Carbon Footprint of IT-Services – A comparative Study of Energy Consumption for Offline and Online Storage Usage

Completed Research Paper

Daniel Grimm
Technical University of Berlin
d.grimm@tu-berlin.de

Koray Erek
Technical University of Berlin
koray.erek@ikm.tu-berlin.de

Ruediger Zarnekow
Berlin Institute of Technology
ruediger.zarnekow@ikm.tu-berlin.de

ABSTRACT

This paper focusses on the Carbon Footprint of IT-Services (CFIS) by presenting a comparative study of energy consumption for Offline and Online Storage. We therefore conducted a case study with an IT-Service provider as well as experimental simulation of customer's ICT hardware. Based on literature review, we initially present related work and describe underlying concepts e.g. Carbon Footprint of Products, Life Cycle Assessment (LCA) as well as ICT energy and performance measurement. The paper proposes a methodological framework for CFIS based on the phases of LCA. Geared towards the framework we present a comparison of ICT-related energy consumptions for Offline and Online Storage as well as allocation and calculation approaches. Finally, presented carbon footprint results are discussed in terms of limitations and further research directions. The CFIS is an inevitable step to advance Green IS/IT research, since it quantifies dependencies between IT-Services, ICT energy consumption and related greenhouse gas emissions.

Keywords

Sustainability, Green IS/IT, Carbon Footprint, Life Cycle Assessment, IT-Service

INTRODUCTION

Climate change and global warming represent significant challenges of the 21st century. Since there is consensus that greenhouse gases (GHGs) are the major cause of climate change, organizations are increasingly faced with the task of quantifying the amount of GHGs emitted through their activities, products and services. Lately, the Carbon Footprint (CF) has been recognized to fulfill this task and it has seen a massive rise in interest, usage and research (Jensen, 2012). Especially for manufacturers of consumer goods, the Carbon Footprint of Products (CFP) has emerged as an approach to quantify the climate change impact based on product-related GHG emissions expressed as CO2-equivalent (CO2-e) (Scipioni, Manzardo, Mazzi and Mastrobuono, 2012). In order to achieve a holistic and realistic CFP result it is necessary to investigate the entire life cycle of a product (Jensen, 2012) which can be achieved through the usage of Life Cycle Assessment (LCA) principles, methodologies and standards. Various methodologies and standards for LCA and CFP have emerged e.g. ISO 14040/44 (ISO, 2006a; ISO, 2006b), ISO 14067 (ISO, 2012), PAS 2050 (BSI, 2011) and Greenhouse Gas Protocol (GHG Protocol, 2011). In addition there is a wide range of databases that can be consulted to conduct LCAs and CFPs. A high level of complexity and pressing issues such as uncertainty and variability of results (Weber, 2012) as well as the variety of methodologies, standards and databases often lead to ambiguity and confusion in users and recipients alike. Nevertheless it is obvious that the Carbon Footprint of IT-Service (CFIS) should adapt LCA and CFP principles, in order to quantify GHG emissions of IT-Service providers' (ISP) "products". This leads to our first research question:

1. How can the principles, methodologies and standards of LCA and CFP be adopted in order to assess GHG emissions related to IT-Services?

The forces that drive organizations to use tools such as CFP are multifaceted. Governmental as well as societal pressure to determine and subsequently decrease GHG emissions can be seen as major drivers (Bocken and Allwood, 2012). In order to put pressure on organizations, governments can take manifold national measures such as GHG reporting rules and forced purchases of carbon offsets (Chowdhury, 2012) as well as introducing mandatory carbon accounting (Ascui and Lovell, 2011) or carbon emission taxes and product labeling (Bocken et al., 2012). Furthermore, the increasing consumer awareness of environmental issues and the resulting increased demand in sustainable products also exert pressure on organizations to monitor carbon emissions (Scipioni et al., 2012). These aspects which affect the Information and Communication Technology (ICT) industry as well and the fact that environmental sustainability has become a huge concern to IS practice and academic community (Watson, Boudreau and Chen, 2010) motivate our research towards the CFIS. Studies revealed that in 2008 the ICT industry already accounted for a significant climate change impact with roughly 2-3% of global carbon emissions (Gartner, 2007; The Climate Group, 2008). At the same time, the ICT industry is identified as an enabler with the potential to reduce global GHG emissions of other industries and society in general by 23-30% (The Climate Group, 2008). These two different perspectives are discussed under the superordinate terms of "Green IT/IS". "Green IT" covers measures aiming at the assessment respectively reduction of energy consumption and thereby GHG emissions of ICT itself, whereas Green IS primarily refers to measures that reduce GHG emissions of non-ICT activities through the intelligent use of ICT (Chowdhury, 2012). The CFIS aims at the assessment of ICT-related energy consumption and its allocation to IT-Services, which characterizes the CFIS more as a measure in context of Green IT than Green IS. Due to the complex ICT infrastructure and the huge amount of ICT hardware that is used to distribute IT-Services from the ISP to its customers, the allocation of ICT-related energy consumption can be very extensive. In comparison to other IT-Services the underlying ICT infrastructure for the IT-Service Online Storage is manageable. In addition the Market-research firm IDC predicted an increase of the share for Storage-Services in total cloud-computing revenues from 5 percent in 2008 to 13 percent in 2012 (Leavitt, 2009), which underlines the relevance of the energy assessment and allocation for this fast growing market. Because of the doubtful validity of only one single CFIS value for Online Storage, the decision to conduct a comparative study was made by choosing the IT-Service Offline Storage as an alternative. Our second research questions arising from this:

2. How can ICT-related energy consumptions be allocated to IT-Services in order to conduct a comparative CFIS study for Online and Offline Storage?

