Data Center Green Performance Measurement: State of the Art and Open Research Challenges

Completed Research Paper

Björn Schödwell
Technische Universität Berlin
b.schoedwell@tu-berlin.de

Koray Erek
Technische Universität Berlin
koray.erek@tu-berlin.de

Rüdiger Zarnekow
Technische Universität Berlin
ruediger.zarnekow@tu-berlin.de

ABSTRACT

Data centers (DC/DCs) are indispensable elements of information systems. The increase in information technology service demand drives their worldwide grow in number, size and energy consumption. In the light of depleting raw natural resources and climate change induced by greenhouse gases (GHG) the environmental impacts of DCs have received particular attention. This paper reviews literature to highlight major issues that contribute to DCs ecologic sustainability, and explores the state of the art of green performance indicators (GPIs) to assess DCs environmental performance, in particular the energy, GHG and resource efficiency. Afterwards, the identified GPIs are classified and clustered to construct a green performance measurement system. Furthermore, the paper generates insights in relation to the recognition and application of proposed GPIs in practice through 13 questionnaires and two expert interviews. Thus, the paper provides academics and practitioners with the body of knowledge on DC green performance measurement, and moreover formulates open research challenges.

Keywords

Sustainability, Green IT, Data Center, Performance Measurement, Green Performance Indicators, Metrics

INTRODUCTION

The increasing pervasion of information systems and technology (IS/IT) into all parts of the globalized economy and human life have led to major concerns in relation to their environmental sustainability (eSustainability). In particular, data centers (DC/DCs) have been upgraded by IS organizations continuously to offer institutional and private customers a constantly growing variety of IT services. As a consequence, inventory, power density and energy use of DCs are rising steadily (EPA, 2007). Recently, grow has slowed down; however, in the year 2010 approximately 34 million servers have been deployed worldwide that DCs caused almost 1.5 percent of the total global electricity demand (Koomey, 2011). As long as power generation refers to the combustion of fossil fuels, this development directly confronts efforts to tackle climate change through the avoidance of greenhouse gases (GHG), respectively carbon dioxide equivalent (CO_2-eq) emissions. Moreover, in the light of depleting raw natural resources and fast increasing waste streams the manufacturing, transportation and disposal of the DC infrastructure have a non-negligible environmental impact as well (Elliot and Binney, 2008). To provide decision makers and technology managers of IS organizations, customers and other stakeholders valuable information in a compact fashion a set of green (key) performance indicators (GPIs) is needed assessing the environmental performance of DCs.

Although much research effort has been made in the field of greening DC operation so far, there is only little research on DC green performance measurement systems. Moreover, to the knowledge of the authors there is no information on the current situation in regard to the recognition and application of proposed GPIs in IS organizations available.

In this light, the paper addresses two major research questions:

> RQ1: What aspects contributing to DCs eSustainability were treated by proposed GPIs, how can these GPIs be integrated towards a holistic framework and which environmental impacts of DCs lack corresponding GPIs?

> RQ2: Which of the proposed GPIs are known and used by IS organizations for green performance measurement?

To answer these questions, the paper is organized as follows: The next chapter explains the research approach and ranges the paper into the context of related work. We then highlight major aspects contributing to DCs eSustainability, review GPIs to construct a holistic framework dedicated to DCs green performance measurement, and furthermore evaluate the recognition and application of GPIs in practice. Afterwards, we generalize the survey results taking expert opinion into account, formulate open research challenges and point out the limitations. Finally, the conclusion summarizes the findings.

METHODOLOGY AND RESEARCH FOUNDATION

Research Approach

We apply the paradigm of design sience with the goal to create an artifact, in this case the green performance measurement system (Hevner, March, Park, & Ram, 2004). The research is mainly exploratory driven using quantitative (questionnaire) and qualitative (expert interviews) methods. We first conduct an extensive literature review on the state of the art of GPIs (step 1). In this context we also explore DCs architecture and DC systems interrelations by reverting to data on typical DC infrastructure which have been collected through our DC benchmarking tool (http://dcb.ikm.tu-berlin.de). Based on these results, we design a green performance measurement system with a holistic set of GPIs. In the next step the GPIs are evaluated in terms of their recognition and application within 13 German IS organizations using a standardized questionnaire (step 2). This approach helped us to explain the current challenges while using these GPIs in the practice, especially with regard to assess the overall eSustainability. Finally, we generalize the results of the survey with two subject-matter expert interviews (step 3) and derive further research challenges (step 4).

Figure 1: Research Approach

Related Work

In the course of depleting natural resources and increasing negative environmental impacts the report "The Limits to Growth" provoked an ongoing discussion about the sustainability of our globalized economy (Meadows, Meadows, Randers, & Behrens, 1972). Today, authors mostly refer to the “Triple Bottom Line” model that fosters the equal recognition of economic, environmental and social aspects alike the stages of value chains (Elkington, 1997). Recently, this concept was transferred for IS organizations through the sustainable information management model (Schmidt, Erek, Kolbe, & Zarnekow, 2009). In particular, the eSustainability of IS/IT is addressed with the umbrellas "Green IT", "Green IS" or "Green through IT": "Green IS" and "Green through IT" cover approaches to make implications of business and human life through the use of IT and IS environmentally conform (Jenkin, Webster, & McShane, 2010; Watson, Boudreau, & Chen, 2010). Meanwhile, sub-disciplines like “Green Business Process Management” or “Energy Informatics have been defined (vom Brocke, Seidel, & Recker, 2012; Watson & Boudreau, 2011). In contrast, "Green IT" focuses the environmental sound manufacturing, use and disposal of hardware and the greenness of software (Loos, et al., 2011; Naumann, Dick, Kern, & Johann, 2011).

In this context, the energy efficiency of DCs has received particular attention due to the immensely grow of power consumption over the last decade. The manifold efforts aim to improve DCs architecture, systems and processes through identification and application of best practices and the development of GPIs to assess DCs green performance (EPA, 2007). Research that directly relates to our work present an energy efficiency model based on metrics (Belady and Malone, 2007; Daim, Justice, Krampits, Letts, Subramanian, & Thirumalai, 2009), a layered framework determining DCs energy efficiency based on resource usage (Kipp, Jiang, Fugini, & Salomie, 2012), a taxonomy study of DCs performance metrics (Wang & Khan, 2011), a framework that assesses DCs operational energy efficiency on multiple levels (Schödwell, Wilkens, Erek, & Zarnekow, 2012), and a first maturity model dedicated to DCs sustainablility (Singh, Azevedo, Ibarra, Newark, O’Donell, Strategy Group, Ortiz, Pfleuger, Simpson and Smith 2011). However, except the latter authors predominantly focus on the operational energy efficiency and productivity of DCs. In fact, there is currently no applicable framework determining DCs eSustainability on multiple levels of aggregation and from different perspectives available.

STATE OF THE ART OF GREEN PERFORMANCE INDICATORS

Architecture and Environmental Impacts of DCs Infrastructure

DCs house centralized servers, data storages and network devices to provide IT services and site infrastructure (SI) to secure the reliable operation of the hardware (Kant, 2009). Regularly, the IT is operated 24/7 hours 365 days a year, whereas its capacity is designed to meet agreed service levels (SLAs). To guarantee a reliable power provisioning energy systems mostly cover backup generators and uninterruptible power supplies (UPS). If appropriate DCs generate power onsite (OSG) through photovoltaik, wind or combined heat and power plants (CHP). In the last case the extracted heat usually supplies absorption chillers for trigeneration. As all consumed elecricity is converted into heat it must be removed by the heating, ventilation, air-conditioning system (HVAC-S) to maintain air temperature and humidity within recommended ranges. Traditional HVAC-S cover chillers, cooling towers or dry coolers, economizers, computer room air conditioners/handlers (CRAC/H), direct expansion air handling units (DX AHU) and multiple liquid cooling cycles. If appropriate DCs may also apply geothermal, river or sea water free cooling or reuse the rejected heat, whereas the applicability of those technologies highly depends on the location of the particular DC (region, mixed/standalone). Recently, growing power densities lead to the return of direct liquid cooling solutions. Figure 2 classifies the typical inventory of DCs into functional systems.

