 257] Use Phase values were estimated using Figure 6.

in kg CO_2 eq./a	**Server**	**Storage**	**Network**	**Rest**	**Combined**	**Use Phase**
Emmy, 2021	-	-	-	-	-	**2,514,120**
Emmy, 2022	-	-	-	-	-	**233,940**
DC1	335,493	136,995	63,776	154,657	690,921	**614,920**
DC2	161,126	52,133	24,301	103,354	340,914	**323,868**
DC3	253,762	42,557	50,310	158,097	504,726	**469,395**

3.3 Resource Efficiency

Given the values for IT Performance and Consumption of Natural Resources, the Resource Efficiency of Emmy can now be calculated.

$$\text{Resource Efficiency}_{\text{KEA}} = \frac{\text{computational performance}}{\text{KEA}} = \frac{4.76 PFlop/s}{31\ 556\ 952\ MJ/a} \approx 4.76 \frac{GFlop/s}{W} \quad (10)$$

Since the LINPACK benchmark was used instead of the SPECint_rate, the results are not comparable to the example data centers in the report.
However, one can compare the Resource Efficiency calculated with the KEA to the Resource Efficiency given by the Green500 list [TOP22a]. On the current list (June 2022) Emmy would be ranked 83. The Green500s Energy Efficiency (GFlop/s/W) should be comparable to the Resource Efficiency$_K EA$, because it is calculated using the LINPACK Benchmark and the power consumption during benchmarking[Ge+07]. To calculate the Resource Efficiency of Emmy, 80 % of the peak performance was used, but as 1 MW is also 80 % of the electricity used and we take a ratio, this does not matter.
It is unclear why Emmy is not on the Green500 List, as it is on the TOP500 list. The power consumption value is missing in the dataset submitted to TOP500, but it should be known as I was told[4] that 1 MW is 80% of the LINPACK benchmark power, so clearly Emmy has run on 1.25 MW during the benchmark.

$$\text{Resource Efficiency}_{\text{GWP, 2021}} = \frac{\text{computational performance}}{\text{GWP}_{2021}} = \frac{4.76 PFlop/s}{2\ 514\ 120\ kg\ CO_2} \approx 1.9 \frac{GFlop/s}{kg\ CO_2} \quad (11)$$

$$\text{Resource Efficiency}_{\text{GWP, 2022}} = \frac{\text{computational performance}}{\text{GWP}_{2022}} = \frac{4.76 PFlop/s}{233\ 940\ kg\ CO_2} \approx 20 \frac{GFlop/s}{kg\ CO_2} \quad (12)$$

Since the LINPACK benchmark was used instead of the SPECint_rate, the results are not comparable to the example data centers in the report.
However, one can compare the Resource Efficiency using conventional and green electricity. In our calculation Emmy emitted roughly 10x less CO_2 equivalents when running on green electricity. Therefore, the Resource Efficiency was about 10x better. However, some assumptions were made. Especially the emissions with green electricity should be viewed as an estimation, as the "CO_2-Calculator" of the German Environmental Agency was likely designed for other use cases[Umwa].

4 Summary and Conclusions

4.1 The KPI4DCE method

The KPI4DCE method, developed in Schödwell et al. (2018)[Sch+18] was presented. The method calculates the resource efficiency of data centers or their subsystems from an environmental perspective.
Resource Efficiency is defined as the IT Performance divided by the Consumption of Natural Resources. The IT Performance is measured as computational, data storage and data transmission performance. The Consumption of Natural Resources is measured as the water consumption, the abiotic resource depletion potential, the cumulative energy

[4] Sebastian Krey provided this helpful information.

expenditure and the global warming potential. An aggregation rule is not defined due to the possible loss of transparency and objectivity. However, this is at the cost of the simplicity of a single value, as this leads to a multitude of different resource efficiencies.
An inherent problem of the method is, that all IT load is considered good. This means, that one could in theory optimize for the benchmark, i.e. filling up storage with junk files to optimize the used storage space parameter. However, this is a problem of all similar performance indicators.
Three data centers were used to test the KPI4DCE method in Schödwell et al. (2018)[Sch+18]. The results were presented and discussed. Summarizing, one can say, that the biggest challenge is the collection of the required data but the method is usable and provides insight that can help to optimize data centers as a data center operator or to make a business decision as a potential customer.