Initially the paper presents related work, giving a brief literature review of existing research in the field of ICT-related LCA and CF. In order to address the first research question, we describe underlying concepts e.g. CFP, LCA, energy and performance measurement to further propose a methodological framework for CFIS based on the phases of LCA. Derived from a case study and experimental simulation, energy and performance data of ICT hardware were collected. In order to answer the second research question these data are used to present an energy respectively CF comparison for Offline and Online Storage usage. We finally discuss the results, existing limitations of CFIS and further research directions.

RELATED WORK

Research focusing on ICT-related CFs and LCAs is seeing a steady increase in interest. There are various contributions that show a wide range of investigated subjects within the field of ICT. Since this paper seeks to address the CFIS, the main focus of this section is to present selected publications of this particular field and adjacent fields, sorted into adequate categories (workplace-related ICT hardware; datacenter; networks and IT-Services).

There is a multitude of publications concerning workplace-related ICT hardware such as PCs and laptops including or excluding monitors. Kim, Hwang and Overcash (2001) investigated the environmental impact of a 17-inch color computer monitor with an assumed lifetime of six years and various use scenarios. Williams and Sasaki (2003) assessed the life cycle energy use for PCs in terms of three different end-of-life scenarios. Williams (2004) used a hybrid assessment, combining process and economic input-output methods to estimate the total energy and fossil fuels used in producing a desktop computer with a 17-inch CRT monitor. Hoang (2009) conducted a full LCA to determine the GHG emissions of a laptop manufactured and used in the USA. O'Connel and Stutz (2010) assessed the CFP of a Laptop comparing three regions in order to highlight the impacts that surrounding characteristics can have on CFPs. Multiple contributions came to similar conclusions, namely that the use phase usually has the strongest influence on the environmental impact.

Concerning the category datacenter (DC) The Green Grid recently released guidelines to conduct a LCA of the whole DC (Aggar, Banks, Dietrich, Shatten, Stutz and Tong-Viet, 2012). Previous publications for example studied the environmental impact of DC designs across the lifecycle (Meza, Shih, Shah, Ranganathan, Chang and Bash, 2010), developed scenarios for creating carbon-neutral DCs (Welch, 2011) and discussed how different design and operational decisions in a DC's life cycle affect the environmental impact (Shah, Chen, and Bash, 2012). Representing the most important ICT hardware in DCs, servers are of major interest to several publications that for example analyzed the lifetime exergy consumption of an enterprise server (Hannemann, Carey, Shah and Patel, 2010), presented a methodology based on lifecycle exergy consumption from a server architectural perspective in order to holistically address the environmental impacts of servers (Chang, Meza, Ranganathan, Shah, Shih and Bash, 2012) and estimated the CFP of a specific rack server using the ISO methodology as a guideline (Stutz, O'Connell and Pfleuger, 2012).

Publications dealing with the LCA or CF of networks are rare. We found studies that for example presented network-based models for the Internet energy consumption (Baliga, Hinton, Ayre and Tucker, 2009) as well as for the energy consumption of optical IP networks (Baliga, Ayre, Hinton, Sorin and Tucker, 2009). Another publication assessed the CF of a virtual private cloud, more precisely energy consumption and the CF of a Wide Area Network (WAN) of DCs (Moghaddam, Cheriet and Nguyen, 2011).

Research concerning the CFs and LCAs of IT-Services has seen a few publications. Gard and Keoleian (2003) for example analyzed the energy consumption of digital and printed scholarly journal collections. Reichart and Hischier (2002) compared reading a printed newspaper and reading the news online as well as TV news and online news. Toffel and Hovrath (2004) carried out a comparative study concerning the environmental impacts of reading a newspaper vs. news via Personal digital assistant (PDA) and teleconferencing vs. business travelling. Younger publications conducted LCAs for printed vs. electronic teaching aids (Enroth, 2009), analyzed the environmental impact of virtual meeting solutions (Guldbrandsson and Malmodin, 2010) or presented a comparative CF study for online vs. offline movie rental (Velásquez, Ahmad, Bliemel and Imam, 2010). Research about the environmental impact of IT-Services is clearly at the beginning. Most of the publications are presented as comparative studies and show that IT-Services can significantly reduce the environmental impact in comparison to their “traditional” counterparts without IT support. However, with IT-Services being the focus of this paper it has to be pointed out that there is a gap in this research area, giving more strength to our motivation.