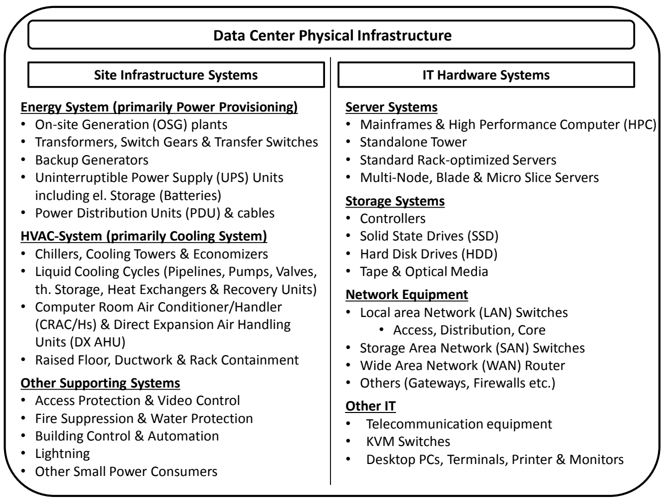

Figure 2: Classification of DCs inventory into functional systems

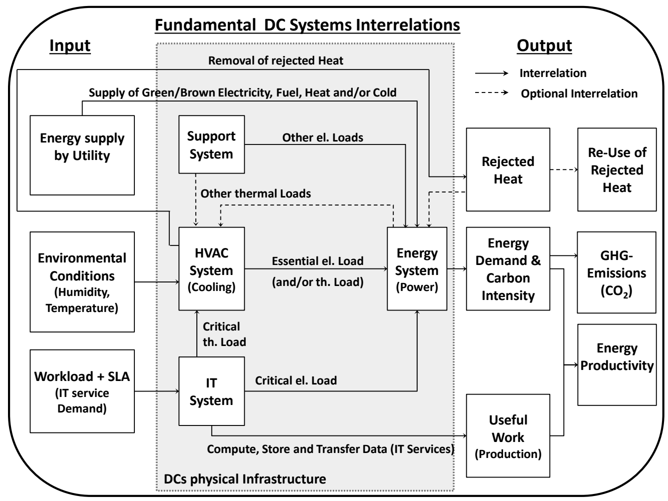

Figure 3: Interrelations of DCs functional systems

The IT energy, cooling and availability requirements determine the installed and operated capacity of SI systems. The interplay of software layers in conjunction with the peak workload determines the required hardware capacity. Power-aware software design and causal allocation of IT energy use to applications foster architectures that minimize the required IT capacity whereas high utilization increases resource efficiency (Kansal & Zhao, 2008); Costa & Hlavacs, 2010). However, as peak load occur irregularly, IT often is slightly utilized wasting power due to insufficient energy proportionality of legacy systems (Barroso & Hölzle, 2007). In the near future, new hardware and volatile workloads likely will lead to variable energy use and heat rejection of the IT that will directly affect utilization and energy efficiency of SI systems. Being aware of these fundamental interrelations IS organizations can minimize DCs energy use during operation through right-sized (modular), excellent energy proportional and productive IT and SI systems. Optimized air handling, application of free cooling and trigeneration can improve SI energy efficiency, whereas CO_2-eq can be reduced by purchasing and OSG of green energy.

The operational energy and resource efficiency are eminent drivers to increase DCs eSustainability. However, the restricted use of water for humidification, cooling towers and fossil OSG plants is important as well. Other environmental impacts relevant to particular DCs include noise, air pollution, land use and/or effects on the local biodiversity (Garnier, Aggar, Banks, Dietrich, Shatten, Stutz and Tong-Viet, 2012). From lifecycle perspective, energy, water and raw material use for the construction of the building and the manufacturing of IT and SI systems are non-negligible (Garnier et al., 2012). Lifecycle assessment (LCA) in relation to exergy use shows that focusing on operational energy efficiency while designing DCs may not always lead to the most sustainable solution (Meza, Shih, Shah, Ranganathan, Chang, & Bash, 2010). Moreover, the restricted use of hazardous and toxic substances as well as use of raw natural resources while manufacturing and the environmentally-sound disposal of equipment through high-quality recycling should be guaranteed (Elliot and Binney, 2008, Garnier et al., 2012).

Review and Classification of proposed GPIs

GPIs coordinate efforts to increase DCs eSustainability representing one particular or several optimization objectives at once. Stakeholders interested in such information include architects, operators, customers, and policy makers for regulation. GPIs for different environmental impacts identify correlated or conflictive optimization objectives. For example, high IT utilization accounts for high ressource efficiency but also fosters energy efficiency if the IT lacks energy proportionality. Otherwise, HVAC-S may cover DX AHUs instead of chillers and cooling towers, that energy use of the HVAC-S is high, but water use stays low. Furthermore, GPIs on multiple levels of aggregation secure the ability to derive appropriate improvement measures, as DC level GPIs enable benchmarking with others, but may also hide the origin cause of the problem. Table 1 shows our classification scheme of GPIs dedicated to DCs eSustainability.

<table>
<tr><td>Vision/Strategy</td><td colspan="6">Reduce DCs environmental impacts</td></tr>
<tr><td>Optimization Objective (Operationalization)</td><td colspan="2">Minimize Energy Use
(Energy Efficiency & Productivity, Trigeneration)</td><td>Minimize GHG–Emissions
(Green OSG & Procurement of Green Energy Certificates)</td><td>Maximize Resources Use
(increase utilization)</td><td colspan="2">Minimize other Impacts
(Space, Water, Waste, Noise, Air Pollution etc.)</td></tr>
<tr><td>Aggregation</td><td>Data Center</td><td>Main Functional System</td><td>Functional System</td><td>System Tier</td><td>System</td><td>Component</td></tr>
</table>

Table 1: Classification of GPIs

Reviewing the GPIs we limit the presentation to name, symbol, metric and purpose due to paper space limitations. We harmonize metric terminology (see reference for orginal terminology), consolidate GPIs that uses anloge metrics but other names (see footnotes), and extract embodied sub-level GPIs through decomposition to put them on the appropriate level.

Data Center Level GPIs

Name, Symbol & Metric	Purpose	Reference
Coefficient of Energy Efficiency (CEE) $\text{CEE} = \frac{\text{computing components energy use [kWh]}}{\text{DC energy use [kWh]}} = \frac{\text{DCiE}}{\text{H-EOM}}$	characterize SI´s and IT´s internal power and cooling components energy efficiency	(Aebischer, Eubank, & Tschudi, 2004)
DC energy Productivity (DCeP) $\text{DCeP} = \frac{\text{IT useful work [-]}}{\text{DC energy use [kWh]}} = \text{DCiE} \times \text{ITeP}$	measures IT´s energy productivity as sum of weighted use of completed IT tasks relative to DC energy use	(Anderson, Cader,Darby, Gruendler, Hariharan, Holler, Lindberg, Long, Morris, Rawson, Rawson, Saletore, Simonelli, Singh, Tipley, Verdun and Wallerich, 2008)
DC Energy Efficiency & Productivity (DC-EEP) $\text{DC-EEP} = \text{PUE} \times \text{IT-PEW}$	assesses IT´s energy productivity and SI´s energy efficiency (conflictive optimization directions of sub-level metrics)	(Brill, 2007)
Compute Power Efficiency (CPE) $\text{CPE} = \frac{\text{ITEU}}{\text{PUE}}$	quantifies SI´s energy efficiency and IT resource efficiency	(Belady and Patterson, 2008)
Corporate Average DC Efficiency (CADE) $\text{CADE} = \text{FA} \times \text{ITAE}$	accounts for SI´s and IT´s energy and resource efficiency	(Kaplan, Forrest and Kindler, 2008)
DC Performance Per Energy (DPPE) $\text{DPPE} = \text{ITEU} \times \text{ITEE} \times \text{DCiE} \times \frac{1}{1 - \text{GEC}}$	measures SI´s energy efficiency, DC green energy use and IT energy productivity and ressource efficiency	(GITPC, 2012)
Electronics Disposal Efficiency (EDE), Material Recycling Ratio (MRR)	EDE will measure efficiency of equipment disposal MRR will measure ratio of recycled material, metric is work-in-progress	(Brown, Banks, Benjamin, Calderwood, Gonzalez, Llera, Pflueger, Schroeder, Singh, Stawarz and Watson, 2012)