4.2 Resource Efficiency of Emmy

To test the usability of the KPI4DCE method, a selection of Resource Efficiency indicators were calculated for the HPC system Emmy. Since the LINPACK benchmark was used for the computational performance, the results are not comparable to the example data centers in the report, because the KPI4DCE method uses the SPECint_rate instead of the LINPACK performance benchmark.
Nevertheless, it is possible to say that Emmy should rank place 83 on the Green500 list[TOP22a]. Furthermore, it can be seen, that with switching to green electricity roughly 10 times as much work can be done with the same amount of CO_2 emissions. This is of course a calculation one can make before switching to green electricity to estimate the areas where the resource efficiency of the data center can be improved the most. Therefore, the method could be very useful for finding high impact improvements. The method should be especially easy to use, as [Sch+18] provides an Microsoft Excel sheet, that should in theory reduce friction a lot. However, this Excel sheet could not be found or provided in the time frame of this seminar project. Nevertheless, it would be an interesting topic for a small project for another student to find and try this Excel sheet. Another software one could try is the OpenLCA[Del22] used by the authors of [Sch+18] to calculate the different resource efficiencies in their examples. Moreover, at a meeting of the comity for the new Blue Angel for data centers somebody hinted that they are developing a tool to make the calculation of the ADP very easy.
Additionally, comparing different data centers on an environmental level is desirable from a customers perspective. This is difficult with the KPI4DCE method, because an aggregation rule is not defined and a ranking like the Green500 is therefore not possible. However, an environmental certificate, like the Blue Angel for Data Centers [Eng] would make a comparison unnecessary.

Moreover, it was not easy to obtain the data needed to calculate the Performance and Consumption of Natural Resources dimensions. Calculating the ADP would have been far to much work for this seminar report. The consulting company "Data Center Excellence GmbH" offers consulting and courses on the Blue Angel certificates and helps developing the new Blue Angel for Data Centers[Gmb]. They seemed very competent at the meeting of the comity for the new Blue Angel for Data Centers and would probably be a good starting point if one would like to obtain the respective certificates.

References

[AE15] Anders S. G. Andrae and Tomas Edler. "On Global Electricity Usage of Communication Technology: Trends to 2030". In: *Challenges* 6.1 (2015), pp. 117–157. ISSN: 2078-1547. DOI: 10.3390/challe6010117. URL: https://www.mdpi.com/2078-1547/6/1/117.

[Ang20] Blue Angel. *The Blue Angel for Climate Friendly Colocation Data Centers (DE-UZ 214)*. Jan. 2020. URL: https://www.blauer-engel.de/en/publications/detail/blue-angel-climate-friendly-colocation-data-centers.

[Biz+21] Daniel Bizo et al. "Uptime Institute Global Data Center Survey 2021". In: *Uptime Institute | Intelligence* (2021). URL: https://uptimeinstitute.com/uptime_assets/4d10650a2a92c06a10e2c70e320498710fed2ef3b402aa82fe7946fae3887
2021-data-center-industry-survey.pdf.

[Bra+13] Gemma A. Brady et al. "A case study and critical assessment in calculating power usage effectiveness for a data centre". In: *Energy Conversion and Management* 76 (2013), pp. 155–161. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2013.07.035. URL: https://www.sciencedirect.com/science/article/pii/S0196890413004068.

[Dar14] Waltenegus Dargie. "A Stochastic Model for Estimating the Power Consumption of a Processor". In: *IEEE Transactions on Computers* 64 (Apr. 2014). DOI: 10.1109/TC.2014.2315629.

[Del22] Green Delta. *OpenLCA*. Sept. 2022. URL: https://www.openlca.org/.

[Eng] Blauer Engel. *Blue Angel for Data Centers*. URL: https://be-rechenzentren.de/.

[Eng15] Blauer Engel. *Energy-Efficient Data Center Operation (DE-UZ 161)*. Feb. 2015. URL: https://www.blauer-engel.de/en/productworld/data-centers.