UNDERLYING CONCEPTS

GHGs, CFP and LCA

The Green House Gas Protocol defined three Scopes of GHGs in order to differ between direct and indirect emission sources. Scope 1 covers direct GHG emissions occurring from sources owned or controlled by the company, Scope 2 describes indirect GHG emissions from the generation of purchased electricity consumed by the company and Scope 3 accounts for all other indirect emissions from sources not owned or controlled by the company (GHG Protocol, 2011). For conceptualizing CFIS we need to understand the term Carbon Footprint, its origins and related terms. This paper follows the definition of CF as the “[…] quantity of GHGs expressed in terms of CO2-e, emitted into the atmosphere by an individual, organization, process, product or event from within a specified boundary” (Pandey, Agrawal and Pandey, 2011). CF is not a new concept, since it has always been the result of the impact category indicator global warming potential (GWP) in LCA (Finkbeiner, 2009). LCA is a more complex approach creating a holistic picture, where besides GWP multiple environmental impact categories are assessed (Weidema, Thrane, Christensen, Schmidt and Løkke, 2008). The International Organization for Standardization (ISO) divides the LCA process into the four phases goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation (ISO, 2006a). The ISO is recognized as the world’s largest and most widely known standards development organization and any new ISO standard in the environmental field will have a sizable influence (Morikawa and Morrison, 2004). Currently, the ISO is developing a specific standard, which includes requirements and guidelines for the quantification and communication of the CFP which is being used to determine GHG emissions on a product level (Jensen, 2012). The standard is based on principles of LCA and it is now available in second draft ISO/DIS 14067.2:2012 (ISO, 2012). Because of its expected influence we chose ISO/DIS 14067 for applying a transfer-oriented approach to develop a methodological framework for CFIS.

Energy Measurement

Real-time measurement of ICT energy consumption recently receives increasing attention especially within DC. The measurement may be established following the guidance of The Green Grid and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Ashrae, 2009). Energy consumption of ICT subsystems can be determined through the deployment of intelligent Power Distribution Units (iPDU). Moreover, manufacturers successively equip ICT hardware with additional intelligence to log and report energy consumption.

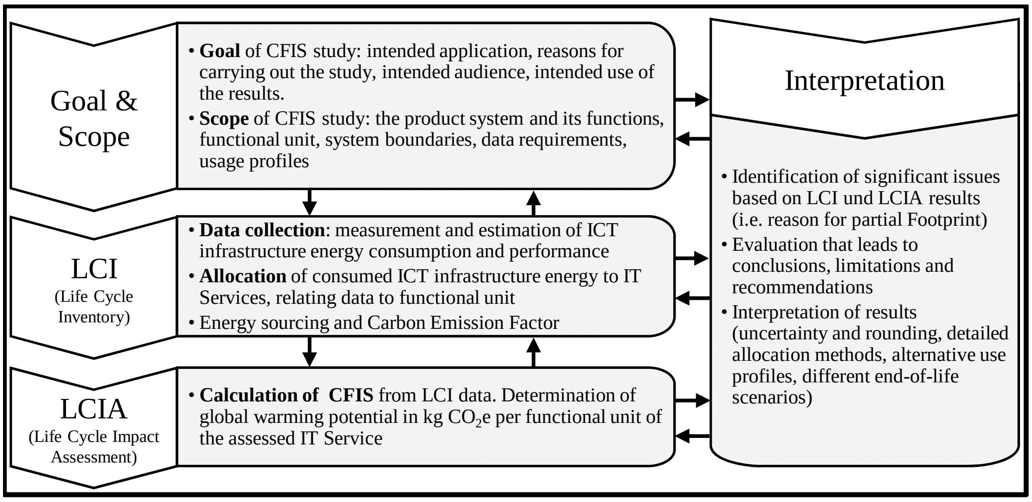
Performance Measurement

The measurement of total and IT-Service specific performance of ICT hardware is necessary to allocate total energy consumption of ICT hardware to an IT-Service. Simplified, performance may regard:

- in case of servers to the amount of servers used, the utilization of the central processing units or processed data volume,
- in case of storage to the used storage capacity for active data and input/output operations for backup and archives and
- in case of network equipment to data volume transmitted (network traffic).

METHODOLOGICAL FRAMEWORK

A CF study that applies ISO/DIS 14067 focusses on the assessment of the GWP of products and uses the four main phases of LCA. These phases form the methodological framework for our CFIS concept as shown in Figure 1. The framework specifies the process phases of CFP in order to accomplish a CFIS study by defining necessary tasks. The following sections are geared towards the methodological framework and present a comparative study of energy consumption for Offline and Online storage usage.