Table 2: DC Level GPIs

SI system & SI systems Level GPIs

Name (Symbol) & Metric	Purpose	Source
Facility Efficiency (FE) $FE = FU \times DCiE$	measures SI´s energy and resource efficiency	(Kaplan et al., 2008)
Power Usage Effectiveness (PUE) & DC infrastructure Efficiency (DCiE)[1] $PUE = \frac{\text{DC energy use [kWh]}}{\text{IT energy use [kWh]}} = \frac{1}{DCiE} = PLF + CLF + OLF + 1$	characterize SI´s total energy efficiency	(Belady, Rawson, Pfleuger and Cader 2008)
Carbon Usage Effectiveness (CUE) $CUE = CEF \times PUE$	assesses DC operational CO_2-eq relative to IT energy use	(Belady, Azevedo, Patterson, Pouchet and Tipley, 2010)
Carbon Emission Factor (CEF) $CEF = \frac{CO_2\text{-eg of DC energy [kg } CO_2\text{-eq]}}{\text{DC energy use [kWh]}}$	accounts for the CO_2-eq per unit of used energy (i.e. by electricity or chilled water generation through utilities)	(Belady et al., 2010)
Energy Reuse Effectiveness (ERE) $ERE = (1 - ERF) \times PUE$	quantifies how much of DC energy use can be reused outside the DC relative to IT´s energy use	(Patterson, Tschudi, Vangeet, Cooley and Azevedo, 2010)
Energy Reuse Factor (ERF) $ERF = \frac{\text{Reused energy outside DC [kWh]}}{\text{DC energy use [kWh]}}$	represents share of DC energy use that is reused outside the DC	(Patterson et al., 2010)
Water Usage Effectiveness (WUE) $WUE = \frac{\text{DC water use [l]}}{\text{IT energy use [kWh]}}$ $WUE_{source} = EWIF \times PUE + WUE$	characterizes DC water use relative to IT´s energy use, WUE_{source} includes water use through sourced energy supplied by utility	(Patterson, Azevedo, Belady and Pouchet, 2011)
Energy Water Intensity Factor (EWIF) $EWIF = \frac{\text{water use to generate DC source energy [l]}}{\text{DC source energy [kWh]}}$	accounts for the water use by utility to provide DC sourced energy (i.e. water use through electricity generation)	(Patterson et al. , 2011)
Green energy Coefficient (GEC) $GEC = \frac{\text{DC green energy use [kWh]}}{\text{DC source energy use [kWh]}}$	ratio of DC green energy relative to DC`s energy use, green energy accounts for OSG and purchased certificates of green energy	(GITPC, 2012)
Energy Carbon Intensity (ECI) $ECI = \frac{CO_2 \text{ emitted [} CO_2\text{-eg kg]}}{\text{DC secondary energy use [kWh]}}$	represents the carbon intensity of secondary energy (electricity, cold) used in the DC	(GITPC, 2011)
Onsite Generation Efficiency (OGE) $OGE = \frac{\text{DC secondary energy use [kWh]}}{\text{DC source energy use [kWh]}}$	represents DC OSG energy efficiency in relation to utilities electricity generation efficiency	(GITPC, 2011)
Facility Utilization (FU)[2] $FU = \frac{\text{IT energy use [kWh]}}{\text{DC´s IT energy use capacity [kWh]}}$	measures SI´s resource efficiency (power provisioning utilization), may be also defined as minimum of utilization of IT´s energy use, cooling, space, weight and airflow capacity (Belady and Patterson, 2008)	(Kaplan et al., 2008)
Power Load Factor (PLF) $PLF = \frac{\text{energy system energy losses [kWh]}}{\text{IT energy use [kWh]}}$	ratio of energy use of energy (original: power) system including switch gear, UPS, PDU, etc. relative to IT energy use	(Belady et al., 2008)
Electricity Production Rate (EPR) $EPR = \frac{\text{generated electricity [kWh]}}{\text{source energy use [kWh]}}$	assesses share of electricity generated onsite through CHP relative to source energy used	metric = own proposal, definition see (Azevedo and Rawson, 2008)
(energy) Storage Efficiency (eSE)	measures energy efficiency (energy losses) of energy	metric = own proposal,

[1] PUE = SI Energy Efficiency Ratio (Brill, 2007) = SI Power/Energy Overhead Multiplier (Stanley, Brill and Koomey, 2007), DCiE = K = C1 (Aebischer, Eubank, & Tschudi, 2004) = Computer Power Consumption Index (Greenberg, Mills, Tschudi, Rumsey and Myatt, 2006a) = Facility Energy Efficiency (Kaplan et al., 2008)

[2] FU = DC utilization (U_{DC}) (Belady and Patterson, 2008)

$eSE = \frac{\text{energy storage output [kWh]}}{\text{energy storage input [kWh]}}$	storages (e.g. batteries)	definition (Azevedo and Rawson, 2008)
(energy) Distribution Efficiency (eDE) $eDE = \frac{\text{energy distribution output [kWh]}}{\text{energy distribution input [kWh]}}$	measures energy efficiency (energy losses) of energy system due to distribution and line switching	metric = own proposal, definition (Azevedo and Rawson, 2008)
(energy) Conversion Efficiency (eCE) $eCE = \frac{\text{energy conversion output [kWh]}}{\text{energy conversion input [kWh]}}$	assesses energy efficiency (energy losses) of energy system due to energy conversion	metric = own proposal, definition (Azevedo and Rawson, 2008)
Critical Power Path Efficiency (CPPE) $CPPE = UPS\text{-}SE \times Trafo\text{-}SE \times PDU\text{-}SE$	represents energy losses from DCs entrance to IT (should include transformer, switchgear, UPS and PDU losses)	metric = own proposal, definition (Singh et al., 2011)
UPS Load Factor (UPS-LF) $UPS\text{-}LF = \frac{\text{UPS electricity output [kWh]}}{\text{UPS electricity output capacity [kWh]}}$	accounts for resource efficiency (utilization) of UPS	(Mathew, Greenberg, Sartor, Bruschi and Chu, 2010)
UPS System Efficiency (UPS-SE) $UPS\text{-}SE = \frac{\text{UPS output power [kW]}}{\text{UPS input power [kW]}}$	accounts for energy efficiency of UPS system	(Mathew et al., 2010)
HVAC System Effectiveness (HVAC-SE)[3] $HVAC\text{-}SE = \frac{\text{IT energy use [kWh]}}{\text{HVAC energy use [kWh]}}$	characterizes energy productivity of HVAC-S	(Mathew et al., 2010)
DC Cooling System-Efficiency (CS-E) $CS\text{-}E = \frac{1}{COP} = \frac{\text{cooling system energy use [kWh]}}{\text{DC cooling load [kWh]}}$	accounts for energy productivity of cooling system (chillers, pumps, and cooling towers but no CRAC/H), inverse COP represent energy productivity of single chiller, DXAHU, CRAC or of ensemble	(Mathew et al., 2010)
DC Cooling System Sizing Factor (CS-SF) $CS\text{-}SF = \frac{\text{installed chiller cooling capacity [kWh]}}{\text{peak chiller cooling load [kWh]}}$	measures resource efficiency in terms of installed cooling capacity of chiller relative to peak cooling load	(Mathew et al., 2010)
Cooling Load Factor (CLF) $CLF = \frac{\text{HVAC energy use}}{\text{IT energy use}}$	measures HVAC-S´ energy overhead relative to IT´s energy use	(Belady et al., 2008)
Chiller Efficiency (Ch-E) $Ch\text{-}E = \frac{\text{chiller energy use [kWh]}}{\text{chiller cold production [kWh]}}$	measures the energy productivity of chillers	(Greenberg Tschudi and Weale, 2006b)
Cooling Tower Efficiency (To-E) $To\text{-}E = \frac{\text{cooling tower energy use [kWh]}}{\text{cooling tower cold production [kWh]}}$	measures the energy productivity of cooling towers	(Greenberg et al., 2006b)
Water Pump Efficiency (WP-E) $WP\text{-}E = \frac{\text{water pump energy use [kWh]}}{\text{cold transported [kWh]}}$	measures the energy productivity of water pumps	(Greenberg et al., 2006b)
Rack Cooling Index (RCI) $RCI_{high} = (1 - \frac{\text{Total Over-Temp}}{\text{Max Allowable Over-Temp}})$ $RCI_{low} = (1 - \frac{\text{Total Under-Temp}}{\text{Max Allowable Under-Temp}})$	measures how effectively IT are cooled in racks within thermal guidelines at high and low end of recommended temperature range	(Herrlin, 2005a)
Return Temperature Index (RTI) $RTI = \frac{\text{CRAC return - supply air temperature}}{\text{rack outlet - inlet air temperature}}$	measures energy efficiency of air handling in terms of avoiding cold and warm air mixing (recirculation, bypass, negative pressure)	(Mathew et al., 2010)
Airflow Efficiency (AE) $AE = \frac{\text{fan energy use [kWh]}}{\text{volume of airflow [m}^3\text{]}}$	accounts for energy productivity of air flow generating units (CRAC/H, DXAHUs)	(Mathew et al., 2010)
Air/Water Economizer Utilization Factor	percentage of hours in a year that air- or water side	(Mathew et al., 2010)