[Fon14] Mark Fontecchio. *What is data center infrastructure efficiency (DCIE)?* Sept. 2014. URL: https://www.techtarget.com/searchdatacenter/definition/data-center-infrastructure-efficiency-DCIE.

[Ge+07] R Ge et al. "Power measurement tutorial for the Green500 list". In: *The Green500 List: Environmentally Responsible Supercomputing* (2007).

[Gie+12] J. Giegrich et al. "Indikatoren / Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion". In: (2012). URL: https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4237.pdf.

[Gmb] Data Center Excellence GmbH. *Data Center Excellence GmbH*. URL: https://datacenter-excellence.de/.

[Goo22] Google. *Efficiency*. 2022. URL: https://www.google.com/about/datacenters/efficiency.

[Gri22a] The Green Grid. *Glossary - PUE*. Sept. 2022. URL: https://www.thegreengrid.org/en/resources/glossary.

[Gri22b] The Green Grid. *Members*. Sept. 2022. URL: https://www.thegreengrid.org/en/about-us/members.

[Gri22c] The Green Grid. *Members*. Sept. 2022. URL: https://www.thegreengrid.org/en/about-us/.

[GWD20] GWDG. *GWDG Press release*. Mar. 2020. URL: https://www.gwdg.de/about-us/press-releases/2020/press-release-3-2020.

[GWD21] GWDG. *GWDG Press release*. Apr. 2021. URL: https://www.gwdg.de/about-us/press-releases/2021/press-release-4-2021.

[IO522] IO500. *IO500*. 2022. URL: https://io500.org/.

[Mas+18] V. Masson-Delmotte et al. "IPCC: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty". In: *Cambridge University Press, Cambridge, UK and New York, NY, USA* (2018). URL: https://doi.org/10.1017/9781009157940.001.

[Myh+13] G. Myhre et al. "Anthropo-genic and Natural Radiative Forcing". In: *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2013).

[Neh21] William Nehra. *Energy consumption in Germany is falling as prices continue to rise*. Apr. 2021. URL: https://www.iamexpat.de/housing/real-estate-news/energy-consumption-germany-falling-prices-continue-rise.

[Net] Global Ecolabeling Network. *Global Ecolabelling Network: Full members list*. URL: https://globalecolabelling.net/gen-members/gen-full-members-list/.

[New15] Liam Newcombe. *Look at the size of my pue!* Jan. 2015. URL: https://web.archive.org/web/20150924091952/http://www.romonet.com/blog/opinions/blogart39.

[Ogh17] Michael Oghia. *Shedding light on how much energy the internet and icts consume*. Mar. 2017. URL: https://circleid.com/posts/20170321_shedding_light_on_how_much_energy_internet_and_ict_consume.

[One22] Boden Type DC One. *Boden Type DC One*. 2022. URL: https://bodentypedc.eu/.

[Sch+18] Björn Schödwell et al. *Kennzahlen und Indikatoren für die Beurteilung der Ressourceneffizienz von Rechenzentren und Prüfung der praktischen Anwendbarkeit*. Umweltbundesamt, 2018. URL: https://www.umweltbundesamt.de/publikationen/kennzahlen-indikatoren-fuer-die-beurteilung-der.

[Smo] Grace Smoot. *What is the carbon footprint of renewable energy? A life-cycle assessment*. URL: https://impactful.ninja/the-carbon-footprint-of-renewable-energy/.

[SPE06] SPEC. *SPEC CPU 2006*. 2006. URL: https://www.spec.org/cpu2006/.

[TOP22a] TOP500. *Green500 List - June 2022*. June 2022. URL: https://www.top500.org/lists/green500/list/2022/06/.

[TOP22b] TOP500. *TOP500 list - June 2022*. June 2022. URL: https://www.top500.org/lists/top500/2022/06/.

[TOP22c] TOP500. *TOP500 ranking of Emmy*. June 2022. URL: https://www.top500.org/system/179883/.

[Umwa] Umweltbundesamt. *CO2 Rechner*. URL: https://uba.co2-rechner.de/de_DE/living-pt#panel-calc.

[Umwb] Umweltbundesamt. *Herkunftsnachweisregister*. URL: https://www.hknr.de/Uba.

[UNF] UNFCCC. *The Paris Agreement*. URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.