- **Goal** of CFIS study: intended application, reasons for carrying out the study, intended audience, intended use of the results.
- **Scope** of CFIS study: the product system and its functions, functional unit, system boundaries, data requirements, usage profiles

- **Data collection**: measurement and estimation of ICT infrastructure energy consumption and performance
- **Allocation** of consumed ICT infrastructure energy to IT Services, relating data to functional unit
- Energy sourcing and Carbon Emission Factor

- **Calculation of CFIS** from LCI data. Determination of global warming potential in kg CO_2e per functional unit of the assessed IT Service

- Identification of significant issues based on LCI und LCIA results (i.e. reason for partial Footprint)
- Evaluation that leads to conclusions, limitations and recommendations
- Interpretation of results (uncertainty and rounding, detailed allocation methods, alternative use profiles, different end-of-life scenarios)

Figure 1. Methodological framework for CFIS based on ISO/DIS 14067

GOAL AND SCOPE

Study Objectives

The lifecycle of ICT hardware is subdivided in classical stages of product life e.g. raw material extraction, pre-production of components, manufacturing and distribution of end-products, their use stage and end-of-life treatment. This study focusses on the energy assessment of ICT hardware in use stage. Prior and following lifecycle stages are out of scope for now. The limitation to selected lifecycle stages characterizes the study as a partial CF (ISO, 2012). Based on the allocated energy consumption, the study quantifies indirect carbon emissions (scope 2) induced by IT-Service alternatives (Offline and Online storage), which basically provide the same functionality. The results represent comparable CFs (in kg CO2-e) referring to production, distribution and consumption of the assessed IT-Service alternatives.

Functional Unit and System Boundaries

In order to refine the scope of the study, a functional unit (FU) has to be determined. Its primary purpose is the quantification of a product system's performance to provide a reference to which the inputs and outputs are related. The FU quantifies a specific benefit coming from the output of the assessed IT-Service alternatives. The FU for this study is: The operation and usage of storage for one user in the period of 12 months.

Considering the IT-Service alternative Online Storage an ISP operates ICT hardware e.g. servers, storage systems and networks as well as ancillary site infrastructure (ASI) e.g. cooling, power, and support systems in DCs. Using these systems the ISP is able to provide Online Storage. Customers consume the IT-Service as needed by means of workplace-related ICT hardware e.g. desktop PCs, laptops and networks. The networks of provider and consumer are connected through the internet which allows the distribution of Online Storage. However, we developed a network model (see Figure 2) which specifies system boundaries as well as involved ICT hardware. The network model assumes that the customer connects to the Internet Service Provider's infrastructure, which is called Point of Presence (PoP). For the customers internet connection we assumed a download bandwidth of 16,9 Megabit per second (Mbps) and 2,39Mbps upload bandwidth[*]. The PoP is connected to the Internet Backbone which is a collection of high performance routers. Trace route commands were used to indicate the

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[*] The data was extracted from http://www.netindex.com/download/2,7/Germany/, accessed: December 5, 2012

number of routers between customer's laptop workplace and storage server in DC. This configuration leads to ICT-related energy consumption on ISP's DC, customer's home and occurring from internet infrastructure.

Offline Storage infrastructure is only located at the private customer's home. A Network Attached Storage (NAS) device is used within Local Area Network (LAN) to access and save data. The NAS device was chosen because of its ability to simulate online storage advantages e.g. data reliability through RAID functionality.

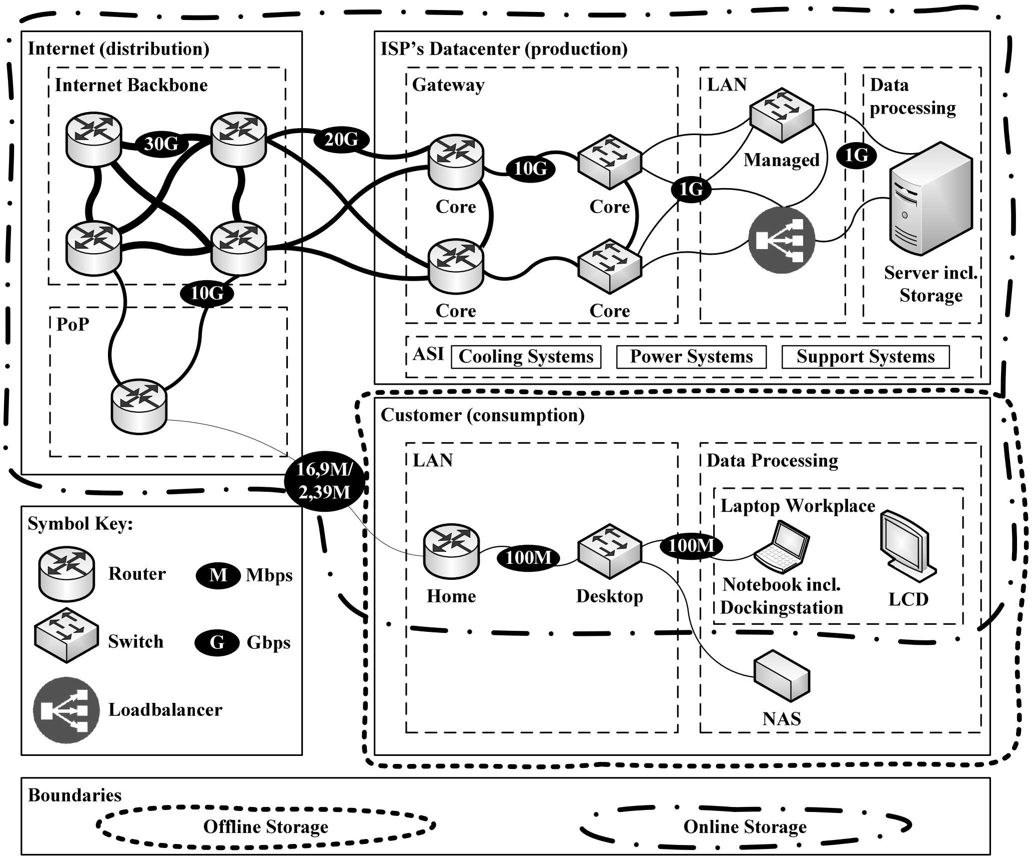

Figure 2. Network model with boundaries of IT-Service alternatives and involved ICT hardware