[3] HVAC-SE = HVAC Effectiveness Index (Greenberg et al., 2006a)

$EUF = \frac{\text{economizer full or partial cooling hours [h]}}{\text{8760 [h]}}$	economizers provides full or partial cooling	
Others Load Factor (OLF) $OLF = \frac{\text{Others energy use}}{\text{IT energy use}}$	measures energy overhead of DC systems that not belong to energy or HVAC system relative to IT energy use	Own proposal
Lighting Power Density (LPD) $UPS\text{-}SE = \frac{\text{lights power demand [kW]}}{\text{DC floor space [m}^2\text{]}}$	accounts for DC lighting energy efficiency	(Mathew et al., 2010)

Table 3: SI-Level GPIs

IT System Level GPIs

IT Productivity per Embedded Watt (IT-PEW) $IT\text{-}PEW = \frac{\text{IT work [Trans/IO/Cycles]}}{\text{IT energy use [kWh]}}$	Measures IT energy productivity, work defined as network transactions, storage or computing cycles	(Brill, 2007)
IT energy Productivity (ITeP) $ITeP = \frac{\text{IT useful work [-]}}{\text{IT energy use [kWh]}}$	measures IT energy productivity as sum of weighted use of completed tasks relative to IT energy use	Own proposal, see (Anderson et al., 2008)
IT Asset Efficiency (ITAE) $ITAE = ITEE \times ITEU$	measures energy productivity and resource efficiency of IT systems	(Kaplan et al., 2008)
IT Equipment Efficiency (ITEE) $ITEE = \frac{\text{IT work [OPS/IOPS/GbPS]}}{\text{IT energy use [kWh]}}$	for DPPE: sum of normalized rated peak energy productivity of servers, storage and network (normalized to 2005 devices) for CADE: future metric	(GITPC, 2012), (Kaplan et al., 2008)
IT Equipment Utilization (ITEU) $ITEU = \frac{\text{IT capacity used [kWh]}}{\text{IT capacity installed [kWh]}}$	for CPE: CPU-utilization or server, storage and network utilization for CADE: CPU-utilization for DPPE: actual IT energy use relative to rated IT energy use	(Belady and Patterson, 2008), (Kaplan et al., 2008), (GITPC, 2012)
Data Center & Server compute Efficiency (DCcE/ScE $DCcE = \sum_{i=1}^{n} ScE_i = \sum_{i=1}^{n} \frac{\text{primary services server i}}{\text{total services server i}}$	Measures share of primary services relative to secondary IT services (virtualization, virus protection, backup etc.)	(Blackburn, Azevedo, Hawkins, Ortiz, Tipley and Van Den Berghe, 2010)
DC storage Efficiency (DCsE)	will assign for the efficiency of storage system	(Blackburn et al., 2010)
DC network Efficiency (DCnE)	will assign for the efficiency of network system	(Blackburn et al., 2010)
IT Hardware Energy Overhead Multiplier (H-EOM)[4] $H\text{-}EOM = \frac{\text{IT energy use}}{\text{computing components energy use}}$	characterize the energy overhead induced by the IT system`s internal power and cooling components	(Stanley et al., 2007)
Deployed Hardware Utilization Ratio (DH-UR) $DH\text{-}UR_{Server} = \frac{\text{servers running live application}}{\text{servers deployed}}$ $DH\text{-}UR_{Storage} = \frac{\text{amount of frequently accessed data}}{\text{mount of storage deployed}}$	determines fraction of servers that is running productive applications and the fraction of storage that is holding active data	(Stanley et al., 2007)
Deployed Hardware Utilization Efficiency (DH-UE) $DH\text{-}UE_{Server} = \frac{\text{servers necessary to handle peak load}}{\text{servers deployed}}$	determines efficiency of server capacity planning	(Stanley et al., 2007)
Server utilization (Server-U) $Server\text{-}U = \frac{\text{Activity of CPU [cycles]}}{\text{CPU capacity [cycles]}}$	CPU activity relative to its maximum ability (highest frequency), may be defined as minimum of utilization of CPU, memory bandwidth/space, disk IO/space and NIC/HBA bandwidth	(Belady and Patterson, 2008)

[4] $H\text{-}EOM = \int H\text{-}POM = 1/C2$ (Stanley et al., 2007), (Aebischer, Eubank, & Tschudi, 2004)

Storage utilization (Storage-U) $\text{Storage-U} = \frac{\text{used storage space [TB]}}{\text{storage space capacity [TB]}}$	percentage of used storage space relative to storage space capacity, may be also defined as utilization of storage IO capacity	(Belady and Patterson, 2008)
Network utilization (Network-U) $\text{Network-U} = \frac{\text{used bandwidth [Gbps]}}{\text{bandwidht capacity [Gbps]}}$	percentage of bandwidth used relative to bandwidth capacity	(Belady and Patterson, 2008)
Compute Load Density (CLD) $\text{CLD} = \frac{\text{IT power use [kW]}}{\text{computer floor area [m}^2\text{]}}$	characterizes resource efficiency in terms of area usage, similar metrics may be defined like IT power use per rack, DC power use per DC area etc.	(Mathew et al., 2010)
IT Recycling Metric (ITRM) $\text{ITRM} = \frac{\text{Weight Responsibly Disposed [ton]}}{\text{Weight Disposed [ton]}}$	measures resource efficiency in terms of eSustainable disposal of IT assets, work-in-progress	(Brown et al., 2012)

Table 4: IT-Level GPIs

IT benchmarks

Energy performance benchmarks exercise one or multiple performance benchmarks extended by energy measurement. They can guide procurement, system design and configuration decisions and be used for labeling of products. Analog metrics for SI systems exist (see COP), but are not considered due to paper space limitations.