LIFE CYCLE INVENTORY (LCI)

Data collection and data quality

In order to gather necessary data for the IT-Service alternative Online Storage we conducted a case study with a large ISP operating in Germany, Austria, Switzerland, the UK, USA and Spain in the context of a research project funded by German Federal Ministry of Economics and Technology. Primarily the ISP offers Web hosting, Domain and Mail services, Server hosting as well as Cloud services. The ISP's DC is located in Germany and operates with a mean yearly Power Usage Effectiveness (PUE) of 1,35. PUE is known as the most popular energy efficiency metric for DCs in order to factor energy consumption of ASI into overall energy consumption of the DC (Belady, Rawson, Pfleuger and Cader, 2008). The Online Storage Service can be accessed through the FTP protocol and customers can order different storage capacities. We developed a questionnaire in order to collect necessary ISP and product data, ICT hardware and energy as well as performance data. Online Storage is used by 4350 customers, who stored an overall quantity of 112 Terabytes (TB) of data. The ISP afforded primary data sourcing from its own energy and performance measurement, covering Server and Storage systems, LAN components as well as ASI. Primary data for ISP's gateway infrastructure and internet infrastructure was not available, which is why we estimated energy consumption using secondary data sources (e.g. network models and ICT hardware data sheets).

Customer-related data for both IT-Service alternatives were collected through experimental simulation and energy measurement of involved ICT hardware. We therefore established a laboratory environment, consisting of typical ICT hardware at customer's home and simulated Offline and Online Storage usage. Simultaneously, we monitored energy consumption of ICT hardware by means of an iPDU.

Table 1 provides an overview of the assessed ICT hardware for both of the IT-Service alternatives, their measured or estimated average active power as well as data source and data quality. We differentiated between dedicated and shared usage of ICT hardware as well as three possible operating modes causing different energy consumptions of customer's hardware.

Loca-tion	**Subsystem name**	**ICT hardware name**	**Data source, Data quality**	**Online Storage**		**Offline Storage**	
				component count	**average active power (W)**	**component count**	**average active power (W)**
Datacenter (ISP)	Data processing	Server incl. Storage[d]	questionnaire, measurement	14 3	307 317	x	x
	LAN	Managed Switch[d]	questionnaire, measurement	2	150	x	x
		Load balancer[d]	questionnaire, measurement	2	150	x	x
	Gateway	Core Switch[s]	secondary, estimation	2	5300	x	x
		Core Router[s]	secondary, estimation	2	3500	x	x
Internet	Backbone	Backbone Router[s]	secondary, estimation	2	3500	x	x
	Point of Presence	PoP Router[s]	secondary, estimation	1	1300	x	x
Customer	LAN	Home Router[d]	simulation, measurement	1	11	1	11
		Desktop Switch[d]	simulation, measurement	1	4	1	4
	Data processing	Laptop Workplace[a,d]	simulation, measurement	1	68 / 12 / 2	1	68 / 12 / 2
		NAS[a,d]	simulation, measurement	x	x	1	28 / x / 2

Table 1. Energy consumption, data source and quality of involved ICT hardware

General Allocation Approach

If multiple IT-Services share the underlying ICT hardware, a systematic process namely allocation is necessary to determine a specific share of ICT subsystems' total energy consumption. An ICT subsystem is a collection of ICT hardware that provides the same functionality within the network model. The allocation of an ICT subsystem's energy consumption (EC) to an IT-Service can be realized through different performance measures. ICT subsystem performance or capacity utilization (CU) covers client devices, server-, storage- and network systems and may refer to volume of data traffic, processing time, quantity of processed or stored data and number of used components. The equation of an ICT subsystem's energy consumption related to the assessed IT-Service follows a generic metric.

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[a] Includes power ratings for different operating modes (active / power saving / off)

[d] Dedicated ICT hardware is used exclusively for the assessed IT-Service

[s] Shared ICT hardware is used for multiple IT-Services

$$\mathrm{EC}^{\text{Subsystem i}}_{\text{IT-Service X}} = \mathrm{EC}^{\text{Subsystem i}}_{\text{Total}} \cdot \mathrm{PF} \quad \text{where} \qquad \mathrm{PF} = \text{Performance Factor} = \frac{\mathrm{CU}^{\text{Subsystem i}}_{\text{IT-Service X}}}{\mathrm{CU}^{\text{Subsystem i}}_{\text{Total}}};$$

$$\mathrm{EC}^{\text{Subsystem i}}_{\text{Total}} = \begin{array}{l}\text{total energy consumption}\\ \text{of IT subsystem i}\end{array}; \qquad \mathrm{CU}^{\text{Subsystem i}}_{\text{IT-Service X}} = \begin{array}{l}\text{IT subsystem's i performance (capacity}\\ \text{utilization) induced by the IT-Service}\end{array};$$

$$\mathrm{CU}^{\text{Subsystem i}}_{\text{Total}} = \begin{array}{l}\text{IT subsystem's i total perfor-}\\ \text{mance (capacity utilization)}\end{array}$$

ICT subsystems located in DCs usually need additional ASI. The overhead energy consumption of ASI can be allocated in a proportional manner through the usage of the PUE metric (Belady et al., 2008).

$$\mathrm{PUE} = \frac{\text{total facility power}}{\text{IT equipment power}} = \frac{\text{IT equipment power + ancillary site infrastructure power}}{\text{IT equipment power}}$$

Applying this relation to our notation and expressions, the overhead energy consumption of ASI induced by the IT-Service X can be determined for each ICT subsystem.

$$\mathrm{EC}^{\text{ASI}}_{\text{IT-Service X}} = (\mathrm{PUE}-1) \cdot \mathrm{EC}^{\text{Subsystem i}}_{\text{IT-Service X}}$$

In order to demonstrate how we used the general allocation approach as well as relating data to the FU, we provide examples in the following section.

Examples for Energy Allocation and Relating Data to Functional Unit

Server and Storage

The results of Online Storage questionnaire revealed that the ISP operates 14 servers with an average active power of 307 Watts and another 3 servers with an average active power of 317 Watts. These Servers provide an overall storage capacity of 181 TB of which 112 TB are actually used. Thus the DC ICT subsystem Data processing (see Figure 2) consumes (14*307Wh+3*317Wh=) 5249Wh energy per hour. These dedicated Servers are used exclusively to provide Online Storage, which implies an allocation of the whole energy consumption. The determination of a specific energy share induced by the IT-Service is not necessary for dedicated ICT hardware. In order to relate the energy consumption to the FU we assumed that Server and Storage hardware is equally used by all provided customers, which is why an energy consumption of (5249Wh/4350users=) 1,207Wh per hour can be related to one user of Online Storage. Since the Servers operate (365days*24h=) 8760 hours per year their allocated energy consumption related to the FU is (1,207Wh/h*8760Wh=) 10,570kWh per year and user.

Shared Network Devices

In the proposed network model shared and dedicated network devices handle the data traffic between data processing ICT hardware (e.g. clients and servers). The data traffic is generated by multiple IT-Services, which is why network devices' overall energy consumption needs to be allocated by dint of a specific performance factor. The most precise performance factor would be the device's handled data traffic over a given time period, for example the Internet backbone router X handled 20 TB data traffic per month of which 1 TB was induced by the usage of Online Storage. This setting would indicate a performance factor of 1/20 for backbone router X. Since there is no data of handled traffic for shared network devices, especially on internet infrastructure, we devised a different approach to evaluate performance. All shared network devices have a theoretical maximum bandwidth (TMB) in our network model. Staying with the example of a backbone router, its TMB is 30 Gigabit per second (Gbps) which means the router theoretically processes 30 Gigabit data every second. Operating at this level the router would have no capacity reserve. The average link utilization in backbone networks of large Internet service providers was estimated to be around 30-40% in 2010 (Fisher, Suchara and Rexford, 2010). Assuming that internet network utilization increased since 2010, we chose 50% of TMB to create a plausible indicator for shared network devices' total performance. The next step to create a performance factor is the determination of shared network devices' performance induced by Online Storage. We therefore used the customer internet connection's bandwidths (ICB) since these measures are the limiting factors for uploading and downloading data. Applying this approach, shared network devices can be differentiated in two operating modes: upload and download. Thus internet backbone routers' allocated energy consumptions per user were calculated as follows:

General calculation:

$$EC^{BackboneRouters}_{OnlineStorage} = EC^{BackboneRouters}_{Total} \cdot PF$$

$$EC^{BackboneRouters}_{Total} = 2 \cdot 3500Wh = 7000Wh$$

Upload calculation:

$$PF_{up} = \frac{ICB_{up}}{\frac{1}{2} \cdot MTB} = \frac{2{,}39Mbps}{\frac{1}{2} \cdot 30 \cdot 1024Mbps} \sim 0{,}000155599$$

$$EC^{BackboneRouters}_{UpOnlineStorage} = EC^{BackboneRouters}_{Total} \cdot PF_{up}$$

$$= 7000Wh \cdot 0{,}000155599 \sim \mathbf{1{,}089Wh}$$

Download calculation:

$$PF_{down} = \frac{ICB_{down}}{\frac{1}{2} \cdot MTB} = \frac{16{,}9Mbps}{\frac{1}{2} \cdot 30 \cdot 1024Mbps} \sim 0{,}00110026$$

$$EC^{BackboneRouters}_{DownOnlineStorage} = EC^{BackboneRouters}_{Total} \cdot PF_{down}$$

$$= 7000Wh \cdot 0{,}00110026 \sim \mathbf{7{,}702Wh}$$

The highlighted values stand for the energy consumption of a backbone router related to one hour continuous uploading to respectively downloading from storage server per user. In order to relate this data to a one year usage, we defined a profile which specifies amounts of uploaded and downloaded data per user (see Table 2). By relating the data amounts per year to ICB, we determined (3.588.096Mb/2,39Mbps/3600s=) 417,0 yearly upload operating hours and (2.990.080Mb/16,9Mbps/3600s=) 49,1 yearly download operating hours for Online Storage per user. Multiplying yearly operating hours and determined energy consumptions per hour relates the data to the FU. Thereby, backbone routers' yearly allocated energy consumption per user is (417,0h*1,089Wh$_{/h}$/1000=) 0,454kWh for uploading data and another (49,1h*7,702Wh$_{/h}$/1000=) 0,379 kWh for downloading data.