Name (Symbol)	Purpose	Source
SPECpower_ssj2008	first energy performance benchmarks for servers, measures average server side java operations per watt	(SPEC 2013)
Server Efficiency Rating Tool (SERT)	energy performance benchmarks for servers, provides energy efficiency information across a range of application environments	(SPEC 2013)
TPC-Energy	energy measurement specification to augment existing energy performance benchmarks	(TPC, 2013)
Green500-List	energy performance benchmark for supercomputer, measures peak floating point operations (FLOPS) per watt, based on LINPACK	(CompuGreen, 2013)
Green Computing Performance Index (GCPI)	measures peak performance per watt based on industry standard HPCC benchmark suite	(West, 2009)
Space, Wattage and Performance (SWAP) $\text{SWAP} = \frac{\text{Performance benchmark}}{\text{Space [RU]} \times \text{Power [W]}}$	energy performance benchmark augmented by space use, space refers to chassis height in rack units, performance = any benchmark	(Greenhill, 2005)
SPC1(C)/E & SPC2(C)/E	first energy performance benchmark for storage equipment	(SPC, 2013)
SNIA Emerald	energy performance benchmark for storage equipment	(SNIA, 2012)
Energy Consumption Rating (ECR)	energy performance benchmark for network equipment	(ECR, 2013)
Telco Energy Efficiency Ratio (TEER)	energy performance benchmark for telecommunication equipment	(ATIS, 2009)

Table 5: IT energy performance benchmarks

Green Performance Measurement Framework

Based on our classification scheme presented in Table 1 and the identified GPIs we construct a holistic multilevel framework. As can be seen in Figure 4, most GPIs measure the energy or resource efficiency of functional systems and subsystems (including energy performance benchmarks). Other aspect have received nor, respectively less attention. The MRR and the EDE i.e. are the first GPIs that describe the recycling quality of DC equipment. GPIs to measure the deployed raw substances within a DC are missing completely, whereat such GPIs on component and system level could help to design DCs infrastructure in a more environmental conform way or guide adequate purchasing decisions. Furthermore, figure 4 shows that there are currently no GPIs available characterizing the energy or resource efficiency of the software layers.

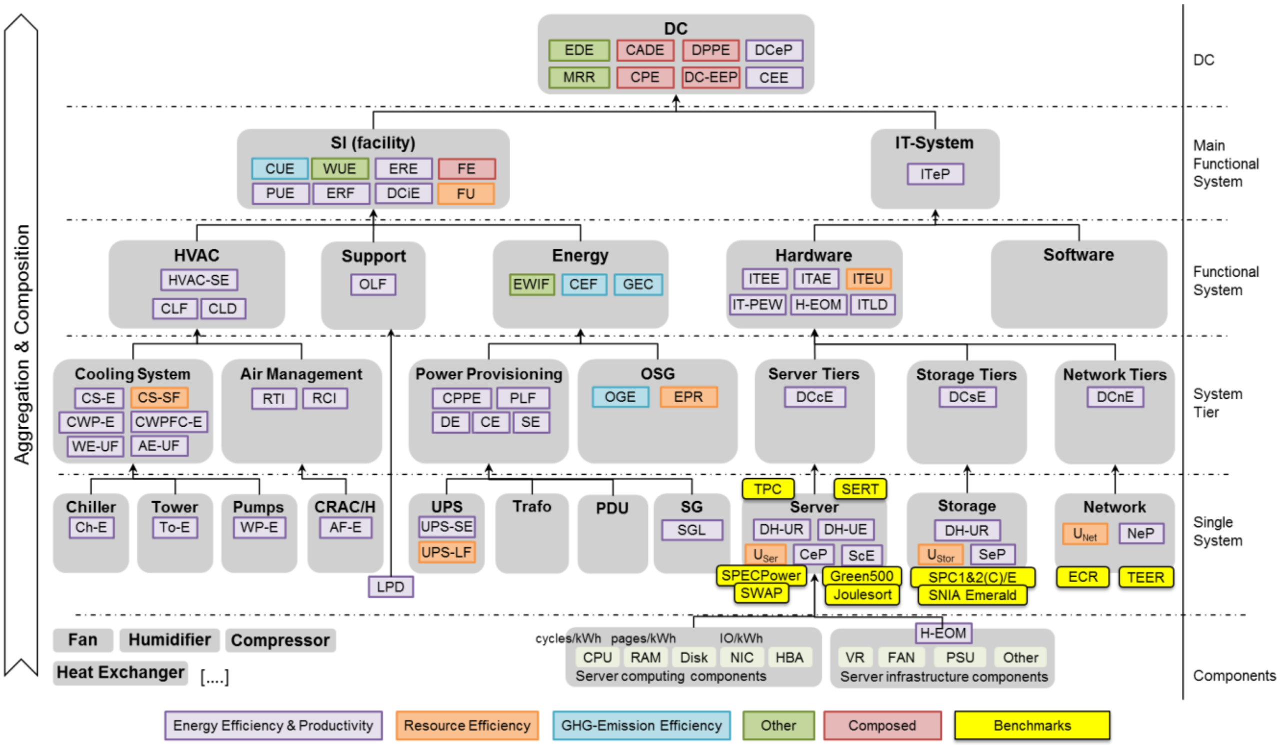

Figure 4: GPI Framework for DCs

Recognition and Application of proposed GPIs

To answer RQ2 being interested in the recognition and application of the identified GPIs by IS organizations we conducted an explorative survey in January 2013 consulting 13 DC operators in Germany using a structured questionnaire. First, we explored the importance of environmental aspects within the IS organization and for DC operation as well as the attitude and expertise of the respondents in this field (see figure 5). As can be seen, most organizations and respondents have a positive attitude towards eSustainability and belief that they have good knowledge in relation to GPIs.

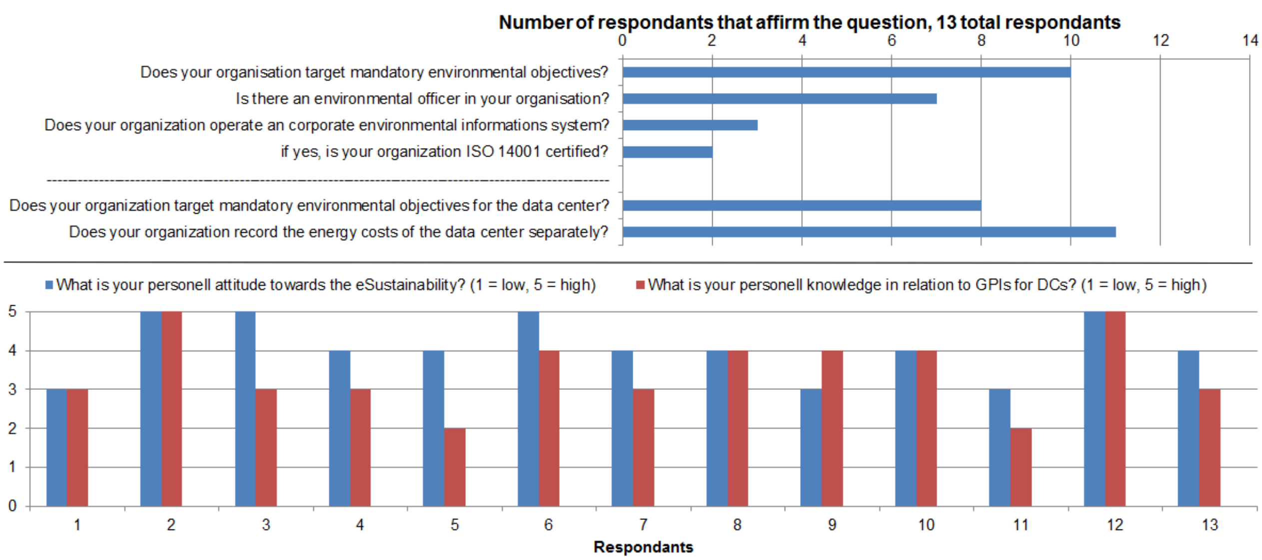

Figure 5: Importance of eSustainability to the organization, the DC and the respondent

Second, we ask for the implementation and granularity of measurements within DCs (see figure 6). As shown in figure 6 most of the respondents measure the energy use of IT systems especially of servers. However, the energy use of network and storage receives less attention. A similar behavior can be observed for the measurement of energy losses of the energy systems that are assessed by 8 of 14 respondents with a clear focus on the UPS sub-system. Furthermore, the measurement of HVAC energy use is conducted by the majority of the interviewed IS organizations. Moreover, almost every DC quantifies the temperatures within the computer rooms as wells as the utilization of the equipment.