Direction	data (GB/day)	data (GB/year)	data (Mb/day)	data(Mb/year)
Upload	1,2	438	9.830,4	3.588.096
Download	1	365	8.192	2.990.080

Table 2. Usage profile of transferred data per storage user

Laptop Workplace

The Laptop Workplace comprises a 17 inch laptop, docking station and a 24 inch LCD monitor. Table 3 gives daily parameters for active power, time, and energy consumption associated with a laptop workplace. The parameters for active power have been measured in experimental simulation whereas daily operating hours for each mode were estimated.

Operating Mode	Active Power (W)	operating hours (h/day)	total EC (Wh/day)
active	68	8	544
power saving	12	4	48
off	2	12	24

Table 3. Laptop Workplace energy parameters and operating hours

We assume an exclusive usage of the laptop workplace for upload and download activities, which is why an allocation due to multiple IT-Services by dint of a performance factor is not necessary. Considering Online Storage the laptop workplace operates (419,0h+49,1h=) 466,2 hours in active mode. Hence, it consumes (466,2h*68Wh$_{/h}$/1000=) 31,700kWh for uploading and downloading data.

In addition to energy consumption while uploading and downloading data (active mode), a specific share of overhead energy consumption for power saving and off modes must be related to this activity. Based on the values from Table 3 overhead energy consumption was allocated by means of relative daily operating hours which indicates yearly ((4/24)*466,2h/(8/24)*12Wh$_{/h}$/1000=) 2,797kWh overhead energy consumption due to power saving mode and another ((12/24)*466,2h/(8/24)*2Wh/h/1000=) 1,399kWh due to off mode of laptop workplace. The same approach was used to calculate data for Offline Storage usage at which operating hours for active mode (36,5h) were actually measured in experimental simulation.

Table 4 provides an overview of parameters, which have been used to allocate energy consumptions of involved ICT hardware to the FU as well as the results of Life Cycle Inventory analysis.

Alter-native	Loca-tion	Subsystem name	ICT hardware name	allocated EC total (Wh per hour)	allocated EC per user (Wh per hour)	IT- Service operating hours per user (h per year)	yearly allocated EC per user (kWh per year) FU
Online Storage	Datacenter (ISP)	Data processing	Server incl. Storage[d]	5249	1,207	24 x 365 = 8760	10,570
		LAN	Managed Switch[d]	300	0,069	8760	0,604
			Load balancer[d]	300	0,069	8760	0,604
		Gateway	Core Switch[b,s]	x	4,948 / 34,988	417,0 / 49,1	2,063 / 1,720 total: 3,781
			Core Router[b,s]	x	1,634 / 11,553	417,0 / 49,1	0,681 / 0,568 total: 1,249
		ASI$^{PUE=1,35}$		x	x	x	5,884
	Internet	Backbone	Backbone Router[b,s]	x	1,089 / 7,702	417,0 / 49,1	0,454 / 0,379 total: 0,833
		Point of Presence	PoP Router[b,s]	x	0,607 / 4,291	417,0 / 49,1	0,211 / 0,253 total: 0,464
		ASI$^{PUE=1,5}$		x	x	x	0,648
	Customer	LAN	Home Router[d]	11	11	466,2	5,128
			Desktop Switch[d]	4	4	466,2	1,865
		Data processing	Laptop Workplace[a,d]	68 / 12 / 2	68 / 12 / 2	466,2 / 233,1 / 699,3	31,700 / 2,797 / 1,399 total: 35,895
						Online Storage total:	67,528
Offline Storage	Customer	LAN	Home Router[d]	11	11	36,5	0,435
			Desktop Switch[d]	4	4	36,5	0,158
		Data processing	Laptop Workplace[a,d]	68 / 12 / 2	68 / 12 / 2	36,5 / 18,3 / 54,8	0,485 / 0,219 / 0,110 total: 2,814
			NAS[a,d]	28 / x / 2	28 / x / 2	2920 / x / 5840	93,440 / x / 11,680 total: 105,120
						Offline Storage total:	96,847

Table 4. Used parameters and results of LCI

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

For the calculation of carbon footprints, we assumed that the involved ICT hardware consumes a hundred percent grid-sourced energy in Germany, which is why a specific carbon emission factor (CEF) of the consumed energy-mix is needed. The CEF (kg CO2-e/kWh) converts energy usage rates into carbon equivalent emissions in order to quantify GWP. The estimated CEF for domestic electricity consumption in Germany (566 g CO2-e/kWh) was used to calculate the following results (German Federal Environment Agency, 2012).