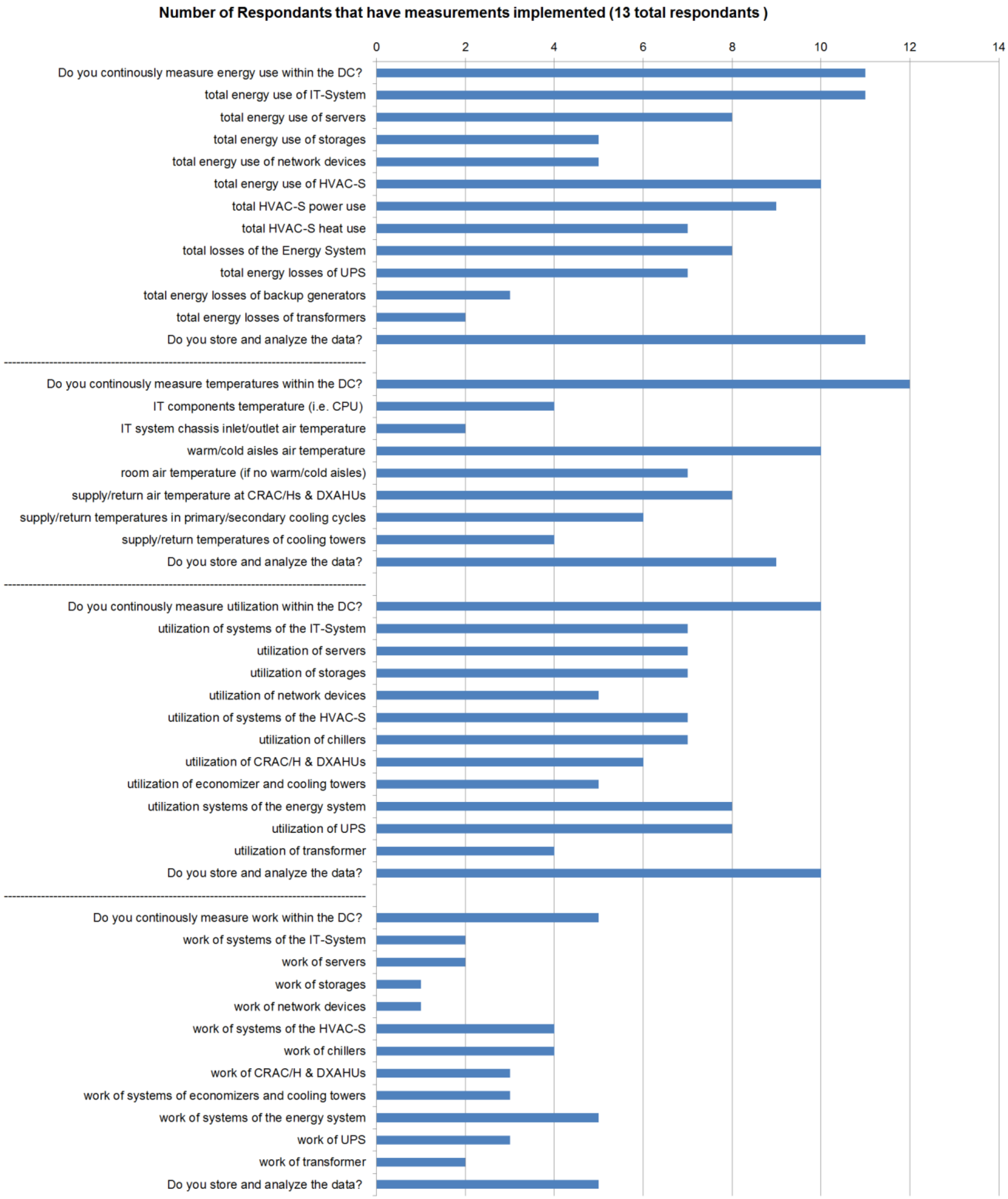

Figure 6: Implementation of measurement of energy use, temperature, utilization and work in the DC

Finally, we prove the recognition and application of GPIs. Figure 7 shows, that the PUE is well known and measured in most cases, whereat other GPIs lack recognition.

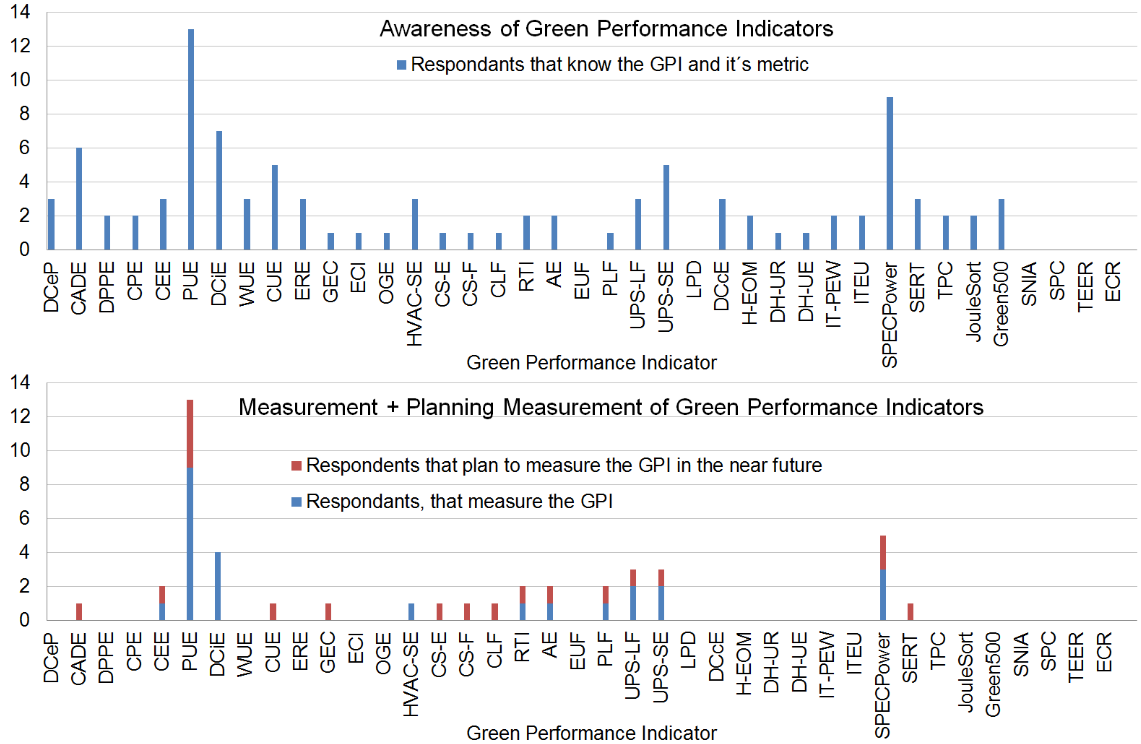

Figure 7: Recognition and application of GPIs in practice

DISCUSSION

The results of the survey do not represent the German market, but nevertheless we have identified some interesting points. We found that most organizations have mandatory environmental goals for the organization and the DC. Most respondents have a positive attitude towards eSustainability and belief to have good knowledge in relation to GPIs. In most cases energy use, temperature and utilization is measured in the DC, although with different granularity, whereas the assessment of produced work in all cases needs further improvement.

However, in terms of RQ2 most questioned respondents don´t know the identified GPIs, except the PUE, even if they collect and analyze the related data. The lack of knowledge is troublesome insofar that the PUE only characterizes the energy efficiency of the total SI, but isn´t saying anything about the energy efficiency of the IT system. Furthermore, the PUE may hide the origin cause of an energy inefficient SI system, as only additional GPIs on subsystem-level support the derivation of appropriate improvement measures. The use of GPIs dedicated to different environmental impacts thereby identify correlated or conflictive optimization objectives.

Verification of Results through Expert Interviews

To generalize the results of the survey we conducted two unstructured expert interviews with DC consultants. Presenting figure 6 experts argued, that measurements in DCs still mostly refer to availability or capacity planning activities, rather than aiming to assess and to improve the green performance of DCs in a holistic manner. Furthermore, they notice that DC operators often use a variety of different, partly proprietary monitoring tools to collect and to analyze the data and that data often can not be extracted and combined easily for green performance measurement. Moreover, they argued that there is a strong difference between new DCs that have been instrumented with multiple sensors during construction in contrast to legacy DCs that would need to implement additional measurement equipment during operation. Finally, experts think that DCs that provide standardized IT services on the market competing directly with other DCs are much more cost-aware than DCs that provide IT services to their own organization only, and thus will be much more interested in increasing the energy (Opex) and resource (Capex) efficiency of DCs as well as in presenting customers green DCs for marketing purposes.