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[a] Includes allocated energy consumption and operating hours for different operating modes (active / power saving / off)

[b] Differentiation of allocated energy consumption and operating hours for different modes (upload / download)

[d] Dedicated ICT hardware used exclusively for the assessed IT-Service

[s] Shared ICT hardware used for multiple IT-Services

RESULTS AND INTERPRETATION

Figure 3 represents our main results. The CFIS for operating and using Online Storage within a period of 12 months related to one user is nearly 35kg CO2-e, whereat the laptop workplace is the dominating ICT subsystem, contributing the highest emission share (53%). The main reason for that is the limiting character of ICBs, which literally doom customers' data processing devices to wait for upload and download. ISP's DC infrastructure accounts for nearly 34% of calculated emissions at which classical Green IT measures such as hardware virtualization may lower DC's emission contingent. The CFIS for Offline Storage related to the FU is nearly 55kg CO2-e, at which the NAS system contributes mostly all of the emissions (96%). This is reasonable due to the facts that the NAS operates exclusively to provide storage to one user and laptop workplace as well as home LAN devices operate just a few hours (see Table 4). We realize that the study considers a very specific setting including very specific results, but it also provides a structured approach to assess GHG emissions of IT-Services and reveals potentials for emission reduction.

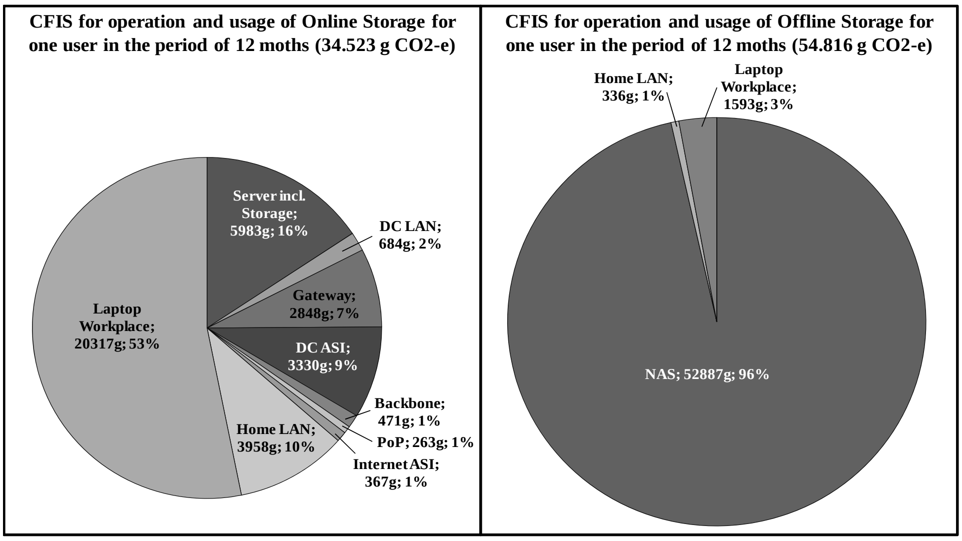

Figure 3. CFIS results including shares of involved ICT subsystems

CONCLUSION AND FURTHER RESEARCH

CF and LCA are well known concepts providing structured approaches to assess environmental impacts of individuals, countries, organizations, processes, products or events. In practice the CF concept is being used for the declaration and labeling of consumer products to present their impact on global climate change along product's lifecycle. GHG assessment of IT-Services is very rare due to the fact that IT-Services and underlying ICT infrastructures are complex constructs. Energy consumption of ICT hardware and related environmental impacts occurring from GHG emissions are major issues in the focus of Green IT. In order to address our first research question we developed a methodological framework to assess CFIS, which is based on standards for CFP. The framework specifies the phases of LCA by defining necessary tasks. We applied the methodological framework to conduct a comparative study which assesses energy consumptions and GHG emissions related to the IT-Service alternatives Offline and Online Storage. The study addressed the second research question by presenting a network model that refines system boundaries. The study further demonstrates energy assessment of ICT hardware as well as performance measures in order to allocate energy consumption. For the comparison of IT-Service alternatives we presented allocation approaches and calculation examples in order to relate specific energy consumption shares of ICT hardware to IT-Services. The comparative study of energy consumption for Offline and Online Storage revealed that the calculation of carbon footprint values can only illuminate specific settings. Thus, the main issues on further research will be the identification of general CFIS drivers through sensitivity analyses of input variables and the evaluation of the concept in case studies, examining IT-Services within multiple scenarios. The main boundaries of CFIS for now are its limitation to scope 2 GHGs from energy consumption and its particular focus on the use stage of ICT hardware lifecycle, which is why CFIS will be expanded by the assessment of downstream and upstream lifecycle stages of ICT hardware. An approach to consider missing lifecycle stages is the application of determined performance factors and operation times from use stage in order to allocate up and downstream carbon emissions. To create a comprehensive CFIS it is further necessary to analyze sourcing processes, software engineering as well as other GHGs scopes (e.g. direct emissions from usage of coolants in DC).

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