Open Research Challenges

Based on the results of the literature review, the questionnaire and the insights of the conducted expert interviews we formulate three major open research challenges:

1. Evaluation of the implementation of the green performance measurement systems in DCs
2. Proposal of GPIs to characterize the energy and resource efficiency of software
3. Proposal of GPIs to characterize DC lifecycle relevant aspects (i.e. raw material use)

We prioritize the prototypical implementation of the presented framework for our own future research.

Limitations

Although the identification of GPIs in this paper is based on comprehensive literature review, the authors cannot guarantee for its completeness as new GPIs probably will occur in the near future. Furthermore the empirical study produces descriptive results, but the amount of questioned respondents is too small and the specific German focus limits its generalizability. A broader and deeper survey including qualitative analysis is needed and will be part of our future work as well.

CONCLUSION

This paper analyzed the body of knowledge in the field of DC green performance measurement. In terms of RQ1 the paper contributes to the academic IS community by providing a classification scheme for GPIs and proposing a novel framework that integrates multiple levels of aggregation and perspectives on DCs eSustainability. Practitioners can use the framework as guidance and extract GPIs to implement a green performance measurement system to analyze and to optimize the green performance of DCs in a compact, but detailed fashion, and to identify correlated or conflictive environmental objectives.

Furthermore, RQ2 was answered by conducting an explorative survey and two expert interviews. Results show that the PUE is widely accepted and measured, whereas other GPIs are much less recognized. This implicates that other GPIs need more communication. However, the generalization of the derived findings through subject-matter expert interviews pointed out that DC measurements still predominately aim to secure the reliable DC operation, whereat the application of green performance measurement systems in DCs highly depends highly on cost pressure i.e. induced by the market competition.

REFERENCES

1. Aebischer, B., Eubank, H. and Tschudi, W. (2004) Energy Efficiency Indicators for Data Centers, in *Proceedings of the International Conference on Improving Energy Efficiency in Commercial Buildings (IEECB´04)*, April 21–22, Frankfurt, Germany, ECEEE.
2. Anderson, D., Cader, T., Darby, T., Gruendler, N., Hariharan, R., Holler, A., Lindberg, C., Long, C., Morris, P., Rawson, A., Rawson, F., Saletore, V., Simonelli, J., Singh, H., Tipley, R., Verdun, G. and Wallerich, J. (2008) A Framework for Data Center Energy Productivity, *White Paper #13*, The Green Grid, Beaverton, OR, USA, www.thegreengrid.org/~/media/whitepapers/whitepaper13frameworkfordatacenterenergyproductivity5908.pdf, last accessed 13.05.2013.
3. ATIS. (2013). Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting for Router and Ethernet Switch Products, *ANSI Standard*, Alliance for Telecommunications Industry Solutions http://webstore.ansi.org/RecordDetail.aspx?sku=ATIS-0600015.06.2011, last accessed 13.05.2013.
4. Azevedo, D. and Rawson, A. (2008) Measuring Data Center Productivity, The Green Grid, Presentation held on 1st Annual Green Grid Technical Forum and Members Meeting 2008, February 5-6, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/TechForumPresentations2008/Measuring_Data_Center_Productivity.pdf, last access: 13.05.2013.
5. Barroso, L. A. and Hölzle, U. (2007) The Case for Energy-Proportional Computing. *Computer*, 40, 12, 33-37.
6. Belady, C. L. and Malone, C. G. (2007) Metrics and an Infrastructure Model to Evaluate Data Center Efficiency. Proceedings of the 2007 *ASME InterPack Conference (IPACK'07)*, July 8-12, Vancouver, BC, Canada, ASME, 751-755.
7. Belady, C. and Patterson, M. (2008) The Green Grid Productivity Indicator, *White Paper #15*, The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/whitepapers/white_paper_15_-_tgg_productivity_indicator_063008.pdf, last access: 13.05.2013.

8. Belady, C., Rawson, A., Pfleuger, J. and Cader, T. (2008) The Green Grid Data Center Power Efficiency Metrics: PUE and DCIE, *White Paper #6*, The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/WhitePapers/White_Paper_6_-_PUE_and_DCiE_Eff_Metrics_30_December_2008.pdf, last access: 13.05.2013.

9. Belady, C., Azevedo, D., Patterson, M., Pouchet, J. and Tipley, R. (2010), Carbon Usage Effectiveness (CUE): A Green Grid Data Center Sustainability Metric, *White Paper #32*, The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/WhitePapers/CarbonUsageEffectivenessWhitePaper20101202.ashx, last access: 13.05.2013.

10. Blackburn, M., Azevedo, D., Hawkins, A., Ortiz, Z., Tipley, R. and Van Den Berghe, S. (2010) The Green Grid Data Center compute Efficiency Metric: DCcE, *White Paper #34*, The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/WhitePapers/DCcE_White_Paper_Final.pdf, last access: 13.05.2013.

11. Brill, K. G. (2007) Data Center Energy Efficiency and Productivity, *White Paper*,. The Uptime Institue, Santa Fe, NM, USA, http://www.uptimeinstitute.org/symp_pdf/%28TUI3004C%29DataCenterEnergyEfficiency.pdf, last access: 13.05.2013.

12. Brown, E., Banks, M., Benjamin, E., Calderwood, T., Gonzalez Llera, R., Pflueger, J., Schroeder, G., Singh, H., Stawarz, S. and Watson, M. (2012). Electronics Disposal Efficiency:An IT Recycling Metric for Enterprises and Data Centers, *White Paper #53*, The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/whitepapers/wp53-electronics disposal efficiency an it recycling metric for enterprises and data centers.pdf, last access: 13.05.2013.

13. Butler, T. (2011) Institutional Imperatives on Environmental Sustainability: A Sense Making Perspective on Green IS, *Strategic Information Systems*, 20, 1, 6-26.

14. CompuGreen. (2013). The Green500 List, http://www.green500.org, last access: 13.05.2013.

15. Costa, G. and Hlavacs, H. (2010). Methodology of Measurement for Energy Consumption of Applications. in *Proceedings of the 11th IEEE/ACM International Conference on Grid Computing*, October 25-28, Brussel, Belgium, IEEE, 290-297.

16. Daim, T., Justice, J., Krampits, M., Letts, M., Subramanian, G. and Thirumalai, M. (2009) Data Center Metrics: An Energy Efficiency Model for Information Technology Managers. *Management of Environmental Quality: An International Journal*, 20, 6, 712-731.

17. ECR (2013) The Energy Consumption Rating (ECR) Initiative, http://www.ecrinitiative.org, last access: 13.05.2013.

18. Elkington, J. (1997) Cannibals With Forks: The Triple Bottom Line of 21st Century Business, Capstone, Oxford, UK.

19. Elliot, S. and Binney, D. (2008) Environmentally Sustainable ICT: Developing Corporate Capabilities and an Industry-Relevant IS Research Agenda, in *Proceedings of the 12th Pacific Asia Conference on Information Systems (PACIS´08)*, July 3-7, Suzhou, China.

20. EPA (2007) Report to Congress on Server and Data Center Energy Efficiency, U.S. Environmental Protection Agency, http://www.energystar.gov/ia/partners/prod_development/downloads/EPA_Datacenter_Report_Congress_Final1.pdf, last access: 13.05.2013

21. Garnier, C., Aggar, M., Banks, M., Dietrich, J., Shatten, B., Stutz, M. and Tong-Viet, E. (2012) Data Centre Life Cycle Assessment Guidelines, *White Paper #45*, The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/WhitePapers/WP45v2DataCentreLifeCycleAssessmentGuidelines.pdf, last access: 13.05.2013.

22. GITPC (2011) Proposal of OGE, On-site Generation Efficiency Metric, and ECI, Energy Carbon Intensity Metric, *White Paper*, Green IT Promotion Council, Tokyo, Japan, http://home.jeita.or.jp/greenit-pc/topics/release/pdf/dppe_e_20110222.pdf, last access: 13.05.2013.

23. GITPC (2012) DPPE: Holistic Framework for Data Center Energy Efficiency, *White Paper*, Green IT Promotion Council, Tokyo, Japan, http://home.jeita.or.jp/greenit-pc/topics/release/pdf/dppe_e_20120824.pdf last access: 13.05.2013.

24. Greenberg, S., Mills, E., Tschudi, B., Rumsey, P. and Myatt, B. (2006a) Best Practices for Data Centers: Lessons Learned from Benchmarking 22 Data Centers, in *Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings*, August 13-18, Pacific Grove, CA, USA, ACEEE, 77-87.

25. Greenberg, S., Tschudi, W. and Weale J. (2006b). Self Benchmarking Guide for Data Center Energy Performance Version 1.0, *White Paper*, Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA, http://hightech.lbl.gov/documents/data_centers/self_benchmarking_guide-2.pdf, last access 13.05.2013.
26. Greenhill, D. (2005) SWaP - Space, Watts and Power, *Presentation held on the EPA Power Efficiency Forum*. http://www.energystar.gov/ia/products/downloads/Greenhill_Pres.pdf, last access: 13.05.2013.
27. Hannemann, C. R., Carey, V. P., Shah, A. J. and Patel, C. (2008) Lifetime Exergy Consumption of an Enterprise Server, in *Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment (ISEE '08)*, Washington, DC, USA, IEEE, 1-5.
28. Herrlin, M. K. (2005) Rack Cooling Effectiveness in Data Centers and Telecom Central Offices: The Rack Cooling Index (RCI), *ASHRAE Transactions*, 111, 2, 725-731.
29. Hevner, A. R., March, S. T., Park, J. and Ram, S. (2004) Design Science in Information Systems Research. *MIS Quarterly*, 28, 1, 75-105.
30. Jenkin, T., Webster, J. and McShane, L. (2010) An Agenda for 'Green' Information Technology and Systems Research, *Information and Organization*, 21, 1, 17-40.
31. Kansal, A. and Zhao, F. (2008) Fine-grained Energy Profiling for Power-aware Application Design. *SIGMETRICS Performance Evaluation Review*, 36, 2, 26–31.
32. Kant, K. (2009) Data Center Evolution: A Tutorial on State of the Art, Issues, and Challenges. *Computer Networks*, 53, 17, 2939–2965.
33. Kaplan, J. M., Forrest, W. and Kindler, N. (2008) Revolutionizing Data Center Energy Efficiency, *White Paper*, McKinsey & Co. http://www.ecobaun.com/images/Revolutionizing_Data_Center_Efficiency.pdf, last access: 13.05.2013.
34. Kipp, A., Jiang, T., Fugini, M. and Salomie, I. (2012) Layered Green Performance Indicators, *Future Generation Computer Systems*, 28, 2, 478–489.
35. Koomey, J. (2011) Growth in data center electricity use 2005 to 2010, Analytics Press, Oakland, CA, http://www.analyticspress.com/datacenters.html, last access: 13.05.2013.
36. Loos, P., Nebel, W., Gómez, J. M., Hasan, H., Watson, R. T. and vom Brocke, J. (2011) Green IT: A Matter of Business and Information Systems Engineering?, *Business & Information Systems Engineering*, 3, 4, 245-252.
37. Mathew, P., Greenberg, S., Sartor, D., Bruschi, J. and Chu, L. (2010) Self-benchmarking Guide for Data Center Infrastructure, *White Paper*, Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA, http://www1.eere.energy.gov/femp/pdfs/dc_benchmarking_infrastructure.pdf, last access: 13.05.2013.
38. Meadows, D. H., Meadows, D. L., Randers, J. and Behrens, W. W. (1972) The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind, 2nd Edition, Universe Books, New York, NY, USA.
39. Meza, J., Shih, R., Shah, A., Ranganathan, P., Chang, J. and Bash, C. (2010) Lifecycle-based Data Center Design, in *Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition (IMECE´10)*, November 14-17, Vancouver, BC, Canada, ASME.
40. Naumann, S., Dick, M., Kern, E. and Johann, T. (2011) The GREENSOFT Model: A reference model for green and sustainable software and its engineering, *Sustainable Computing: Informatics and Systems*, 1, 1, 294–304.
41. Patterson, M., Tschudi, B., Vangeet, O., Cooley, J. and Azevedo, D. (2010) ERE: A Metric for Measuring the Benefit of Reuse Energy from a Data Center, *White Paper #29*, The Green Grid, Beaverton, OR, USA http://www.thegreengrid.org/~/media/WhitePapers/ERE_WP_101510_v2.pdf, last access: 13.05.2013.
42. Patterson, M., Azevedo, D., Belady, C. and Pouchet, J. (2011) Water Usage Effectiveness (WUE) - A Green Grid Data Center Sustainability Metric. *White Paper #29*, The Green Grid, Beaverton, O, USA, http://www.thegreengrid.org/~/media/WhitePapers/WUE_v1.pdf last access: 13.05.2013
43. Rivoire, S., Shah, M. A., Ranganathan, P. and Kozyrakis, C. (2007). JouleSort: a balanced energy-efficiency benchmark, in *Proceedings of the ACM 2007 International Conference on Management of Data (SIGMOD'07)*, June 11 – 14, Bejing, China, ACM, 365-376.

44. Schmidt, N., Erek, K., Kolbe, L. and Zarnekow, R. (2009) Sustainable Information Systems Management. *Business & Information Systems Engineering*, 1, 5, 400-402.

45. Schödwell, B., Wilkens, M., Erek, K., & Zarnekow, R. (2012). Towards a holistic multi-level green performance indicator framework (GPIF) to improve the Energy Efficiency of data center operation - A resource usage-based approach. in *Proceedings of the Electronics Goes Green (EGG'12)*, September 9-12, Berlin, Germany, IEEE, 1-6.

46. Singh, H., Azevedo, D., Ibarra, D., Newark, R., O'Donell, S., Strategy Group, Ortiz, Z., Pfleuger, J., Simpson, N. and Smith, V. (2011) Data Center Maturity Model, *White Paper #36* The Green Grid, Beaverton, OR, USA, http://www.thegreengrid.org/~/media/WhitePapers/Data%20Center%20Maturity%20Model%20White%20Paper_final_v2.pdf, last access: 13.05.2013.

47. SNIA (2013) Storage Networking Industry Association Emerald, http://snia.org/emerald, last access: 13.05.2013.

48. SPC (2013) Storage Performance Council, http://www.storageperformance.org/specs, last access: 13.05.2013.

49. SPEC (2013) Standard Performance Evaluation Corporation, http://www.spec.org/power_ssj2008, last access: 13.05.2013.

50. Stanley, J.R., Brill., K. G. and Koomey, J. (2007) Four Metrics define Data Center Greenness, *White Paper*, The Uptime Institue, Santa Fe, NM, http://www.dcxdc.ru/files%5C4ede4eff-13b0-49d9-b4da-b0406bfc190e.pdf, last access: 13.05.2013

51. TPC (2013) Transaction Processing Performance Council, http://www.tpc.org/tpc_energy, last access: 13.05.2013.

52. vom Brocke, J., Seidel, S. and Recker, J. (2012) Green Business Process Management: Towards the Sustainable Enterprise, Springer, Berlin.

53. Wang, L. and Khan, S. U. (2011) Review of performance metrics for green data centers: A taxonomy study, *The Journal of Supercomputing*, 58, 1, 1-18.

54. Watson, R. T. and Boudreau, M.-C. (2011) Energy Informatics, Green ePress, Athens, GA

55. Watson, R., Boudreau, M.-C. and Chen, A. (2010) Information systems and environmentally sustainable development, *MIS Quarterly*, 34, 1, 23-38.

56. West, J. (2009) SiCortex revises green performance index, http://insidehpc.com/2009/04/21/sicortex-revises-green-performance-index-intros-tool/, last access: 13.05.2013.